GROUND WATER AND HUMAN SECURITY

EDITED BY

FABRICE RENAUD AND
CORINNE SCHUSTER-WALLACE

UNITED NATIONS UNIVERSITY
UNU-INWEH
Institute for Water, Environment and Health

UNITED NATIONS UNIVERSITY
UNU-EHS
Institute for Environment and Human Security

United Nations Educational, Scientific and Cultural Organization

International Hydrological Programme

Groundwater and Human Security

Edited by
Fabrice Renaud and
Corinne Schuster-Wallace

Available from:
United Nations University
Institute for Water, Environment and Health (UNU-INWEH)
175 Longwood Road South, Suite 204
Hamilton, ON L8P 0A1 CANADA

Telephone: +1-905-667-5511
Fax: +1-905-667-5510
E-mail: contact.inweh@unu.edu

Web: inweh.unu.edu
Facebook: facebook.com/UNUINWEH
Twitter Handle: @UNUINWEH

Available for download at:
http://inweh.unu.edu

ISBN: 978-92-808-6082-5

UNU-INWEH is supported by:

Global Affairs Canada Affaires mondiales Canada

UNITED NATIONS UNIVERSITY

UNU-INWEH

The United Nations University Institute for Water, Environment and Health is a member of the United Nations University family of organizations. It is the UN Think Tank on Water created by the UNU Governing Council in 1996. The mission of the institute is to help resolve pressing water challenges that are of concern to the United Nations, its Member States, and their people, through knowledge based synthesis of existing bodies of scientifi cdiscovery; through cutting edge targeted research that identifi es emerging policy issues; through application of on-the-ground scalable solutions based on credible research; and, through relevant and targeted public outreach. It is hosted by the Government of Canada and McMaster University.

Table of Contents

CHAPTER 3 THE EFFECTS OF GROUNDWATER ARTIFICIAL RECHARGE ON HUMAN SECURITY IRAN CASE STUDY

CHAPTER 4 TRA VINH CASE STUDY – VIETNAM: VULNERABILITY OF COASTAL COMMUNITIES TO GROUNDWATER DEPLETION

CHAPTER 5 VIETNAM – BINH THUAN CASE STUDY: EXAMPLE OF AQUIFER RECHARGE

Acknowledgements

The publication of "Groundwater and Human Security" was a collaborative project between United Nations University Institute for Environment, Water and Health (UNU-INWEH), United Nations University Institute for Environment and Human Security (UNU-EHS), and the International Hydrological Programme at the United Nations Educational Scientific and Cultural Organization (UNESCO-IHP).

Many thanks are due to Adeel Zafar (UNU-INWEH) who was instrumental in all aspects of the project and Birgitte Schuster (UNU-INWEH) who was the key motivator and organised the original workshop for the Groundwater and Human Security Project.

We wish to thank Olivia Dun (UNU-EHS) who ensured the smooth administration of the project, overcoming logistical and communication challenges with good humour and efficiency, José Luis Martin-Bordes, in his function of UNESCO-IHP expert, and Jaroslav Vrba, in his function of UNESCO-IHP Senior Consultant, for their contribution to the preparation of the report.

We are also grateful to Leslie Barker, whose eye for detail helped guide this book through production, and to Kelsey Anderson (UNU-INWEH) for the design and layout of the book.

Foreword

This book synthesises the results of the Groundwater and Human Security – Case Studies (GWAHS-CS) project which was overseen by the United Nations University Institute for Water, Environment and Health, the United Nations University Institute for Environment and Human Security, the International Hydrological Programme of the United Nations Educational, Scientific and Cultural Organization, and the UN-Water Decade Programme on Capacity Development. The project was implemented by scientists and experts in four case study areas in Egypt, I.R. Iran, and Viet Nam. An additional case study from Bangladesh was added to the project, although not funded directly through it.

The GWAHS-CS project was operational from 2008 until 2010, and it is only later on that the idea of compiling the case studies into a single publication was put forward. Even though a few years have elapsed between the end of the project and the decision to publish this book, the processes, problems, and lessons learned are still relevant. It is now 2017 and international agreements on sustainable development, climate change adaptation and mitigation, disaster risk reduction, and urban development have been endorsed, and groundwater is relevant to all of them. Agenda 2030, in particular, was designed to explicitly deal with the integration between Goals and not simply the Goals themselves. The intersection between groundwater and human security is one such example, impacting economic growth, human development, and environmental integrity.

We are convinced that the case studies presented in this book can inform some of these processes. Indeed, case study regions still face problems with their groundwater resources, from the 2016 drought and saltwater incursion affecting the Mekong Delta, to megacity groundwater withdrawals in Bangladesh and Iran's ongoing water crisis. It is nonetheless important, when reading this book, to keep in mind the timeframe of the GWAHS-CS project: the case studies have not been updated from the time when the core activities of the project took place and the literature, with the exception of a few updates, reflects the status quo at the time of project execution.

Fabrice Renaud
Corinne Schuster-Wallace
July 2017

This spring is the source of drinking water for the city of Kumamoto and the site of a temple.
Photo: Corinne Schuster-Wallace

CHAPTER 1

Introduction to the Groundwater and Human Security – Case Studies Project

Fabrice G. Renaud

United Nations University Institute for Environment and Human Security, Bonn, Germany

1.1 Introduction[1]

Groundwater represents close to 96% of unfrozen fresh water resources and 25-40% of the world's drinking water (UNESCO-WWAP 2006). It is an essential resource for the livelihoods of over a billion people in rural areas of Africa and Asia and for the domestic supply of people globally (UNESCO 2012). Global groundwater resources are primarily used for agriculture, but are also widely used as a source for drinking water and by industries. Recent decades have seen an increased exploitation and reliance on groundwater resources, enabling many people, particularly in developing countries, to secure their livelihoods through agricultural production or industry. According to UNESCO (2012), groundwater abstraction rates over the past 50 years have at least tripled. Unfortunately, in many instances, groundwater resources are being overexploited, with withdrawal rates exceeding recharge rates (UNESCO 2012). Human land-use patterns and changes further affect groundwater recharge and quality. Pollutant sources affecting groundwater quality include industrial wastes, urban wastewater, and agricultural runoff (including nutrients and pesticides). These pressures can overwhelm the attractive characteristics of groundwater resources mentioned above. Degradation of groundwater resources is thus a pressing global problem that requires urgent attention from a multitude of stakeholders (Morris et al. 2003).

Unsustainable groundwater use has a negative impact on human livelihoods, human health, and food security, three of the seven pillars of the definition of Human Security of UNDP (1994). These impacts are either direct (e.g. diseases from polluted groundwater for drinking purposes, land subsidence caused by over-extraction), or indirect, affecting ecosystem function and services, which in turn further affect communities (MA 2005). Anthropogenic effects on groundwater (such as the mining of irreplaceable fossil water) can be dispersed and gradual, representing 'creeping threats' that are not always fully appreciated by managers and decision-makers. Superimposed on this, the anticipated effects of climate change on the hydrologic cycle, precipitation patterns, and the interdependent biosphere, could make a difficult situation even worse in the future.

Recognising the importance of the links between groundwater resources management and human security, UNESCO-IHP[2], UNU-EHS[3], UNU-INWEH[4] and UNW-DPC[5] initiated the Groundwater and Human Security – Case Studies (GWAHS-CS) project with colleagues in Egypt, I.R. Iran, and Vietnam in January 2008. The main goal of GWAHS-CS was to study the relationship between human well-being and groundwater in low and middle income (see Renaud et al. 2010, Vrba and Renaud 2016). Human wellbeing and vulnerability concepts were used as proxy indicators of human security as "human security" is indeed a broad field which, according to the definition from UNDP, comprises seven pillars: economic, food, health, environmental, personal, political, and community security (UNDP 1994). This definition highlights that human security is closely linked to the concept of sustainable development and therefore the Sustainable Development Goals. For a discussion on the subject of human security see Brauch (2005 a, b).

A specific component of the research in the GWAHS-CS project consisted of vulnerability assessments of communities who relied on groundwater for their every day subsistence. Vulnerability assessment frameworks were used in order to determine the vulnerability of coupled social-ecological systems (defined below). Two broad objectives were to (1) address the threats to human security and well-being currently posed by water scarcity and water quality degradation, and (2) strengthen the role of groundwater management and protection in alleviating such threats (see Renaud et al. 2008). Specific activities included:

- the adaptation of existing vulnerability assessment frameworks;
- the development of socio-environmental indicators of vulnerability; and,
- vulnerability assessments in the four case study areas.

---

[1] Sections 1.1, 1.3 and 1.4 of this chapter are mostly taken from Renaud and Schuster (2008) with some adaptations
[2] United Nations Educational, Scientific and Cultural Organization - International Hydrological Programme
[3] United Nations University Institute for Environment and Human Security
[4] United Nations University Institute for Water, Environment and Health
[5] UN-Water Decade Programme on Capacity Development

Throughout the project an emphasis was placed on engaging relevant government institutions to foster broad uptake of the approach as a decision-making and planning tool.

1.1.1 Systems under consideration

The GWAHS-CS project addressed interactions between a biophysical system (groundwater aquifers) and a social system (household, community, region; but also various economic sectors that depend on the groundwater resources; and, a body of institutions and legislation that describes user rights and protection of the resource) in five case studies around the world (see Section 1.2). This system was considered a so-called coupled social-ecological system (SES), which is defined as a system that includes societal (human) and ecological (biophysical) subsystems in mutual interaction (Gallopín 2006). The concept reflects the idea that human action and ecological structures are closely linked and dependent on each other, thus sharp separation of social and natural systems is arbitrary (Berkes et al. 2003). Social-ecological systems emanate from the concept of sustainable development where societies' needs should be attained without sacrificing the state of our environment (e.g. Turner et al. 2003a). Social-ecological systems are complex systems characterised by multiple, non-linear interactions between elements of the system (Renaud et al. 2011). For GWAHS-CS, SESs were broadly described as the groundwater resources (aquifer, but also overlying soil and vegetation which will, in part, dictate recharge rates, quality of recharge water, etc.) and the people who rely on these resources (economic sectors, communities, social groups, households, individuals). This SES has links to outside elements and factors which can feedback to the coupled system.

The research phase of the GWAHS-CS project was concluded in 2010 when the idea of compiling the case studies into a book emerged. While many of the case studies have been published independently, their compilation into a single publication provides the opportunity to identify emerging themes as well as highlight the complex interactions within any given situation. The case studies compose the next five chapters of this book and the last chapter draws conclusions from these case studies. All of the case studies results, except the one from Bangladesh which was not funded through the GWAHS-CS project, follow a similar format. The case studies also adhered to the research approach outlined in the remainder of this chapter with some deviations when required by circumstances in the field.

1.2 The Case Studies

This book reports on the results of the four case studies that were funded through the GWAHS-CS project (Beni Salama, Wadi El Natrun in Egypt; Shibkouh County, Fars province in I.R. Iran; Tra Vinh Province in Vietnam, and Binh Thuan Province also in Vietnam) plus an additional case study that had been implemented in Bangladesh outside the project, and which did not follow the broad approach outlined in the sections below, but which was discussed throughout the project and represented an interesting case.

1.2.1 Beni Salama, Wadi El Natrun, Egypt

This case study (Chapter 2) was selected because of the prevailing arid climate and the almost complete dependency of people and economic sectors on groundwater supply. The case study reports in detail on the use of GWAHS-CS indicators and complements this approach with in-depth descriptions of the hydrogeological characteristics of the area, its socio-economic characteristics, prevailing ecosystems, and legal and policy frameworks related to groundwater use. This allowed the authors of the case study to highlight the principle factors of vulnerability in the region and to identify the social groups that were the most vulnerable, partly depending on which aquifer layers they could access. The importance of access to information and access to knowledge as indicators of resilience was particularly highlighted. The chapter provides useful policy advice with respect to the management of groundwater resources, some of which were considered by the city council in the aftermath of the project. Finally, this case study also makes some useful suggestions with respect to improving the approach, and in particular the indicator set for future studies. Some of the research from this case study was already published (see King and Salem 2012).

1.2.2 Shibkouh County, Fars province, I.R. Iran

This case study (Chapter 3), also set in an arid environment, brings an additional dimension to the vulnerability analysis in the sense that part of the region under consideration is under managed aquifer recharge. Recharge is ensured by blocking and infiltrating seasonal flood water. The region, which is dedicated to agricultural production, sees its water tables decline rapidly and also experiences groundwater quality degradation. The case study provides in-depth information on groundwater quality. It also considered all the indicators of the project in various localities of the region and was able to show geographical, social, and biophysical differences in vulnerability through a qualitative analysis of the indicators. Some of the research from this case study was already published (see Mesbah et al. 2015).

1.2.3 Tra Vinh Province, Mekong Delta, Vietnam

In this coastal province of Vietnam, the population increasingly relies on groundwater resources for domestic supply, drinking, and irrigation. There is increasing competition between different users to access groundwater and the resource is put under pressure both from quantity and quality perspectives (see Wagner et al. 2012). In this case study (Chapter 4), the researchers investigated the vulnerability patterns of different social groups in a few communes of Tra Vinh Province. Although some of the GWAHS-CS indicators described above were used, the researchers concentrated their research on the Sustainability Livelihood Framework discussed below. Through a qualitative analysis of the indicators and parameters, the chapter identifies which social groups are the most vulnerable in the case study region and suggest some measures to attempt reducing the pressure on groundwater resources.

1.2.4 Binh Thuan Province, Vietnam

The case study in Binh Thuan Province, Vietnam (Chapter 5) is in a completely different environment than the one in Tra Vinh Province. The latter region is located in a delta where agricultural activities predominate and where groundwater is over-exploited, whereas Binh Thuan Province is a rapidly developing region of Vietnam where tourism and industry are eclipsing agriculture as primary economic sectors, and where for the moment, communities rely principally on surface water resources. It is however anticipated that these fresh water resources will be insufficient in the future and increased pressure is being put on fragile aquifers in the region. The case study looks principally at the advantages of managed aquifer recharge and although it addresses most of the indicators developed in the project, the main focus was put on providing a detailed description of the hydrogeology, and what can be done to sustainably increase fresh water supply to the region from fragile aquifers.

1.2.5 Arsenic in Bangladesh

The case study from Bangladesh (Chapter 6) is indirectly related to the GWAHS project as the research had already been completed when GWAHS-CS was put in place. However, the researchers involved in the case study were part of the GWAHS-CS team. The case study reports on the critical issue of arsenic contamination of groundwater which is affecting millions in that country and surrounding region with extremely serious health consequences. The case study reports on the extent of the problem, and proposes remedial actions (policy-relevant, including legal and technical issues).

1.3 Approach to Vulnerability Assessment

1.3.1 Definitions

The scientific literature on vulnerability and risk assessment in the context of environmental hazards is extensive and different schools of thought exist (e.g. linked sustainable development, disaster risk reduction, or climate change adaption contexts). Many different frameworks and definitions of vulnerability and risk also exist. An overview of vulnerability concepts is given in Birkmann (2006), and Thywissen (2006) compiled a list of some 36 definitions of the term "vulnerability" (which was not an exhaustive list). For the GWAHS-CS project, it was agreed that the following definition for vulnerability would be used (adapted from Thywissen 2006, p 34):

"Vulnerability is the dynamic feature of an element at risk (community, region, state, infrastructure, environment etc.) that determines the expected damage/harm resulting from a given hazardous event and is often affected by the event itself. Vulnerability changes continuously over time and is driven by physical, social, economic, and environmental factors."

Linked to the concept of vulnerability is the concept of resilience of SESs. Here again definitions and assessment frameworks vary greatly. When it comes to SESs, the resilience concept was originally introduced by Holling (1973) within the ecological literature as a way to understand nonlinear dynamics of ecological systems. Carpenter et al. (2001, p 766) presented three essential properties of resilience:

- the amount of change a system can undergo and still remain within the same domain of attraction;
- the degree to which the system is capable of self-organisation; and,
- the degree to which the system can build and increase the capacity for learning and adaptation.

The linkages between resilience and vulnerability are briefly discussed below, but it was decided that in the GWAHS-CS project, resilience would be used within the context of vulnerability (see e.g. Turner et al. 2003a), and not within the context defined by Carpenter et al. (2001) above, which would imply defining thresholds between various states of coupled systems, a non-trivial exercise.

1.3.2 Ecosystem services

Before discussing vulnerability assessment frameworks, it is important to consider who is vulnerable, to what, and at which scale is this vulnerability considered. As noted above, we are concerned with coupled SESs (humans, groundwater system, and all the elements that are linked to them). This can, however, be too difficult to work with as coupled SESs are, by definition, complex systems that are not easily captured in their entirety. The focus in GWAHS-CS was on humans and the groundwater resources hence, the analysis was limited to this simplified system. However, this simplification does not eliminate complex interactions between humans, economy, aquifers, and ecosystems. Indeed in the case study areas of the project, humans rely on aquifers for the provisioning of fresh water and so do various economic sectors; the groundwater resource is in turn affected by human activity and a set of biophysical factors that will determine groundwater recharge and groundwater quality. Many of these interactions are well captured by the notion of ecosystem services as presented in the Millennium Ecosystem Assessment (MA 2005).

The Millennium Ecosystem Assessment (MA 2005) described the pressures that are being put on our ecosystems and the subsequent loss of ecosystem services. Provisioning services were defined by the MA as products obtained from ecosystems such as food and fibre, fuel, and fresh water. Regulating services are processes such as air quality maintenance, as well as climate and water regulation (among others). In the MA conceptual framework, provisioning services contribute to human wellbeing and poverty reduction together with other types of services. Provisioning and regulating services are affected by direct drivers of change which are influenced by indirect drivers of change, a driver being any factor that changes an aspect of an ecosystem. Indirect drivers, as conceptualised in the MA do not include environmental influences. These are, however, captured in the direct drivers with examples such as changes in land use and land cover, climate change, the use of external inputs, and so forth. In this sense we can see the intricate weave of social, economic, and political factors influencing the state of the environment.

Fresh water provisioning is an essential service obtained from ecosystems. It is nevertheless important to consider that groundwater also plays an important role in maintaining ecosystems, in addition to providing an essential fresh water resource to humans. As individuals and communities may rely on these ecosystems for their livelihoods, it is thus important to also understand the role groundwater plays in the maintenance of these ecosystems. There are therefore two potential negative consequences for humans when groundwater resources are degraded: a direct one affecting the provisioning of fresh water and an indirect one potentially affecting important ecosystems on which populations may rely on.

Another point considered in the project was the issue of scale. In GWAHS-CS we focused on specific communities who were facing fresh water supply problems, so the principal scale of analysis was the local scale. However, the local scale is also affected by processes at higher (regional, national, international) scales. It was impossible to account for all of these interactions within the remit of the GWAHS-CS project, but efforts were made to capture elements of the most important ones (e.g. laws and regulations pertaining to groundwater exploitation, supply, costing mechanisms).

1.3.3 Vulnerability assessment frameworks

Several vulnerability assessment frameworks have already been developed with respect to environmental hazards and the most important ones have been reviewed by Birkmann (2013). Only three of these, parts of which were used in the GWAHS-CS project, are briefly described below. For further information on the frameworks and their graphical representations see Renaud and Schuster (2008), Birkmann (2013), or the original references provided below.

The SUST model

The first is the framework developed by Turner et al. (2003a), also known as the SUST model. The framework is closely linked to sustainability science, considers coupled systems (referred to as Human-Environment systems in the original publication), and comprises multiple scales of interactions. Vulnerability is composed of exposure, sensitivity, and resilience.

Exposure in the Turner framework allows the determination of the components at risk (such as individuals, but also e.g. industry and/or ecosystems), and includes the characteristics of the hazard itself in terms of frequency, magnitude, and duration. This conceptualisation was useful for the GWAHS-CS project and, as already discussed above, the components affected by groundwater degradation or the components whose vulnerability will be reduced by managed aquifer recharge clearly need to be identified. As groundwater degradation can be either a creeping process taking several years or decades to affect people and other ecosystems, or be a rapid process (e.g. impacts of tsunamis, coastal storm surges, and chemical pollution by industry), two different sets of characteristics of exposure will be required.

Sensitivity is characterised for both subsystems and the conditions of the systems determine the sensitivity of the coupled SES (Turner et al. 2003a, p 8077). Conditions include entitlements and endowments which can be interacting within a feedback loop system and which are influenced by external parameters such as policies and legislation. It is difficult to quantify and even qualify sensitivity and no prescribed set of indicators have been developed. The concept was however retained for application in the GWAHS-CS project as an important factor. Access to the resource (and also the dependency with respect to this resource), was incorporated in the analysis as were elements from the sustainable livelihood framework which is described in this section.

The SUST model is an example where terminology (vulnerability – resilience) is mixed (see also Renaud et al. 2011). Turner et al. (2003a, p 8075) consider resilience as the system's capacities to cope or respond including the consequences and attendant risks of slow (or poor) recovery and the system's restructuring after the responses have taken place (adjustments or adaptations). Although they note where the concept of resilience emanates from, the way resilience is incorporated into the SUST framework differs from some of the concepts given in Section 1.3.1. Turner et al. (2003a, p 8077) consider that responses to a stressor or shock and their outcomes determined the resilience of the coupled SES, affecting various spatial scales. In this framework, components of resilience include coping, impacts, and adaptation, which are all related to responses. As it is difficult to anticipate what responses might be, it was suggested that resilience be approached differently in GWAHS-CS by concentrating on key social and biophysical features that are known to be critical to determine if a system can or cannot maintain certain structures and functions despite a disturbance. Some of these were linked to the social sub-system: levels of poverty, levels of marginalisation (often linked to the former but also linked to other factors such as ethnicity, gender, etc.), strength of social networks, institutional ability to deal with a crisis linked to groundwater issues, support from government and non-government institutions, and so forth; or to the biophysical subsystem: quality of key environmental features of importance to groundwater, such as land use and land use management, water quality and quantity indicators (of both surface and ground-water), and so forth.

The SUST model is fairly comprehensive in terms of the factors of vulnerability it accounts for at various spatial scales. The number of factors and the complex feedback-loops make a comprehensive assessment unpractical if not impossible, a fact that is acknowledged by Turner et al. (2003a, p 8076). Turner et al. (2003b) used the framework to analyse the vulnerability of three coupled SES: The Southern Yucatan Peninsular Region, the arid Yaqui Valley of northwest Mexico, and the Arctic. These examples illustrate that the SUST model has to be simplified to characterise the vulnerability of the coupled systems.

Two observations can be made regarding the SUST framework. First, for vulnerability assessment to be of interest, it needs to be conducted ex ante, implying that impact data are by definition not there unless one refers to impacts from preceding events. Within GWAHS-CS, given that groundwater degradation is primarily a creeping process, impact data are more likely to be available. However, other data are still required in order to characterise resilience. The second observation is that groundwater can be an element of the vulnerability assessment (Ingram et al. 2006 using the SUST framework, Renaud 2006, Renaud et al. 2011 – all in the context of the 2004 tsumami), demonstrating how the resource comes into play when a disaster strikes. Characterising the importance of groundwater in relation to other hazards is therefore also important.

The BBC conceptual framework

The acronym BBC stands for the last names of the authors of the framework on whose work the concept was based (Birkmann, Bogardi, and Cardona). It is described in detail by Birkmann (2013).

Like the SUST model, the BBC framework is conceptually rooted within sustainable development science as it identifies vulnerabilities, exposure, and coping capacities of the environmental, social, and economic spheres. It was developed with three objectives in mind:

- linking vulnerability, human security and sustainable development,
- providing a holistic approach to disaster risk assessment, and,
- providing a platform to measure environmental degradation in the context of sustainable development.

Vulnerability is seen as a dynamic feature which is highlighted by the fact that it incorporates intervention tools that could reduce said vulnerabilities. In this way, the BBC framework distinguishes between a situation before a disaster manifests itself and the responses when a disaster occurs. Although one can visualise these vulnerability reduction strategies easily in the case of rapid onset hazards such as floods or tsunamis, it is more difficult to grasp them in the context of creeping processes. Yet, they remain relevant for a (predominantly) creeping process such as groundwater resources degradation, as society can either react once a resource has been severely degraded by implementing remediation measures, or can anticipate degradation measures and put in place pre-emptive measures to avoid a water supply-related disaster.

The BBC framework was used in ex post vulnerability assessments following the 2004 tsunami (Birkmann and Fernando 2008). Various key questions to capture “susceptibility”, “coping capacities”, and “intervention tools” were investigated through a questionnaire and Birkmann and Fernando (2008) identified key parameters that characterised vulnerability of certain groups to tsunamis, including gender, age, distance from coast (exposure), employment and activity, land ownership, and social networks. The three dimensions or “spheres” can be assessed using a variety of tools, notably DFID’s Sustainable Livelihood Framework (DFID 1999). This framework is briefly described below.

The Sustainable Livelihood Framework

The sustainable livelihood framework (hereafter SLF) of DFID (1999) offers a conceptualisation and tools that can be used within the vulnerability assessment frameworks that were described above (see in particular Birkmann 2013). Canon et al. (n.d.) further highlighted the links between vulnerability assessment and the SLF. The SLF is composed of (1) a vulnerability context, (2) livelihood assets, (3) transforming structures and processes, (4) livelihood strategies, and (5) livelihood outcomes.

The SLF was originally conceptualised to improve the effectiveness of international development projects by “putting people at the centre of development” and is a tool to be implemented in a participatory manner with target communities. As it was proposed in the GWAHS-CS project that the SLF be used in conjunction with existing vulnerability frameworks, we mainly concentrated on the “livelihood assets” which can be incorporated later on within either the BBC or SUST vulnerability assessment framework/model. Other components of the SLF were either not relevant for the purposes of the project or were addressed directly by the vulnerability frameworks themselves.

Livelihood assets and capital endowments are important factors in vulnerability assessment. However what was more relevant for GWAHS-CS is that assets and capital endowment can be used to characterise specific components of vulnerability, particularly within the social, economic, and environmental spheres.

As per the definitions provided by DFID (1999), Human Capital represents the skills, knowledge, ability to labour, and good health that enable people to pursue different livelihood strategies. At the household level, Human Capital is a factor of the amount and quality of labour available. Social Capital consists of social resources upon which people draw in pursuit of their livelihood strategies. It includes networks and connectedness, membership in formal groups, and relationships of trust, reciprocity, and exchange that facilitate cooperation. It is obvious that the capacity to cooperate or rely on networks will have different implications when it comes to groundwater-related concerns. Natural Capital is used to characterise natural resource stocks from which resource flows and services useful for livelihoods are derived. There is thus a direct link to the ecosystem services concepts described above, and here groundwater is an illustration of this capital. It is not only the availability of certain resources that is important, but also the access different people and social groups have to these resources. Physical Capital represents basic infrastructure and producer goods needed to support livelihoods. As outlined by DFID (1999), lack of particular types of infrastructure is considered to be a core dimension of poverty. Financial Capital represents the financial resources that people use to achieve their livelihood objectives. Examples include available stocks (e.g. various types of savings), and regular inflows of money (e.g. pensions, remittances). Financial Capital will most likely vary greatly between social groups and will again determine the types of resources communities or social groups have available to cope with water supply problems and groundwater-related problems more specifically.

The frameworks and models briefly describe above were then used to derive indicators of vulnerability, which are discussed in detail in the next section.

1.4 Indicators and Approach

1.4.1 Examples of indicators

This section provides some examples of indicators relevant to the GWAHS-CS projects. Please note that these were reviewed in 2008 and other indicators have been published since. Indicators are useful to qualitatively or quantitatively measure vulnerability. A variety of groundwater sustainability-related indicators have been developed by UNESCO-IHP and reported in Vrba and Lipponen (2007). These indicators are listed in Table 1.1. For detailed descriptions, implementation, and case studies, the reader is referred to the original publication. In the context of the GWAHS-CS project some of these indicators could not be directly assessed as they were regional or national level indicators whereas GWAHS-CS case studies were locally-based. However, some indicators were considered and are highlighted in bold-italics in Table 1.1. Their direct relevance is briefly discussed below.

Table 1.1. Groundwater indicators (Vrba and Lipponen 2007). Indicators in bold-italics are those that were suggested for the GWAHS-CS project.

Indicator	Scale	Formulation
Renewable groundwater resources per capita - RGRC (m^3 y^{-1})	National & Regional	RGRC = GWRR/Inhab GWRR = Rech + Seep – BF + I – O + AR
Total groundwater abstraction/ Groundwater recharge (%)	National & Regional	(TGA / GR) x 100
Total groundwater abstraction/ Exploitable groundwater resources (%)	National & Regional	(TGA / EGR) x 100
Groundwater as a percentage of total use of drinking water at national level (%)	***National***	***(Groundwater Source / Total drinking water) x 100***
Groundwater depletion (%)	Regional	(Σ areas with a groundwater depletion problem / Studied area) x 100
Total exploitable non-renewable groundwater resources/ Annual abstraction of non-renewable groundwater resources (years)	National	TENGR / AAGR
Groundwater Vulnerability (%)	***Various***	***(Σ areas with different classes of groundwater vulnerability / Studied area) x 100***
Groundwater quality (%)	***Various***	***(Σ areas with natural groundwater-quality problem[a] / Studied area) x 100*** ***(Σ areas with increment of concentration for specific variable / Studied area) x 100***
Groundwater treatment requirements (%)	Various	Percentages of the groundwater abstraction / Treatment category[b]
Dependence of agricultural population on groundwater (%)	***National (can be downscaled)***	***(Number of farmers dependent on groundwater for agriculture activities / Total population of the country) x 100***

[a]Based on drinking water quality guidelines; [b]Treatment categories are: suitable for specific use without treatment, simple treatment needed, technologically demanding treatment needed

Groundwater as a percentage of total use of drinking water is a crucial indicator as it highlights groundwater dependency. The indicator in Table 1.1 concerns the national level but it was assessed locally within the GWAHS-CS project. In some cases, information was obtained with regional or local water authorities, with cross check through household interviews. Similarly, dependence of agricultural population on groundwater is an important indicator for the case studies, which are predominantly in a rural setting, although the indicator is designed to be applied at the national scale.

It was also decided that wherever possible groundwater vulnerability should be addressed for the areas under investigations. Criteria for aquifer vulnerability are provided by Vrba and Lipponen (2007, p 17). This characterisation is important for GWAHS-CS as it links to groundwater quality issues as well as serving a basis for potential intervention tools (see BBC model).

Groundwater quality was an important parameter to be considered in the project. The nature of the project did not allow for groundwater quality monitoring except in a couple of exceptions. In most cases, secondary data were analysed in order to characterise groundwater quality within the localities under study.

In addition to the indicators noted above, scientists have already tried to capture the vulnerability of communities with respect to groundwater issues. For example, Collins and Bolin (2007) studied the impact of over-exploitation of groundwater aquifers in rapidly urbanising Arizona (USA), a region that experiences water scarcity problems. Geographic Information System (GIS) was used to spatially overlay a series of vulnerability characteristics captured by hydrologic variability in water resource availability within a groundwater basin, water management systems, and socio-demographic indicators (Table 1.2). Both biophysical (particularly dealing with water supply) and socio-economic factors were included in the analysis. No weights were assigned to the various indicators (layers in the GIS) and no determination of cross-correlation between the various indicators was carried out. These represent two potential limitations of the research design. However, an interesting outcome of the research was that the most hazardous places, the most vulnerable populations, and the least secure systems for water management did not necessarily overlap. In addition, Collins and Bolin (2007) noted that there could be spatial correlation of vulnerability within the studied region. The authors also demonstrated that legislation on surface water allocation, urbanisation, and specific institutional arrangements contribute to creating vulnerabilities.

Table 1.2. Vulnerability indicators used in Collins and Bolin (2007).

Indicator Category	Indicator Type
Biophysical	
Groundwater access	Exempt wells overlying hard rock and outside of the basin-fill aquifer complex
Well spacing	Well density
Social **Socio-demographic**	
Population and structure	Total population Total housing units
Access to resources	Number of Hispanic residents Number of non-White residents Number of female-headed households Number of people < age 18 Number of people > age 64
Socioeconomic status	Renter occupied housing units Mean housing unit value
Place dependency	Seasonal/recreational housing units
Water Provider Type	Proportion of housing units within municipal water provider service area Proportion of housing units within private water provider service area Proportion of housing units with exempt wells

1.4.2 Some considerations for indicator selection in the GWAHS-CS project

The purpose of adopting or developing new indicators within the GWAHS-CS project was to characterise the vulnerability (or reduced vulnerability) of communities and/or various social groups with respect to groundwater degradation or improvements in the groundwater resources. This in turn can serve as a basis for the identification and recommendation of intervention tools to reduce the identified vulnerabilities. The indicators were aimed at supporting decision makers in identifying priority areas for action in order to mitigate further groundwater degradation (quantity and quality) problems; and measuring, in the longer term, the reduction in vulnerability of various social groups as a result of management measures, but also in terms of addressing other, non-groundwater related factors that characterise vulnerability.

In general terms, indicators require certain qualities in order to be of any real scientific and/or managerial use. Among these should be:

- Scientifically credible
- Relatively insensitive to expected source of interference
- Sensitive to changes in space
- Sensitive to changes within policy time frames
- Measurable in qualitative or quantitative terms
- Repeatable and reproducible in different contexts
- Resource efficient, with benefits outweighing benefits the costs of usage, resource allocation
- Manageable from a data requirements perspective
- Compatible with indicators developed and used elsewhere
- Linked with specific management practice or interventions
- Able to provide information at appropriate spatial and temporal scales

To this list can be added the following criteria: transparency, understandability, ease of interpretation, and policy relevance (Damm 2010).

1.4.3 Selection of indicators in the GWAHS-CS project

The selection of indicators for the assessment of vulnerability of communities with respect to groundwater degradation was based on a review of available indicators (partly discussed above), and in a participatory workshop in Alexandria, Egypt (24-26 November 2008) where all case study partners discussed advantages and disadvantages of indicators and made a final selection of indicators for the project (Table 1.3). At the Alexandria workshop, preliminary ideas in terms of suitable indicators to characterise vulnerability of communities and economic sectors to groundwater degradation were compiled based on the experience gained by case study partners during the initial stages of their fieldwork. The adjusted SUST vulnerability assessment framework used by the GWAHS-CS project provided the basis for the selection of indicators. Both biophysical and socio-economic indicators were identified to describe and measure the four main components of vulnerability, including:

- hazard: rate, frequency and magnitude;
- exposure: social groups, economic sectors and ecosystems at risk;
- sensitivity of the social and biophysical sub-system; and,
- resilience of the social and biophysical sub-system.

The indicators proposed by case study partners were summarised when commonalities were identified and complemented by additional indicators to fill gaps in terms of measuring all components of the SUST vulnerability model. This exercise resulted in a list of biophysical and socio-economic factors representing the minimum set of indicators that were then assessed at most case study sites (Table 1.3). In addition, Table 1.3 provides a description of the information required to assess these indicators and suggests a range of possible assessment methodologies.

Table 1.3. Minimum set of biophysical and socio-economic indicators to describe and measure the exposure, hazard, sensitivity and resilience components of the adjusted Turner vulnerability framework. These indicators were assessed in most case study sites and reviewed with respect to their suitability to characterise vulnerability at the next GWAHS-CS workshop.

Indicator	Information required	Methodologies
	Exposure	
Dependence of population on groundwater	% of the population relying on groundwater for drinking and/or other purposes	Household interviews, Local statistics
Dependence of major economic sectors on groundwater	% of economic sectors in the study area relying on groundwater (e.g. agriculture, shrimp farming, bottling companies, tourism, etc.)	Desktop analysis, Interviews with land users
Ecological vulnerabilities	List the major effects of groundwater depletion and pollution on natural ecosystems dependent on groundwater resources (e.g. oasis ecosystems, river base flow systems, etc), such as changes in flora and fauna, impacts on conservation efforts and degradation of pertinent ecosystem functions etc.	Literature review, Expert interviews
Well density	Location and density of groundwater wells per unit land indicate the pressure on aquifers. What is of particular interest is the change in well density over time as it indicates the added pressure on aquifers.	Literature review, Expert interviews Expert interviews, Desktop analysis, Household surveys
	Hazard	
Groundwater quantity	Ratio of total groundwater abstraction and groundwater recharge (see Vrba and Lipponen 2007, pp 9 – 12)	Mining of secondary data, Expert interviews
Groundwater quality	Groundwater quality compared to country and/or WHO drinking water standards	Desktop analysis, Secondary data, Expert interviews

Sensitivity		
Groundwater vulnerability	Characterise the intrinsic (natural) vulnerability of the aquifer defined as a function of hyrdrogeological factors, e.g. net recharge, soil properties, topography, unsaturated zone lithology and thickness, aquifer media and aquifer hydraulic conductivity, and groundwater level below ground. Depends on data availability. (see Vrba and Lipponen 2007, p 16-18 for more details)	Mining of secondary data, Literature review, Expert interviews
Population density	Population density in the case study area. If historical data can be found they should be incorporated in the analysis	National census data
Household structure	Number of family members; age and sex of all family members and their relationships; characteristics of the household head	Household interviews
Education level	Education level of household head, distinguishing primary school, secondary school, high school, university, no schooling, technical/ specialised training	Household interviews
Occupation	Main occupation of household head, type of employer, permanent/temporary occupation, years in permanent occupation	Household interviews
Ethnicity	Household (% of population) belongs to what ethnic group	Household interviews
Household income	• Estimated monthly income of household from on-farm activities: type of activity; total production/ yield, area under cultivation/use; price; estimated costs; income • Estimated monthly income of household from off-farm activities: kind of activities, total income, working time • Estimated monthly income of household from other income sources: pension, remittances from relatives, support from development programmes; others	
Access to savings/credit	Household (% of population) with access to savings (bank/savings account) and/or loans/(micro-) credits	Household interviews
Duration since settled in the area	Years since household has settled in the study area	Household interviews

Seasonal or primary house	Household (% of population) with primary house or seasonal house in the study area	Household interviews
Health status related to water-borne diseases	• Number of sick household members, affected by (potentially water borne) diseases • Type of disease	Household interviews, Expert interviews
Type of provider system	Type of provider systems primarily used by household	Household interviews
Resilience		
Access to alternative sources of water	• Household (% of population) with access to alternative water sources • Type of alternative water sources e.g. surface water, bottled water, tanks etc.	Household interviews
Access to knowledge of groundwater degradation processes	• List formal and informal groundwater monitoring networks (both quality and quantity); • % of households/groundwater users aware of groundwater degradation processes; • Indicate knowledge gaps	Expert interviews, Interviews with groundwater users, Household interviews
Institutional set up related to groundwater management	List and briefly describe national and sub-national institutions responsible for groundwater monitoring and management and indicate their responsibilities, their inter-relation, and coordination	Desktop analysis, Expert interviews
Existence and enforcement of legislation and policies related to groundwater management	List and briefly describe national by-laws, pieces of legislation and policies with respect to groundwater management and pollution protection and characterise status of their enforcement	Desktop analysis, Expert interviews, Observation in case study area
Groundwater related infrastructure	List and briefly describe groundwater related infrastructure and characterise its status in terms of effectiveness, age, maintenance etc.	Expert interviews, Interviews with groundwater users, Household interviews
Out-migration from case study sites	% of population who has permanently left the study area	Mining of secondary data, National census, Household interviews
Existence of and participation in social networks	• Household (% of population) with a membership in formal and/or informal social networks, e.g. community organisation, religious group, farmers cooperative, women's groups; • Type and level of support received from these social networks	Household interviews

In practice, not all case studies could collect enough information for all these parameters and the use of the approach varied from case study to case study depending on the technical capabilities available in the local research teams. The project did not aim to generate maps of vulnerability by aggregating indicators, but rather to investigate the explanatory value of given indicators in terms of characterising vulnerability. This was achieved to various degrees by most case studies reported in this book. However, the set of indicators provided above was not the only approach used by project teams and other tools and methodologies were also considered by project teams to characterise the vulnerability of communities and economic sectors exposed to groundwater degradation.

1.5 Conclusions

Globally, groundwater plays, and will increasingly play, a crucial role in terms of water supply for multiple purposes. As a mostly "unseen" resource, groundwater has the tendency to be over-exploited and land surface activities pollute the resource, particularly in the case of shallow aquifers. Greater attention needs to be paid to protect groundwater and, as importantly, understand the vulnerabilities of people, social groups, and economic sectors that would be the most vulnerable in case groundwater degradation processes remain unabated. The purpose of the GWAHS-CS project was to address this later problem by using a combination of conceptual frameworks, indicators, and field research methodologies, and through this approach, provide information useful to decision-making.

1.6 References

Berkes F, Colding J and Folke C (eds). 2003. Navigating social-ecological systems: building resilience for complexity and change. Cambridge University Press: Cambridge

Birkmann J (ed). 2006. Measuring vulnerability to natural hazards. Towards disaster resilient societies. UNU Press: Tokyo

Birkmann J. 2013. Measuring vulnerability to promote disaster-resilient societies} and to enhance adaptation: discussion of conceptual frameworks and definitions. In: Birkmann J (ed). Measuring vulnerability to natural hazards. Towards disaster resilient societies. United Nations University Press, 2nd Edition, Tokyo, pp. 9-79

Birkmann J and Fernando N. 2008. Measuring revealed and emergent vulnerabilities of coastal communities to tsunami in Sri Lanka. Disasters 32:82-104

Brauch HG. 2005a. Environment and human security: towards freedom from hazard impacts. InterSecTions No. 2. UNU-EHS: Bonn. Available at: http://www.ehs.unu.edu/file.php?id=64

Brauch HG. 2005b. Threats, challenges, vulnerabilities and risks in environmental and human security. SOURCE No. 1. UNU-EHS: Bonn. Available at: http://www.ehs.unu.edu/file.php?id=63

Carpenter SR, Walker BH, Anderies JM and Abel N. 2001. From metaphor to measurement: resilience of what to what? Ecosystem, 4:765-781

Collins TW and Bolin B. 2007. Characterizing vulnerability to water scarcity: the case of a groundwater-dependent, rapidly urbanizing region. Natural Hazards, doi:10.1016/j.envhaz.2007.09.009

Damm M. 2010. Mapping social-ecological vulnerability to flooding. A sub-national approach for Germany. PhD Dissertation, Graduate Research Series Nb 3, United Nations University Institute for Environment and Human Security, Bonn, Germany. Available at: http://www.ehs.unu.edu/file/get/8056

DFID (Department for International Development). 1999. Sustainable livelihood guidance sheets. DFID, London. Available at: http://www.livelihoods.org info/info_guidancesheets.html

Gallopín GC. 2006. Linkages between vulnerability, resilience, and adaptive capacity. Global Environmental Change 16:293-303

Holling CS. 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics 4:1-23

Ingram JC, Franco G, Rumbaitis-del Rio C and Khazai B. 2006. Post-disaster recovery dilemmas: challenges in balancing short-term and long-term needs for vulnerability reduction. Environmental Science & Policy 9:607-613

King C and Salem BB. 2012. A socio-ecological investigation of options to manage groundwater degradation in the Western Desert, Egypt. Ambio 41:490–503

MA (Millennium Ecosystem Assessment). 2005. Ecosystems and Human Well-being: Desertification Synthesis. World Resources Institute, Washington, DC

Mesbah SH, Mohammadnia M and Kowsar SA. 2015. Long-term improvement of agricultural vegetation by floodwater spreading in the Gareh Bygone Plain, Iran. In the pursuit of human security, is artificial recharge of groundwater more lucrative than selling oil? Hydrogeology Journal 24(2):303-317 (DOI: 10.1007/s10040-015-1354-y)

Morris BL, Lawrence ARL, Chilton PJC, Adams B, Calow RC, and Klinck BA. (2003) Groundwater and its susceptibility to degradation: a global assessment of the problem and options for management. Early Warning and Assessment Report Series, RS. 03-3. United Nations Environmen Programme, Nairobi, Kenya

Renaud FG 2006. Environmental components of vulnerability. In: Birkmann J (ed). Measuring vulnerability to natural hazards. Towards disaster resilient societies United Nations University Press, Tokyo, pp. 117-127

Renaud F and Schuster B. 2008. Groundwater and human security: capturing elements of vulnerability and human security. Concept Note for GWAHS-CS Project. A report for GWAHS-CS

Renaud F, Martin-Border J-L and Schuster B. 2008. Groundwater and human security – case studies (GWAHS-CS) results from the kick off workshop. Working Paper No. 4, United Nations University Institute for Environment and Human Security: Bonn. Available at: http://www.ehs.unu.edu/file.php?id=391

Renaud FG, Martin-Bordes JL and Schuster B. 2010. Quo Vadis Aquifer? A joint programme addressing the links between ground water and human security. In: Managing shared aquifer resources in Africa. Proceedings. IHP-VII, Series on Groundwater no. 1. UNESCO, Paris, pp. 281–286

Renaud FG, Birkmann J, Damm M and Gallopín GC. 2011. Understanding multiple thresholds of coupled social-ecological systems exposed to natural hazards external shocks. Natural Hazards 55:749-763

Thywissen KT. 2006. Components of risk. A comparative glossary. SOURCE No. 2, United Nations University Institute for Environment and Human Security: Bonn. Available at: http://www.ehs.unu.edu/file.php?id=118

Turner II BL, Kaspersonb RE, Matsone PA, McCarthyf JJ, Corellg RW, Christensene L, Eckleyg N, Kaspersonb JX, Luerse A, Martellog ML, Polskya C, Pulsiphera A and Schillerb A. 2003a A framework for vulnerability analysis in sustainability science. Proceedings of the National Academy of Sciences 100(14):8074-8079

Turner II BL, Matson PA, McCarthy JJ, Corell RW, Christensen L, Eckley N, Hovelsrud-Broda GK, Kasperson JX, Kasperson RE, Luerse A, Mathiesen S, Naylor R, Martello ML Polsky C, Pulsipher A, Schiller A, Selin H, and Tyler N. 2003b. Illustrating the coupled human–environment system for vulnerability analysis: three case studies. Proceedings of the National Academy of Sciences 100:8080-8085

UNDP. 1994. Human Development Report. New dimensions of human security. UNDP, New York

UNESCO. 2012. The United Nations World Water Development Report 4: Managing water under uncertainty and risk (Vol.1) UNESCO, Paris Available at: http://unesdoc.unesco.org/images/0021/002156/215644e.pdf

UNESCO-WWAP. 2006. Water a shared responsibility. The United Nations World Water Development Report 2, UNESCO, Paris

Vrba J and Renaud FG. (2016) Overview of groundwater for emergency use and human security. Hydrogeology Journal 24:273-276

Vrba J and Lipponen A (eds). 2007. Groundwater resources sustainability indicators. IHP – VI Series on Ground water No. 14. UNESCO: Paris Available at: http://unesdoc.unesco.org/images/0014/001497/149754e.pdf

Wagner F, Vuong Bui Tran and Renaud FG. 2012. Groundwater resources in the Mekong Delta: availability, utilization and risks. In: Renaud FG and Kuenzer C (eds). The Mekong Delta system. Interdisciplinary analyses of a river delta. Springer Environmental Science Engineering, Dordrecht, pp. 201-220

CHAPTER 2

Egypt Case Study: Beyond DRASTIC in Wadi Natrun

Boshra Salem[1,4], Mohamed Gad El Hak[2], Sayyid Khalifa[3], Caroline King-Okumu[4]

[1] Alexandria University, Alexandria, Egypt
[2] Desert Research Centre, Cairo, Egypt
[3] Omda, Wadi Natrun, Egypt
[4] Ecosystems and Human Development Association (EHDA), Alexandria, Egypt

2.1 Main Challenges of the Case Study Area

The district of Wadi El Natrun and the village of Beni Salama were selected as the areas for the case study based on consultations with the city council who indicated the high level of dependence on groundwater in the area (close to 100%). The village supplies water to the surrounding area, due to its particularly high quality. Several water bottling factories are also located in the area. Challenges to groundwater management include (Renaud et al. 2008) the rapid pace of groundwater extraction for land reclamation; the slow rate of recharge and non-renewable nature of deep groundwater resources; possible threats to subsurface groundwater quality due to hydrogeological changes; and threats to recharge water quality due to anthropogenic activities including agriculture and urban development.

2.2 Description of the Case Study Area

The study area of Beni Salama (Figure 2.1a and 2.1b) is located in the Wadi El Natrun district. The Beni Salama (Dier Makaryous) anticline is a subsidiary structure of the main Wadi El Natrun depression. The climate of Wadi El Natrun is characterised by scarce rainfall, hot long summers, and short warm winters. The mean annual rainfall is about 35 mm/year. Using the aridity scale of Emberger (1955), the degree of aridity approaches 3.46.

The depression receives surface drainage water from the Nile Delta, located to the north and east. In addition, deep groundwater flows from the South and West Artesian springs which emerge in the depression to create a saline oasis characterised by natural halophytic vegetation and human cultivation, as shown in Figure 2.1a and 2.1b (Taher 1999b, El-Khouly and Zahran 2002, Shaer 2009). The lowest point in the Dier Makaryous depression is 14 m below sea level, whereas the lowest point in the Wadi El Natrun basin as a whole is 23 m below sea level. The village of Beni Salama includes a 1 km² central residential area, surrounded by a series of farms and hamlets.

Figure 2.1a. Location of the case study site: Beni Salama, Wadi Natrun, Egypt (Credit: Ahmed Abdelkhalek).

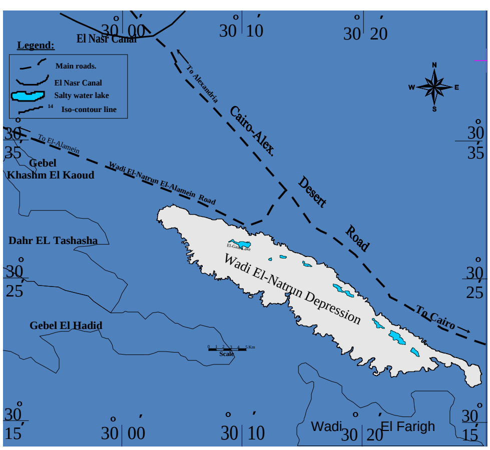


Figure 2.1b. Location of the case study site: Beni Salama, Egypt.

2.2.1 Hydrogeological characteristics

The hydrogeological map of Wadi El Natrun identifies five main aquifers in the study area (RIGW 1990). The areal distribution of three of these is shown in Figure 2.2. These are the main aquifers that are used for irrigation in the study area (El-Fayoumy 1964, El Sheikh 2000). A description of the major characteristics of each aquifer is provided below, followed by a summary of recharge sources and extractions.

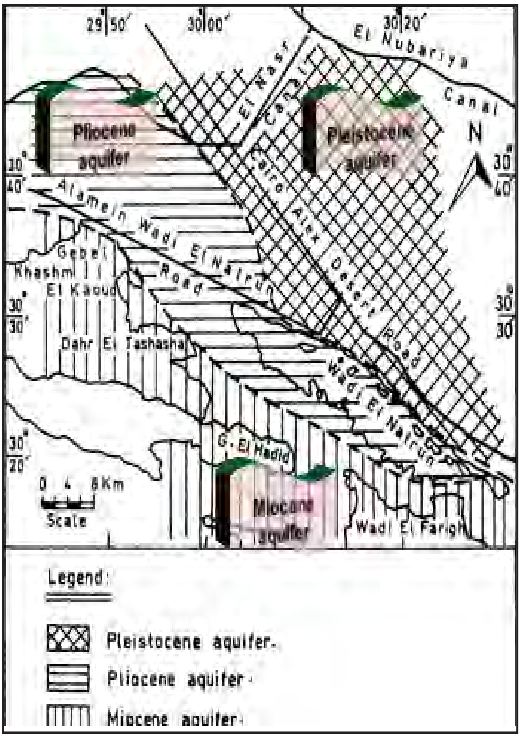


Figure 2.2. Areal distribution of the different aquifers in north-west Wadi El Natrun area and its vicinities (after El Fayoumy 1964 and El Sheikh 2000).

Pleistocene

This aquifer is part of the Nile Delta Aquifer and is an unconfined aquifer, formed of sand and gravel with clay lenses (deltaic deposits). The groundwater flows from east to west and it recharges from the Nile Delta located in the east. From 50-250 m below sea level (RIGW 1990), it is 300 m thick near the delta, 150 m thick north of Wadi El Natrun, and just a few metres thick near the eastern reaches of Wadi El Natrun (Ahmed 1999b).

The aquifer has high potentiality, where its transmissivity (T) values range from 1,291.7 m^2/d to 4,619 m^2/d, while the storativity (S) values range from 2.52×10-3 to 84×10-3 (Saad 1962, Abdel Baki 1983), indicating that the groundwater of this aquifer exists under free water table conditions and partially under semi-confined conditions at some localities where clay lenses are abundant.

Pliocene

Pliocene is the main type of aquifer in Wadi El Natrun and consists of pliocene rock. It is composed of limestone, clay, sand, and gypsum beds. It is multi-layered, alternating between sand and clay, with a semi-confined structure. There are two layers, one upper layer composed of porcellaneous limestone with flint, and a lower layer composed of black shale alternating with argillaceous sandstone.

The Pliocene aquifer is separated from the underlying Miocene aquifer in most of the study area by a thin clay layer. However, faults are present, enabling interconnections between the two layers (Fekry and Salam 2002). In the rest of the area, the aquifers are separated by various types of formations (clay, lagoonal deposits, and calcareous deposits), although this separation is not continuous. Groundwater in the alluvium and the Moghra are in direct contact, either horizontally (in the Khatatba-Abu Rawash area) or vertically (in the Sadat-El Khatatba area).

Miocene

This aquifer extends westward and the water-bearing formation is connected to the Lower Miocene (Moghra Formation). It also outcrops on the surface in Wadi El Natrun and Wadi el Farigh, covering an area of approximately 50,000 km^2 Thickness varies from 50-250 m in the east (Wadi El Farigh) to about 800 m in the west (east of Quattara depression at Moghra). Transmissivity varies from 500 to 5,000 m^2/d (Dawoud et al. 2005).

Cretaceous/Eocene Limestone Aquifer

This aquifer underlies the Oligocene rocks. It has low to moderate productivity (RIGW 1990). It contains a basalt layer separating the Miocene aquifer from the Nubian Sandstone Aquifer System (NSAS) (Idris and Nour 1990). This aquifer is not exploited in the study area.

Although it is fresh elsewhere, the NSAS is saline beneath Wadi El Natrun since it is located north of the saline-freshwater interface. This aquifer is not exploited in the study area. The Nubian Sandstone Aquifer System is connected to the Miocene aquifer outside the study area through a fault plane, although the flow between these aquifers is not well studied (El Tahlawi et al. 2008).

2.2.2 Groundwater recharge

The five aquifer systems beneath the study area all flow towards the Wadi El Natrun depression, creating an endorheic basin, where recharge enters the system upward through the fault planes and laterally from the adjacent aquifers. There are two parallel faults to the north and south of the Beni Salama anticline (see Ahmed 1999b, p. 33). The recharge moves between the interconnected aquifers. Figure 2.3 shows a conceptual model of the relations between the two uppermost aquifers and the deeper aquifer system beneath the study area.

The most comprehensive investigation of the origins of the water in the Pleistocene and Pliocene aquifers at Wadi El Natrun was conducted by Ahmed (1999b). This study used hydro-geochemical and isotope analysis to identify the origins of the water in each aquifer, and to examine their relations to one another.

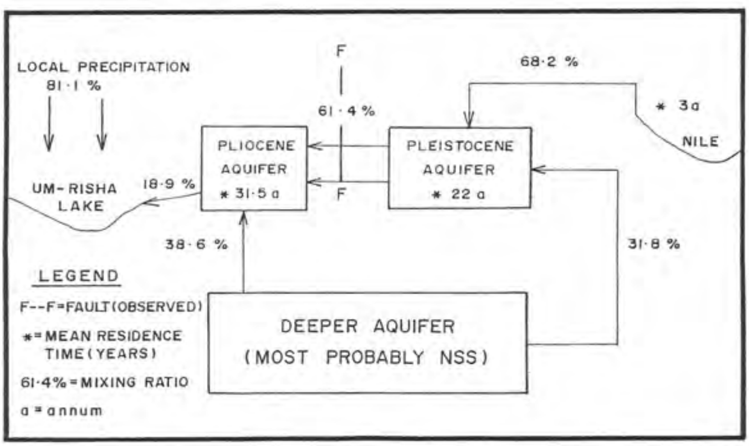


Figure 2.3. Conceptual model of study area. (Ahmed 1999b p171).

The volumes and origins of the recharge waters in each aquifer are herein summarised.

Pleistocene Aquifer Recharge

Estimates of annual recharge volumes vary between 41 million m^3 in 1975 (Abdel Baki 1983) and 160.3 million m^3 per year (Ahmed 1999a). A more recent study indicated this figure to be 70 million m^3 per year (Dawoud et al. 2005). Ahmed calculated the volume of mean annual recharge to the Pleistocene aquifer from the Nile Waters through lateral flow using Darcy's equation (1856). Using isotopic analysis, Ahmed concluded that 68.2% of aquifer recharge is from the lateral flow of the Nile waters and 31.8% from the upward leakage of paleowater. Based on this, we may conclude that the paleowater would contribute a further 7,169,214.5 m^3 of recharge, leading to a total recharge volume of 18,936,065.0 m^3/year of water recharging the Pleistocene aquifer in Wadi El Natrun.

Pliocene Aquifer Recharge

Water moves laterally from the Pleistocene to the Pliocene because the piezometric head in the Pliocene is lower than the piezometric head in the Pleistocene. Ahmed (1999b) calculated the relative volumes of recharge to the Pliocene through seepage from the Pleistocene Nile water (61.4%) and upward leakage of palaeowater (38.6%). Recharge to the Pliocene from the Miocene takes place upwardly through faults in the thin clay layer between the Miocene and Pliocene (Fekry and Salam 2002).

Miocene Aquifer Recharge

Recharge is achieved mainly through deep percolation from the Nile alluvium and groundwater flow laterally across the common boundary of the Moghra and the Nile alluvium (Dawoud et al. 2005).

The Miocene aquifer is connected to the Nubian Sandstone Aquifer System through fault planes and may receive some recharge from this source. However, the flow between these aquifers is not well studied (El Tahlawi et al. 2008). Beneath Wadi El Natrun, these aquifers are separated by a basalt layer (Idris and Nour 1990).

Nubian Sandstone Aquifer System (NSAS)

The NSAS consists of fossil or paleowater. The possibility of some minor present-day recharge taking place in Libya and Chad has been debated in some previous studies (after Ball 1939). More recently, it has been generally accepted that there is no significant recharge occurring at the present time (Robinson et al. 2007). More detailed studies could still shed light on the possibility of recharge to this aquifer in the study area.

2.2.3 Ecosystems present in the area

Naturally occurring ecosystem types and associated vegetation covers are connected with the presence of groundwater, springs, and drainage lakes and include: saline lakes with reed swamp vegetation; salt marsh ecosystems with wet and dry salt marsh and halfa grassland; and sand and gravel desert ecosystems with communities of Artemisia monosperma and Panicurn turgidum (after Zahran and Willis 2009).

2.2.4 Socio-economic characteristics of Beni Salama

Wadi El Natrun is the administrative centre of a region in Egypt which includes the urban area of Wadi El Natrun and five villages, including Beni Salama. In 2006, the total population of the region was approximately 72,100 people, with 18,169 households that averaged around 4 persons each. The population of Beni Salama and its surrounding farms and hamlets was 4,048, 57% of which is male and 43% is female, living in 1,114 households averaging 3.6 persons per household (CAPMAS 2007).

Table 2.1 provides a list of the major economic activities in the study area, according to the last official census (CAPMAS 2007). In Wadi El Natrun, groundwater-irrigated agriculture is the most frequently cited economic activity amongst the population. In the village of Beni Salama, the percentage of the population whose major economic activity is agriculture is even higher. Those who are engaged in service industries effectively serve the agricultural economy, and are therefore also dependent upon it.

Table 2.1. Major economic activities in the study area (based on CAPMAS 2007).

	Beni Salama Village Only				Overall Wadi El Natrun	
Sector	**No. of males engaged in the sector**	**No. of females engaged in the sector**	**Total number of people engaged in the sector**	**% of Popn**	**Total number of people engaged in the sector**	**% of Population**
Agriculture and fishing	525	1	526	42	11,285	55
Retail and wholesale trade and repair of vehicles	38	0	38	3	1,997	10
Transportation and storage	225	1	226	18	1,558	8
Processing or intermediate industries	165	3	168	14	1,502	7

Construction and development	89	0	89	7	1,351	7
Education	46	0	46	4	753	4
Public offices, defence and social security	40	0	40	3	663	3
Food and accom-modation services	24	0	24	2	319	2
Health and social services	2	1	3	0	231	1
Other services	43	0	43	3	252	1
Scientific activi-ties and technical specialist	10	0	10	1	163	1
Energy supply (electricity, gas, steam)	10	0	10	1	152	1
Water supply, sew-age network, and waste mgt	5	0	5	0	84	0
Information and communications	1	0	1	0	75	0
Administrative activities and subsidies	11	0	11	1	61	0
Mining	2	0	2	0	20	0
Financial services and insurance	0	0	0	0	15	0
Arts, recreation, and entertainment activities	0	0	0	0	13	0
Property and busi-ness	0	0	0	0	9	0
International orga-nizations	0	0	0	0	3	0
TOTAL	1,236	6	1,242	100	20,506	100

The industrial heritage of Wadi El Natrun is important. The discovery of natron at this location led to the development of the glass industry. Other chemical industries have also made various uses of the naturally occurring salts in the lakes. Important industries that are currently based in the study area include manufacturing chemicals for construction and water bottling plants, both of which are dependent on the presence of groundwater.

2.2.5 Legal and policy frameworks

Institutions of relevance to groundwater vulnerability

A number of institutions are responsible for the implementation of groundwater management, planning, and policy (for more updated detail see: Arabi 2012):

- The Ministry of Environmental Affairs/Egyptian Environmental Affairs Agency (MoEA/EEAA)) has the responsibility for setting national policy for the environment and coordinating environmental management activities within the government.
- The Ministry of Water Resources and Irrigation (MWRI) is the sole ministry legally responsible for the planning and management of all water resources in Egypt. It also ensures that water of suitable quality is provided to all users.
- The Ministry of Health and Population (MoHP) plays a central role in ensuring water quality management, particularly in setting standards for the quality of potable water sources (Nile river, canals, and groundwater wells) The Ministry of Housing, Utilities and New Communities (MoHUNC) together with the National Organization for Potable Water and Sanitary Drainage (NOPWASD) has the responsibility for the planning, design and construction of municipal drinking water purification plants, distribution systems, sewage collection systems, and municipal wastewater treatment plants.
- The Ministry of the Interior (MoI) is the head of Egypt's national police force. Together with the Inland Water Police, the special police force for enforcement of Law 48 (Protection of the Nile), it is responsible for the general protection of the environment.

Policies and laws of relevance to groundwater

A national strategy for groundwater management was explored in Egypt through a consultation process with stakeholder groups including the People's Councils (Majlis Al Sha'ab) during the period of this study but was not formally adopted. Table 2.2 presents a summary of the existing policies and laws related to groundwater management in the study area.

Table 2.2. A summary of existing legal and policy frameworks for groundwater management in Wadi El Natrun (after Attia et al. 2007).

Law	Date	Purpose of Legislation
National Water Policy: Water for the Future	2005	Integrated Water Resources Management
NEAP, including Law No. 4	2002	National Environmental Action Plan (MSEA)
Agricultural Policy		
National Policy for Inhabitation of the desert (MHUNC)		
Law No. 12, and supplementary Law 213/1994	1984 /1994	Main legislation for irrigation and drainage
Law No. 4 on Environment	1994	Establishment of Egyptian Environmental Affairs Agency
Law No. 27 on Public Water Sources	1978	Protection of public water sources
Law No. 48 on Protection of the Nile	1982	Control of pollution of surface waters
Law No. 31 on Public Cleanliness	1976	Control of solid waste management
Law No. 38 on Public Cleanliness	1967	Control of solid waste management
Law No. 53 on Agriculture	1966	Regulation of pesticides
Law No. 93 on Wastewater and Drainage	1962	Control of wastewater discharges

Local regulation

Groundwater management in the study area is characterised by a regulatory approach, where policies are made at the national level and enforcement is left to the local authorities of the Wadi El Natrun City Council. At this level, capacity is weak, and effective databases are not available to support decision-making. Groundwater source protection is a particular challenge in the study area. The government, through the municipalities, is continuing efforts to provide drinking water supplies to urban and rural households using groundwater. In the village of Beni Salama, most households are already connected to the public water supply network, which is overseen by the City Council of Wadi El Natrun.

Official rights to land are determined at the Governorate level, and water rights are determined at the level of the Ministry of Water Resources and Irrigation (MWRI). A permit is required for groundwater extraction. Permits are granted by the Groundwater Management Office under the MWRI to applicants who can demonstrate that the proposed well is not in an overexploited area by providing the coordinates and specifications for the intended well. The decentralisation of this process has been foreseen through the creation of a local office for groundwater management in Wadi El Natrun. This plan was implemented after the study period.

Economic instruments

Houses that are connected to the public water supply network are charged a monthly water fee. The fee varies from household to household, but averaged US$ 7 (40 EGP) per household during the study period. For those houses not connected to the public water supply network, and for agricultural uses, households use their own wells for which they bear the costs of digging, pumping, and maintenance. The costs of pumping depend on the type of pump (diesel or electric). In order to have an electric pump, a permit from the Office of Water Resources and Irrigation is required. Although tradable water rights are considered a useful management measure in other regions, there is no such system operating in the study area. Local people only have a right to water other than drinking water if they have received a permit.

Participatory aquifer management

Participatory approaches to aquifer management have attracted interest in Egypt, because regulatory measures for groundwater management are very difficult to monitor and enforce (Mukherji 2005). In other regions, participatory approaches have been undertaken through farmers associations or water user associations (eg Hammani et al. 2009). In the study area, there is an agricultural association that supplies agrochemicals and provides other technical support to some farmers, but according to the surveys conducted in Beni Salama, local people indicated that this association did not play a role in improving the management of groundwater.

Land use management and aquifer protection

In the study area, the only designated protected area is a nature reserve established in Wadi El Natrun at Lake Hamra. However, management of the reserve has been constrained by lack of resources. Land reclamation in the desert areas is a national policy objective associated with food security. Agricultural development in the study area relies on groundwater use for irrigation. The use of drip irrigation for agriculture has been promoted and widely adopted in the study area, particularly on larger farms.

Other options referred to by national policies for the improvement of water use efficiency include the reuse of wastewater and the encouragement of water sharing. Close to the study area, wastewater is used to irrigate the Chinese Friendship Forest. For major changes to land and water use, Environmental Impact Assessment (EIA) procedures are required under existing policies (see e.g. Attia et al. 2007). However, these depend on the capacity of officials and consultants and the availability of appropriate information in order to evaluate the likely impacts of land use changes.

Groundwater monitoring

Monitoring of groundwater resources in the study area is carried out by two institutions: the Ministry of Health monitors drinking water quality on a monthly basis, and the Ministry of Irrigation maintains ten wells for monthly monitoring of the quality of water for irrigation. A further ten observation wells are intended to be added to this network.

2.3 Methodologies

Rather than conducting new field sampling of soil and water conditions, the project mainly relied on the review of existing data supplemented by local consultations with people living in the village area and officials responsible for environmental management. A socio-economic survey was also conducted. The primary and secondary data collected were then combined with additional information from satellite imagery and compared using GIS. This was later combined with a DRASTIC analysis and a review of available water balance calculations. A brief explanation of the principal methods used in this approach is provided here.

2.3.1 Review of national statistics and published studies

A review of all available statistics on the study area of Beni Salama was conducted, including data on agricultural productivity in Wadi El Natrun published by the Egyptian Government since 1961, and national census data from every decade since 1986 (CAPMAS 1986, 1996, 2007). Official statistics on the state of groundwater resources in the study area are not published.

2.3.2 A village survey of farms and households in Beni Salama

A survey of farms and households in the village of Beni Salama was completed between March-May 2009 (see questionnaire in King and Salem 2012). The survey design was informed by available surveys that were previously conducted in the study area (eg IFPRI 1999, CAPMAS 2007) and elsewhere (e.g. Sghaier 1984, Kaplan 2006).

Farms in the study area were classed by area and by size, based on conventions established by the Egyptian Ministry of Agriculture and in previous studies (eg Yehia 2004). Farms were then selected at random for land reclamation survey studies based on the availability and willingness of cultivators and their families to participate. The survey included 38 households, representing 14% of the population of the main village of Beni Salama (271 households) and 58 farms.

The survey format consisted of a structured questionnaire including a combination of short-answer and multiple choice questions, initially administered as two parts and with the following purposes: i) farm survey to identify groundwater use and changes affecting quantity and quality; and, ii) household survey to identify the nature of household resource dependence and management.

As the implementation proceeded, the two parts of the survey were combined. The questionnaire was written in both Arabic and English, and designed to take not more than 30 minutes to administer. In practice, it took considerably more time, often involving several visits. Prior to administering the questionnaire, an introduction of the survey and its objectives was provided, facilitated by a trusted local person. Various people volunteered to take this role, including: a local lawyer, two teachers, a graduate, two local farmers, two farm security providers, a former official of Wadi El Natrun City Council, and a retired agricultural expert.

2.3.3 Informal interviews with stakeholders in groundwater management

During the implementation of the surveys, an additional series of extended interviews and visits were made with cultivators and their families living in the village of Beni Salama. These interviews provided additional guidance to the survey implementation.

Additional informal interviews were also conducted with staff of the Egyptian Groundwater Research Institute, the Groundwater Management and Irrigation Office, the Wadi El Natrun City Council, the Office of Land Registration in the Governorate of Behayra, the soil and water analysis laboratory of the American University in Cairo Desert Development Center, the General Company for Research and Groundwater (REGWA), and other private drilling companies working in Wadi El Natrun. These interviews provided essential information concerning the context of groundwater development and management issues in the study area.

Survey questions on water use were developed and collected with the participation of farmers and farm workers. Different approaches to the estimation of water use were adopted for larger and smaller farms, reflecting their different management patterns. The data collected during the field survey were compared to a database of well permits held by the Ministry of

Water Resources and Irrigation (MWRI), which lists permitted extraction volumes for some wells.

2.3.4 Remote Sensing and GIS

The project team developed a geo-database containing both environmental and social information, as described in this report. Land cover changes in the study area were investigated using Landsat images available from the United States Geological Survey and the University of Maryland. A detailed review of methodologies using satellite imagery and their applicability in the study area is presented by Awad (2002). A model grid was laid over the aquifer in order to conduct the DRASTIC model analysis. The socio-economic data collected during the field survey was plotted using GPS coordinates. This data was compared with high resolution images in Google Earth and NDVI analyses conducted using ERDAS Imagine software in order to identify the cultivated landcovers and create a map of agro-ecosystems.

2.4 Results of the Assessments

2.4.1 Groundwater balance calculations and future extraction scenarios

The appropriate scales for calculation of groundwater balance vary according to the spatial extent of the aquifers. As described earlier, there is a wide variation in the scales and extent of the different aquifers in the study area. While the Pliocene, or Wadi El Natrun, aquifer is local, the Miocene aquifer extends far across the Western Desert, and the Nubian Sandstone Aquifer reaches into Sudan and Chad. A comprehensive balance calculation needs to incorporate extraction rates across each of these systems.

The area to the north and east of Wadi El Natrun has been developed through various land reclamation projects including canals bringing irrigation water from the Nile and also wells dug to the Pliocene aquifer. In the absence of precise information concerning extraction rates, the extent of cultivated land is frequently used as a proxy to estimate groundwater extraction. In addition to driving groundwater extraction, land reclamation in the Western Delta has also increased the volume of drainage water returning to the surface aquifer system due to increased irrigation activities and the presence of surface water canals.

Diab et al. (2002) used a 3D finite element model, known as the TRIWACO model, to estimate the local water balance of the Pleistocene and Pliocene aquifers over an area of 500 km^2 between a northern boundary defined at the El-Nasr Canal, and eastern and southern boundaries imposed for the purposes of the model far enough from the well field of new reclamation projects in the area to assume constant piezometric head. The aquifer boundary on the west allowed no flow due to the presence of Gebel Khashm El-Kaoud and Dahr El-Tashasha impervious boundaries. The aquifer was assumed to receive spatially uniform areal recharge from precipitation and excess irrigation water (0.5 mm/day).

The simulation procedure divided the Pleistocene and Pliocene aquifers in the modeled Wadi El Natrun area according to a grid. Vertical homogeneity was assumed adequate to allow treatment as a single layer due to the hydraulic connection between the two aquifers through fault planes. The results of the balance estimation are given in Table 2.3.

Table 2.3. Estimated water balance of the present aquifers using TRIWACO model (Diab et al. 2002)

Aquifer	Component	Calibration run (2002) (m^3/day)	Predicted run in 2015 (m^3/day)
Pleistocene aquifer	Leakage from soil zone (net recharge)	239,140	238,520
	Source / Sink (Extraction)	----	---
	Boundary fluxes (discharge)	-126,640	-105,110
	Leakage from/to deep aquifer	-128,040	-140,550
	Change in storage	15,541	7,142.7
Pliocene aquifer	Net recharge	128,040	140,550
	Source/Sink (Extraction)	-26,568	-53,136
	Boundary fluxes	-101,590	-87,466
	Change in storage	115.6	54.9

Irrigation water requirements of around 6,000 m^3/acre/year were assumed in the cultivated area. The model demonstrated that net recharge to the Pliocene aquifer from the upper Pleistocene aquifer would increase from 128,040 m^3/day in 2002 to 140,550 m^3/day in 2015 due to the increasing pumping rate in the Pliocene, as can be expected from increased reclamation activities. Also, the change in storage of the Pliocene aquifer would be cut in half as pumping doubles. In order for the pumping rate from the Pliocene aquifer not to exceed the net recharge to this aquifer, the critical area of future reclamation activities was calculated to be about 7,790 acres.

Miocene Aquifer

Recharge to the Miocene Aquifer has been estimated at 50-100 million m^3/year (RIGW 1990), while extraction was estimated at 150 million m^3/year in 1993 (see Mostafa in Ahmed 1999b). Although extraction has increased further since that time, Egyptian scientists have ceased trying to quantify the degree to which the water balance has been exceeded, and have instead focused on the visible impacts of the decline (see Ibrahim 2007).

Nubian Sandstone Aquifer System (NSAS)

Recharge and extractions from the NSAS were studied by Ebraheem et al. (2003) in light of intensive development taking place upstream from Wadi El Natrun in the southern part of the Western Desert. This study concluded that the aquifer was being mined and that the planned extraction rate of 1,200 ×106 m^3 $year^{-1}$ in the East Oweinat area was not feasible for the coming 100 years because it would have a negative impact on water levels elsewhere, and could possibly lead to saline intrusion in the north. This study also observed that cones of depression in the potentiometric surface that had already developed elsewhere in the aquifer due to pumping in neighbouring countries (e.g. Libya) could expand into Egypt.

2.4.2 Falling groundwater level

A long-term groundwater fluctuation map covering the period 1960-2003 was constructed, showing that the decline in groundwater level reached 30 m in the south-western part of Wadi El Natrun (Ibrahim 2005). Ibrahim (2005) also studied the medium-term groundwater depletion from 1990-2002 based on a series of wells accessing the Miocene aquifer in Wadi El Natrun and the surrounding area. This study found that the groundwater levels in selected wells fell approximately 8 m during this period.

The accelerated decline of groundwater resources in the Wadi El Natrun area during this 12-year period was a result of excessive drilling of productive wells and over-pumping (Abdel Mogheeth 2004). Water level depletion during this period ranged from 1-12 m. The most affected areas with a drawdown of 8-12 m are the areas close to the Cairo-Alexandria Desert Highway. This may be attributed to cultivation activities. The gradual decrease in the decline direction (towards the west) reflected the effect of the topography.

2.4.3 *Vulnerability of the Pliocene aquifer estimated by use of the DRASTIC model*

Contamination from rapid urban development, industrialisation, and agricultural sources increasingly threatens the groundwater resources in many parts of the Pliocene aquifer of the Wadi El Natrun. The Pliocene aquifer is semi-confined, with shallow water depth in the areas surrounding the salty lakes. The drainage system allows contaminants to travel through the shallow vadose zone, contributing to the pollution of scarce water resources.

Groundwater vulnerability is a complicated issue. Vowinkel et al. (1996) defined vulnerability as sensitivity plus intensity, where intensity is a measure of the source of contamination. Intrinsic vulnerability is controlled exclusively by geological structure and hydrogeological conditions, while specific vulnerability includes, in addition to the former parameters, consideration of the type of contaminant and the character of the contamination source (Vrba 1994).

Due to the groundwater contamination in some samples of the Pliocene aquifer in Wadi El Natrun, a trial to assess the intrinsic groundwater vulnerability was carried out applying the DRASTIC method to delineate the less vulnerable areas suitable for human activities.

2.4.3.1 *The DRASTIC Model*

The evaluation of groundwater vulnerability can be done using a range of different methods (Aller et al. 1987, Foster 1987, Robins 1994, Vrba 1994, Holting 1995, Foster 1997, Gogu 2000, Al Zabet 2002, Daly 2002, Foster 2002). No unified methodology of vulnerability assessment has been accepted for the Pliocene aquifer due to the complexity and variability of recharge and groundwater flow conditions in the hydrogeological medium, although the problem has been studied previously (RIGW/IWACO 1990 , RIGW/IWACO 1991). For this reason, the groundwater vulnerability map for the Pliocene aquifer that is presented here is a subjective interpretation of published concepts.

The study team elected to use the DRASTIC model (after Aller et al. 1987), which is used widely across the region (see e.g. Al-Naqa et al. 2006, Boughriba et al. 2010, Abdelkhalek 2013, Switzman 2013a, Neshat et al. 2014) and internationally (Kwansiririkul et al. 2004, Osborn and Hardy 1999). Critics of the DRASTIC method have pointed out that it may be 'overly complex in its selection of parameters, and arbitrary in its assignment of relative weights to these parameters' (Stempvoort et al. 199,2 p. 29, Switzman, personal communication).

DRASTIC can be used to set priorities for areas to conduct groundwater monitoring. For example, a more intense monitoring system might be installed in areas where aquifer vulnerability is higher and land use suggests a potential source of pollution. DRASTIC can also be used with other information, such as land use, potential sources of contamination, and beneficial uses of the aquifer, to identify areas where special attention or protection efforts are warranted.

The model is based on four assumptions (Aller et al. 1987, p. 42):

i) the contaminant is introduced at the ground surface;
ii) the contaminant is flushed into the groundwater by precipitation;
iii) the contaminant has the mobility of water; and,
iv) the area being evaluated by DRASTIC is 100 acres or larger.

DRASTIC considers seven hydrogeological factors (Aller et al. 1987); Depth to water, net Recharge, Aquifer media, Soil media, Topography (slope), Impact of the vadose zone media and the hydraulic Conductivity of the aquifer. Each of these hydrogeological factors is assigned a rating from one to ten based on a range of values. The ratings are then multiplied by a relative weight ranging from one to five. The most significant factors have a weight of five; the least significant have a weight of one.

The equation for determining the DRASTIC index is (Aller et al. 1987, p. 106):

$$\text{DRASTIC Index} = \\ D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w$$

where D, R, A, S, T, I, C represents the seven hydrogeological factors, r designates the rating, and w the weight. The resulting DRASTIC index represents a relative measure of groundwater vulnerability. The higher the DRASTIC index, the greater the vulnerability of the aquifer to contamination. A site with a low DRASTIC index is not free from groundwater contamination, but it is less susceptible to contamination compared to sites with higher DRASTIC indices (Aller et al. 1987).

The ARC/INFO GIS was used to compile the geospatial data of the Pliocene aquifer of Wadi El Natrun, to compute the DRASTIC indices, and to generate the final vulnerability maps. In this report, digital geospatial datasets generated through previous studies (El Sayed 2007, eg Ali and Baroudy 2008) that describe aquifer characteristics of the Pliocene aquifers were used in the vulnerability mapping. Included in the datasets are the aquifer boundaries, hydraulic conductivity, recharge, and water-level elevations. The datasets are available in non-proprietary ARC/INFO formats in previous works. The Egyptian Geologic Survey and Mining Authority (EGSMA) also created digital surficial geology sets from the hydrologic atlases of Egypt. A model grid was then overlaid on the aquifer and assigned DRASTIC ratings to the grid cells for each of the seven hydrogeological factors. The obtained grid layers were used to compute the final DRASTIC indices and to produce the aquifer vulnerability maps.

2.4.3.2 Hydrogeological factors

The hydrogeological factors considered in the DRASTIC approach include (after Aller et al. 1987) depth to water, net recharge, aquifer media, soil media, topography, and impact of the vadose zone media. Each is described here.

Depth to Water (D) (Aller et al. 1987, p. 44): The depth to water is the distance (in meters) from the ground surface to the water table. It determines the depth of material through which a contaminant must travel before reaching the aquifer. Thus, the shallower the water depth, the more vulnerable the aquifer is to pollution. The grid layers for depth to water were generated by computer subtraction of water-level elevation datasets from land surface elevation derived from a digital elevation model (DEM) for Wadi El Natrun from 1:100,000-scale maps. The water-level elevation data sets were developed from maps published in aquifer reports. Depth to water ranged from more than 4 m above the ground surface in some alluvium and terrace sites to more than 80 m below the ground surface in the western area of the aquifer

Net recharge (R) (Aller et al. 1987, p. 47): The primary source of recharge is precipitation and return flow after irrigation, which infiltrates through the ground surface and percolates to the water table. Net recharge is the total quantity of water per unit area (in inches per year), which reaches the water table. Recharge is the principal vehicle for leaching and transporting contaminants to the water table. The greater the recharge, the greater the chance for contaminants to reach the water table. The grid layers for net recharge were developed from the recharge datasets. Recharge rates for the Pliocene aquifer were usually derived from groundwater flow models and represent averages over large areas. All of the values in this study were in the range of 1.5-1.8 inches per year, and more than 1.8 inches per year.

Aquifer media (A) (Aller et al. 1987, p. 49): Aquifer media refers to the consolidated or unconsolidated rock that serves as an aquifer. The larger the grain size and the more fractures or openings within the aquifer, the higher the permeability, and thus vulnerability, of the aquifer (Aller et al.

1987). In unconsolidated aquifers, the rating is based on the sorting and amount of fine material within the aquifer. In consolidated aquifers, the rating is based on the amount of primary porosity and secondary porosity along fractures and bedding planes. Ratings for the Pliocene aquifer in this study range from six for the northern and central parts of the Pliocene aquifer, to eight for the eastern parts and the alluvium and terrace aquifers.

Soil media (S) (Aller et al. 1987, p. 51): Soil media is the upper weathered zone of the earth, which averages a depth of 2 m or less from the ground surface. Soil has a significant impact on the amount of recharge that can infiltrate into the ground. In general, the less the clay shrinks and swells and the smaller the grain size of the soil, the less likely that contaminants will reach the water table. The general soil associations for an area were determined from soil survey maps. The soil horizons were then evaluated to determine which will most significantly affect groundwater vulnerability, based on texture and thickness of each layer. The current report used the Department of Soil Physics and Chemistry Desert Research Center's Soil Geographic Database to develop the grid layers for soil. Soils in this study varied greatly from being non-existent to gravel, sand, and clay.

Topography (T) (Aller et al. 1987, p. 57): Topography refers to the slope of the land surface. Topography helps to control the likelihood that a pollutant will run off or remain long enough to infiltrate the ground surface. Where slopes are low, there is little runoff, and the potential for pollution is greater. Conversely, where slopes are steep, runoff capacity is high and the potential for pollution to groundwater is lower. A digital elevation model (DEM) was used to calculate percentage slopes. Most of the slopes in this study were in the ranges of 0-2% and 2-6%, depending on the ranges and the ratings for topography.

Impact of the Vadose Zone Media (I) (Aller et al. 1987, p. 57): The vadose zone is the unsaturated zone above the water table. The texture of the vadose zone determines the time it takes for the contaminant to travel through it. In surficial Pliocene aquifers, the ratings for the vadose zone are generally the same as those of the aquifer media; that is, lower for confining layers such as shale, and higher for unconfining layers such as limestone. Sometimes a lower rating is assigned if the aquifer media is overlain by a less permeable layer such as clay.

Hydraulic conductivity of the aquifer (C) (Aller et al. 1987, p. 62): Hydraulic conductivity refers to the rate at which water flows horizontally through an aquifer. The higher the conductivity, the more vulnerable the aquifer is. Conductivity values for the aquifers were usually derived from groundwater flow models and represent averages over large areas. Most of the bedrock aquifers in Wadi El Natrun have hydraulic conductivity values in the range of 0.005-0.05mm/sec. The alluvium and terrace aquifers have higher hydraulic conductivity values, ranging from 0.05 - 1mm/sec .

Using the above data, the vulnerability map of the Pliocene aquifer of Wadi El Natrun was produced (Figure 2.4). Light grey represents the least vulnerable areas, and black represents the most vulnerable areas. The large statewide map is useful for comparing the relative vulnerability of the Pliocene aquifer, and for viewing smaller areas within an aquifer. The DRASTIC indices range from 96 (least vulnerable) in the central Pliocene aquifer to 156 (most vulnerable) for the eastern reach of the Quaternary Alluvium and Terrace aquifer parts.

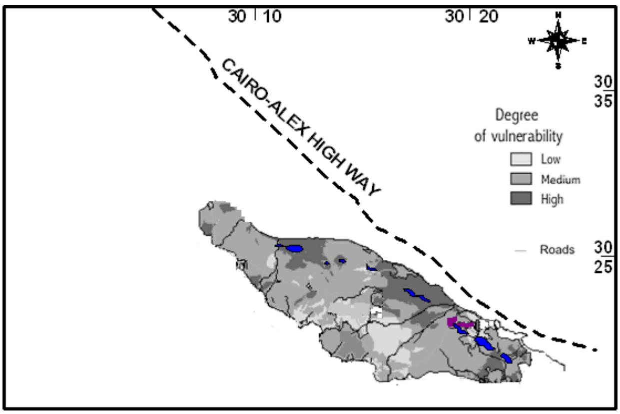


Figure 2.4. Vulnerability map for the Pliocene aquifer of Wadi El Natrun. (Credit: Mohamed Gad El Hak).

There is a correlation between the mean DRASTIC indices and the type of aquifer material. Because DRASTIC indices were calculated only for the areas where the aquifers outcrop, the ratings for aquifer media (A) and the impact of the vadose zone media (I) are usually the same. These factors have weights of five and three respectively, and together they have a strong influence on the final DRASTIC index.

Depth to water (D) is also heavily weighted, with a weighting factor of five, and therefore has a significant influence on the index. The impact of water depth is most apparent in the Pliocene aquifer. Although the high ground elevation areas in the peripheries of the Pliocene aquifer have a high DRASTIC rating for aquifer media (A) and impact of the vadose zone media (I) similar to the alluvium and terrace deposits areas, its great depth to water lowers its mean DRASTIC index.

2.4.3.3 Limitations of the DRASTIC vulnerability map

The aquifer data used in these analyses were taken from various studies conducted by different authors. Values for some factors, such as recharge (R), were determined by different methodologies. Thus, apparent differences in vulnerability may be due to differences in methodology or interpretation.

Another limitation is the accuracy of the depth to water that is a function of the contour interval of the water-level elevations. The larger the contour interval, the less accurate the depths to water. This map describes the relative vulnerability of the Pliocene aquifer based on available data of different levels of precision and resolution. Resolution depends on the number and proximity of data points. For example, the grid layer for topography (T) was derived from a high resolution, 90 m DEM grid, while other layers, such as net recharge (R) and hydraulic conductivity (C), were derived from groundwater flow models and represent averages over large areas. The mixed resolution is acceptable for evaluating relative vulnerability of aquifers, but is not adequate to determine site-specific vulnerability. No attempt has been made to calibrate the DRASTIC results to field data.

2.4.4 Vulnerability of the socio-ecological system

This section of the report considers the vulnerability to groundwater threats in the village of Beni Salama. The system includes the aquifers and the dependent households, communities, economic activities, and ecosystem services (as discussed in King and Salem 2012).

The elements of vulnerability, as defined by the GWAHS-CS project, are explored through the generic set of indicators selected by the project. This case study explores how the indicators could be applied and interpreted in the context of the village of Beni Salama. It explores the relationship between the various individual indicators, and discusses the degree to which the selected indicators capture the intended elements of vulnerability.

2.4.4.1 Exposure

Exposure concerns the degree, duration, and/or extent to which a system is in contact with, or subject to perturbation (Gallopin 2006). The GWAHS-CS project selected the following sub-indicators of exposure: i) percentage of population dependent on groundwater; ii) percentage of major economic sectors dependent on groundwater; iii) dependence of ecosystem services on groundwater; and, iv) well density and groundwater extraction by cultivation type, as an indicative sub-indicator. Each of these four indicators is discussed here.

Dependence on Groundwater for Household Use: The study area is considered a desert area due to its lack of rainfall (less than 50 mm/year). 100% of the population is therefore dependent on groundwater for drinking and household uses, and the water used for these purposes in the study area comes from wells.

Dependence on Groundwater for Economic Activities: As indicated earlier, the major economic activities in the study area are dependent on groundwater either directly in the case of irrigated agriculture, water bottling, and other industrial activities for which groundwater is necessary; or indirectly in the case of other activities that support the agricultural economy in the study area.

Vulnerability of the Ecosystems: The vegetation types mentioned earlier provide ecosystem services which benefit the human population. The ecosystem services provided include provisioning, supporting, and regulating services, as per those used in the Millennium Ecosystem Assessment (MA, 2005). A summary is provided in Table 2.4.

Table 2.4. Ecosystem services in the study area and their exposure to groundwater threats. (based on King and Salem 2013, Zahran and Willis 2009)

Ecosystem	Ecosystem Services			Vulnerabilities
	Provisioning	**Supporting**	**Regulating**	
Saline lakes	Salts for domestic and industrial uses	Habitat for birds and micro-organisms	Natural drainage area, ensuring the quality of the surrounding land for cultivation	Alteration of the quantity and quality of groundwater inflow to lakes affects water levels and chemical conditions for salt production and species habitats
Salt-marsh and halfa grassland	Plants for fiber	Grazing for animals	Drainage water purification, carbon sequestration, and other elements in soils, silt, and plant matter	Falling groundwater tables affect the extent of salt-marsh vegetation
Sand and gravel desert ecosystem	Limited human use of wild animals for medicinal purposes and hunting	Wild plants, insects, reptiles, and mammals create a food chain to break down and remove wastes	Waste decomposition and removal	Alteration of water availability in soil, rocks, and gravels affects the survival of sparse vegetation and wild species
Agro-ecosystems	Food and income	Generation of nutrient rich soil and grazing fodder for animals over wider areas at lower intensity due to drip irrigation	Carbon sequestration and cooling effect where date palm and other trees remain under-cultivated	Altered quality of water limits cultivation options. Falling groundwater table requires digging of deeper wells
Village gardens	Diverse range of food for human consumption and building materials from date palm and other fruit trees	Generation of nutrient-rich soil and grazing fodder for animals	Carbon sequestration and cooling of local microclimate due to date palm and other fruit trees	Alteration of groundwater level reduces range of cultivable species and/or requires deeper wells. Increasing salinity may also affect the diversity of cultivable fruit and vegetable species

The main beneficiaries of the provisioning services provided by these ecosystems are local people living in Beni Salama village, who extract salts from the lake, graze animals in the salt marsh area, and enjoy the recreational value of all three natural systems. However, the supporting and regulating services that are provided by these systems benefit a wider group of people, including other land users in the surrounding large farms, factories, and urban areas.

The three identified vegetation types may be considered semi-disturbed ecosystems. In addition to these, cultivated agro-ecosystems and settled village garden systems are present in the study area. These systems provide different services and are exposed to different threats, as noted in Table 2.4. While the main beneficiaries from the provisioning services provided by the village gardens are the local people of Beni Salama village, the owners of the agro-ecosystems, namely the larger farms and agribusinesses, are often from outside the village. The provisioning services therefore provide benefits to external investors and consumers. The people living in Beni Salama also benefit to some extent from these provisioning services through available employment opportunities.

Well Density and Groundwater Extraction by Cultivation Type: The field survey generated information on groundwater extraction in each of the cultivation types: gardens, small farms, medium-sized farms, large farms/agribusinesses/factories.

The gardens use flood irrigation and natural drainage systems, although sprinklers are also present in some places. Before the 1960s there were shared wells, but now each garden has its own shallow well. The depth of wells in the surveyed gardens ranged 16-42 m in depth, with an average depth of 30 m. The distance to the next well ranged 10-300 m, with an average distance of 100 m.

Small farms in Beni Salama have one or two shallow wells. The deepest wells surveyed were 72 m. Some farms had electric pumps, but most were diesel. Electric pumping is cheaper but requires a permit from the MWIR, as well as the formal registration of the land. The distance to the nearest well on the small farms ranged widely from 10-500 m.

With medium-sized farms, one farm shared a deep well with another; however, the sharing of wells is unusual. Farms over fifty feddan (1 feddan = 4,200 m^2 or 0.42 ha) have at least two wells. Well depths ranged from 60-164 m, and either electric or diesel pumps are used. Crops grown include fruit and vegetables for export, with relatively high water requirements.

Around the study area, there are large farms of up to around 1000 feddan in size, with several hundred wells. The average size of the largest set of farms surveyed in the study area was 260 feddan, although the majority of the farms were less than 200 feddan. The density of wells was around one per 40 feddan.

Based on the above typology, Table 2.5 shows a summary assessment of farm types and groundwater use patterns. A periodic inventory of wells in the study area is conducted by the Egyptian Groundwater Research Institute (RIGW). The most recent inventory took place in 2006; however, this data is not publicly available. A separate database of wells for which permits have recently been issued is also maintained by the MWRI.

Table 2.5. Comparison of farm types and groundwater uses.

Farm size (feddan)	Average size (feddan)	Average well depth (m)	Average feddan/ well	Average well spacing (m)	Type of pump	Most common irrigation methods
1-3	2	25	2	50	Diesel 3 inches 5 hours power	flood
3-20	8	43	8	117	Diesel 8-10 inches *	sprinkler flood and drip
20-100	50	114	50	433	diesel or electric 80-90m³/hr	drip and sprinkler
100 +	264	146	42	700	Electric 110m/r	drip
AVERAGE	81	82	25.5	325		

1 feddan = 4200m² = 0.42ha = 0.0042k m² or 1.038 of an acre
*based on MWRI database

The estimates provided in this chapter are included for indicative purposes only. They are not based on an exhaustive survey of every well in the study area, but rely on the local reports collected during the field survey, triangulated with additional field observations. When compared to the MWRI database on well permits registered in the study area, these estimates showed some discrepancies. Many of the smaller farms are not registered formally, but fall under the traditional system of "Wada Yid" ("placing the hand"). The land management office at the Governorate of Behira could not verify the local estimates of farm numbers and land area shown above.

The first three sub-indicators capture the exposed population in different ways, introducing increasing degrees of specificity in the description of the relationship between the population and its sub-groups to the groundwater resource. The first addresses dependence on groundwater in general, without specifying the nature of the dependence. The second is more specifically targeted to the economic sectors' dependence on groundwater, and the third considers ecosystems' dependence on groundwater. These three sub-indicators capture three dimensions of exposure of the population to groundwater hazards.

The fourth sub-indicator was acknowledged to be imprecise and somewhat problematic. The value of the indicator is that it captures the pathway of exposure to groundwater hazards (wells), and that it enables a geographic analysis of the distribution of this exposure. This sub-indicator might be more relevant in a case where all wells were accessing a single aquifer, and the only groundwater-related hazard to be considered was drawdown. This has been observed to the south of Beni Salama at Wadi El Farigh, where density of wells and high extraction rates have led to the creation of a drawdown effect in the Miocene Aquifer (Ibrahim 2005). However, as indicated earlier, the depletion of the Miocene Aquifer affects the population in other parts of the study area, not only those in the area where the wells are most dense.

However, the hazards of interest concern quality, as well as water levels, and both of these vary in the study area according to the depth of wells. The well density sub-indicator does not consider the depth of the wells and the different aquifers that they are accessing, or the volume of water use, or the nature of the use of the water. All of these factors mediate the exposure of the population to the groundwater hazard. It might be possible to create a sub-indicator focusing on well depth (i.e. differentiating exposure to hazards in each aquifer). This would highlight differences between the nature of exposure of small farms and gardens in the village which rely on the Pleistocene Aquifer, and the exposure of larger farms in the surrounding area, which increasingly draw on the Miocene aquifer. For drinking water supplies, Beni Salama village is also dependent on the Miocene aquifer.

Concerning the evaluation of exposure to groundwater-related hazards in Beni Salama, the indicators focusing on the degree of dependence will all produce scores of 100% since there is no other significant source of water in the area due to its aridity. Where there are public water supplies in the area, these come directly from wells. Overall, the village of Beni Salama is highly exposed to threats from changes affecting groundwater.

In order to consider the nature of the exposure and the relationship between exposure, hazard, sensitivity, and resilience, additional information was provided in the previous section on groundwater extraction volumes and methods. The issue of how groundwater is being used is otherwise not properly captured in the GWAHS-CS framework. The case study team would also recommend consideration of dependence on the different aquifers as an important element in the description of the nature of exposure. In a conventional risk assessment, this might be the pathway element.

2.4.4.2 Hazard

Hazards are threats to a system, comprised of perturbations and stress (Turner et al. 2003, Gallopin 2006). The GWAHS-CS project selected the following sub-indicators of hazard: i) ratio of groundwater abstraction to groundwater recharge; and ii) groundwater quality (as compared to drinking water standards).

Ratio of groundwater extraction to groundwater recharge: Available estimates of the ratio of groundwater abstraction to groundwater recharge are summarised under the section on hydrogeological characteristics. These estimates vary according to the boundaries of the system. A balance calculation was presented for an area of 500 km^3, representing a sub-basin of the West Nile Delta. However, the system boundaries could arguably be considered to encompass the full extent of the Nile Basin and the Nubian Sandstone Aquifer System (NSAS).

Some attempts to model the effects of ongoing climatic changes and effects on the Nile have been published (see Conway 2004, Mohamed et al. 2005). This is important because the Nile provides one of the most significant sources of recharge to the aquifer system of Wadi El Natrun. The other essential source of recharge to the NSAS and the Miocene Aquifer consists of palaeowater flowing beneath the Western Desert. Separate efforts to model this system have been published (CEDARE 2001, Attia 2002, Robinson et al. 2007).

The intersection of the three different systems and their contributions to the recharge processes at Wadi El Natrun has been the subject of a number of theses by Egyptian students (Hamza et al. 1984, Ahmed 1999a, Ahmed 1999b). However, none of these has yet fully taken into account the anticipated climatic and anthropogenic effects. Dawoud et al. (2005) concluded that there was a need for a more detailed analysis with respect to the effect of irrigation improvement in the region in order to understand the effects on the water table in Wadi El Natrun.

Data on groundwater recharge was provided earlier and data on water balance in each aquifer at the regional scale is provided in Table 2.3. Since the study area is located in an endorheic basin, natural discharge of groundwater occurs into saline drainage lakes at the centre of the depression. Recharge occurs from the surface, from below, and laterally. This natural discharge in addition to the extraction of groundwater must be considered in the balance calculation.

In the study area there are three aquifers from which groundwater is extracted within a larger system that has been described earlier as consisting of five major interconnected aquifers. The balance calculation must consider all of these as a whole. If, for example, the Pliocene aquifer is considered in isolation, discharge equals 100% of recharge, as demonstrated by Diab et al. (2002). Even if extraction doubles from the aquifer, the balance between recharge and discharge is retained because it is part of a larger system. The increase in extraction from the Pliocene results in a fall in the balance in the Pleistocene.

When the Miocene Aquifer System is included in the balance calculation, the ratio of discharge to recharge appears to be 2:1. If the NSAS is also added, the ratio of discharge to recharge would be at least an order of magnitude, with most of the discharge taking place outside the study area. For the purposes of this case study, we will choose to set a boundary at the Miocene Aquifer, and take the ratio of groundwater recharge as 1:2, reversing the above, as the final indicator.

Groundwater quality compared to drinking water standards: Overall, the quality of groundwater in the study area may be considered good according to WHO standards . However, the hydrogeological conditions are quite variable with some areas having high salinity. In addition, there is a high potential for future effects on groundwater quality as a result of the anthropogenic changes occurring in the area.

The following main threats to water quality were identified through a review of published secondary information and observations in the study area:

- Salinisation – due to hydrogeological changes associated with groundwater extraction;
- Agrochemicals – used primarily for export crops (generally not practiced by small and medium-sized farms);
- Sewage disposal – due to urban development in the study area which continually requires additions to the provisions for safe sewage disposal; and

- Solid waste disposal – issues with solid waste disposal are visually apparent in the study area, and may be considered to be an important management issue for the protection of groundwater resources.

Chemical analyses that would verify these water quality threats were not included in the activities of the GWAHS-CS project; the project instead reviewed previously generated data. During the survey activities, local people commented on the changes observed in water quality in the study area, in particular, increases in salinisation. Some water quality analyses previously conducted by farmers were also shared with the project by local farmers.

Information on water quality in the study area has been published in previous studies by Egyptian students (eg Ahmed 1999b, Awad 2002, Ibrahim 2007). Data on Total Disolved Solids (TDS) in water samples from the study area in comparison to available drinking water quality standards have been published (Ahmed 1999b) with no major concerns identified in this study. It is important to note that the water samples analysed were taken from farms, and not from public drinking water supplies.

Based on the above information, the sub-indicators do address the two relevant groundwater hazards for the study area: groundwater quality and availability. The ratio of groundwater recharge to abstraction was found to be 1:2, while groundwater quality as compared to WHO drinking water standards was close to 100%.

Concerning the quality sub-indicator, comparison to drinking water standards does not fully address the use of groundwater for agriculture. In light of this, smaller reductions in quality parameters such as salinity or the presence of trace elements could cause a hazard to farmers. Also, the indicator is not able to identify a future hazard as it requires the contamination to be detected in the water at the present time. The presence of pollution sources, such as ineffective waste disposal facilities, would not be registered as a hazard unless or until someone was able to measure the effect on water quality.

On the other hand, the water balance indicator can take into account future scenarios because it considers extraction rates that enable future changes in groundwater levels to be predicted. Unfortunately, there is no need for such an indicator in the study area as there is already a visible and readily measurable indicator of groundwater hazard through the falling water table, as observed in section 2.2.1. The projection of the hazard in relation to present and future extraction rates involves significant unknowns that dilute the message of the indicator. Direct observation of the existing drop in water levels is a more simple way to indicate the presence of the hazard.

Figure 2.4 presents a spatially differentiated representation of the potential contamination hazards in the Pleistocene aquifer where the differentiation is determined by soil quality, relief, and climatic factors. The relationship of the hazard to the community in the study area is mediated by their location within this spatial distribution, and also vertically, depending on which aquifer they are using to supply their groundwater needs. The shallow Pleistocene aquifer is the most prone to contamination and falling water levels, since it has a high transmissivity, and is connected to all of the others by gravity.

2.4.4.3 Sensitivity

Sensitivity concerns the degree to which a hazard affects the exposed population. It has various defintions by different authors (for a review of definitions, see Gallopin 2006).

The generic sub-indicators selected by the GWAHS-CS project to capture sensitivity across all of the case studies include: i) access to savings/credit; ii) education level; iii) occupation; iv) household structure; v) ethnicity; vi) health status related to waterborne diseases; vii) duration since settled in the area; viii) seasonal or primary house; and ix) type of provider system.

Sensitivity indicators are interrelated, and these inter-relationships as related to Beni Salama are described here.

Health status related to waterborne diseases and type of provider system: As a water-savings measure, public water supplies to the village of Beni Salama are interrupted for a period of time during the middle of the day. Families fill a supply of water containers in the morning in order to have enough water and to avoid drinking the water that comes later in the day, which is more heavily chlorinated. Levels of connection to the public water supply are high in the village, but not in the surrounding area. Also, while connection to the public water supply in Beni Salama ensures a high quality water supply, this is not the case for connections to the public water supply in the rest of Wadi El Natrun.

Local people also drink water from wells and from public drinking water supplies. New houses are continually being constructed and extended in the village, requiring new connections. Outside the residential area, households rely entirely on their own wells for drinking water. A few households in the village have not yet been connected to the public water supply network and possible health risks due to the location of the well were identified during the survey. Nevertheless, no chemical analysis was available to confirm this risk. The families using the well did not complain about their health, although a neighbouring health worker did. No substantiated reports of groundwater-related health problems, including waterborne diseases, were noted. However, references were made to numerous anecdotal reports of cases in the urban areas of Wadi El Natrun and Resthouse. People in these areas often resort to buying water from Beni Salama village rather than using their own wells and public supplies.

Duration of settlement in the area, ethnicity, seasonal or primary house, and sensitivity to economic effects: In Beni Salama village, little differentiation amongst the population was identified through the survey in terms of ethnicity and duration since settled in the area. The population are originally Bedouin. Most families interviewed indicated that they had been in the area for at least several generations. They are settled permanently in their houses throughout the year, although some members may move for work. Migrant farm workers and their families come from other regions to live and work on the farms around Beni Salama village. They depend entirely on wells for drinking water in areas that are not connected to public (groundwater-sourced) water supplies.

As identified in the previous section, the groundwater-related hazards in the study area are primarily of an economic nature, rather than posing an obvious health-related threat. Income and capital are threatened when agricultural productivity and farming occupations are threatened. Also, according to local land agents, the value of land and its productivity in the study area is determined by the quality of water and soil resources. Reductions in groundwater quality therefore have a financial implication for land-owners and cultivators. Falling water tables and water quality problems require farmers to make expenditures to dig deeper wells. Those who have sufficient cash to do this are less vulnerable to the changes in groundwater conditions.

In the area surrounding Beni Salama village, and across the rest of Wadi El Natrun, farm owners and investors are a diverse group, often having lived in the Nile Delta, other Arab countries, and in Europe. They visit their farms occasionally, but are not settled in the village. Groundwater for irrigation is a relatively low cost within the overall farm budget. This includes installation and maintenance of wells and their replacement, if needed. A previous investigation of farm budgets in the study area and across Wadi El Natrun (Yehia 2004) demonstrated that the larger the farm size the larger the net profits that can be generated, and that small farms did not generate any significant net profit, but more often ran at a financial loss.

Local people interviewed during the survey did not entirely agree that small farms could not be profitable. This assessment may be due to subsistence uses of the produce, or to the land investment objectives of the farm, as described above. Nevertheless, it was concluded that the small farms and gardens in and around Beni Salama village are the most sensitive group in relation to the economic effects of groundwater hazards because they generate less income and are less able to afford to pay for replacements. A further investigation of sensitivity to the economic dimensions of the groundwater hazards amongst the most vulnerable group of small-scale cultivating households within the village of Beni Salama is explored below.

Household structure and income: Household structure in the village of Beni Salama is complex. Families may include a number of wives, each with children, inhabiting and frequenting several houses. This complexity is not apparent in the census data from the study area presented earlier in this report. During the field survey, some difficulty in obtaining responses about household size were encountered until the question was altered to request the number of houses and the number of family members, and then to divide one by the other to arrive at a simplified household size of usually around 4-6 people. The complexity of household structures and relationships in the village underpins social networks, which are addressed in the following section on resilience.

An average household income of around US $364 (2,000 EGP) was reported during the household survey. This does not include remittances and pensions, and the amount reported is likely to be a conservative assessment. Detailed questions on these issues were not considered to be appropriate for inclusion in the survey. In most cases, the income reported barely covered the costs of living for the household, and was supplemented by groundwater-dependent subsistence food production.

Local people indicated that if the watertable fell or a shallow well became saline, they would be forced to either dig a new well or stop farming. They were not able to describe how they could afford to dig new wells. Effectively, no spare cash to cover the cost of a new well is available in the household budgets. Although some cases were identified where a replacement well had been dug, the owners were not available to explain how they had managed to do it.

Occupations, educational level, and access to savings/credit: The household survey indicated that income is mainly derived from work in agriculture and its related economic activities, such as transportation, storage, farm security, etc. The majority of occupations listed by the village households as those other than agricultural work were low-skilled occupations, such as driving, security, or factory labour. It was found that people living in the village who have access to savings or credit would invest in land, which can be profitably reclaimed and cultivated from the edge of the desert. Those who do not have access to sufficient savings or credit to buy their own land indicated that they managed land belonging to others, or claim land informally.

It was notable that most economically active adult men in the study area have several occupations, usually including cultivation, either of their own land or of someone else's. Although all of the occupations within the village economy are related to groundwater use in one way or another, the mixture of different activities undertaken by each individual and household may in fact reduce the overall vulnerability to groundwater-related threats to some degree, as well as offering additional social networking benefits to the family. More alternative income sources available to a household means they can be less concerned about any given level of groundwater-related hazard (Table 2.6). The data also reveal greater coping ability (adaptations) with increasing occupations.

Table 2.6. Relationship between additional occupations in Beni Salama and concern over groundwater.

Additional occupations	Frequency	Rating of concern regarding groundwater hazards	Adaptations
0	1	high	Could not dig new well
1	11	moderate	Expensive to dig new well – maybe in the future
2	6	moderate	50% had recently dug new wells
3	1	moderate	Would stop cultivating if not working out
5	1	low	Well already 67 m deep
Total	20		

Since alternative occupations are such an important determinant of sensitivity to groundwater hazards, it is necessary to determine what influences the availability of alternative income generating opportunities, and to what extent education may affect the options available. Most of the occupations in Beni Salama do not require formal higher education. Male members of the households surveyed who had received less formal higher education were engaged in farm management and agricultural engineering. The community has significant practical expertise and cultural interest in these areas, and a considerable awareness and interest in groundwater-related threats. Although the older generation in Beni Salama mostly have not received formal higher education, they have obtained many kinds of knowledge during their lives including knowledge on agriculture, engineering, foreign languages, philosophy, and religion.

Many young people in the village now have the opportunity to attend colleges and universities in the nearby cities of Sadat, Ain Shams, and Alexandria. As a result, the availability of educational opportunities and levels in the study area was observed to vary according to age. Skilled jobs available locally include the management, accounting, and legal services required by the large farms and other local enterprises, as well as government jobs and teaching. The courses of study that the youth follow appear to correspond to these opportunities (e.g. law is a popular choice).

In order to take up a job in one of these fields, it is necessary either to commute to Wadi El Natrun and the surrounding area, or to move out of the village. The national census does not provide information at a high enough resolution to identify such migration from a particular village, and the survey only included individuals that were still in the village to describe their households. Some households surveyed had included individuals who had since moved out. However, they were no longer considered part of the immediate household and were not mentioned during the survey, but were identified through subsequent discussions. From this, we might conclude that the small-scale cultivating households surveyed were not benefitting from economic migration, and that it was therefore not affecting their income and economic vulnerability to groundwater-related hazards. It is possible that in fact some financial support might have come from the relatives who had migrated, but this issue was not pursued in detail.

The concept of sensitivity is a challenging one to define, and it is therefore also challenging to capture it through indicators[4]. The working definition of sensitivity selected by the study team focuses on the degree to which the hazard affects the exposed population. This definition thus takes a dose-response approach to defining sensitivity. For example, this is how the concept is understood in chemical risk assessment, where the sensitivity of organisms to chemicals is tested through experimentation with varying doses in order to identify response patterns and possible thresholds.

According to the adopted working definition of sensitivity, two of the selected sub-indicators stood out as particularly important. These were health and socio-economic status (combining several of the identified interrelated indicators such as income, occupation, etc). The preceding section explores the relationships of other proposed indicators to

[4] As noted in the GWAHS-CS concept note, sensitivity, as defined by Turner et al. 2003, combines characteristics from both social and ecological sub-systems.

socio-economic status (combined income and occupation) and of the only physicalindicator (type of provider system) to health status. The findings showed that only 20% of household members were economically active with alternative sources of income. Difficulties in obtaining accurate and comprehensive information about household incomes were also observed in the previous section. This is understandable, since household income is a private matter.

This study failed to produce any results on the health status sub-indicator. The study team encountered difficulties in collecting data to investigate sensitivity in relation to health, and would need to either strengthen cooperation with the relevant departments of the local government, or undertake primary data collection through field sampling in order to address this issue. No effective sub-indicator could be identified to capture the sensitivity of health to groundwater threats, since no health hazard could be verified.

Based on these qualitative observations, it can be concluded that there is a trade-off between the two dimensions of sensitivity: if you live in the village, you can have low groundwater-related health impacts, low groundwater-related income, and high economic vulnerability to groundwater hazards. If you live outside the village, you can have a higher income, but will suffer increased exposure to groundwater-related health threats, and other threats to your well-being until your income reaches a level such that it can cancel these out. The most popular strategy for doing this amongst people living in Wadi El Natrun is to buy water sold by vendors from Beni Salama.

2.4.4.4 Resilience

The concept of resilience originates from the field of ecology, as defined by Holling (1973)[5] , but has recently been more widely used to characterise social-ecological systems (Gallopin 2006, Folke 2006). The application of the resilience concept to dryland agro-ecosystems focuses on local resources management within a defined area (e.g. catchment) even though inevitably social networks will expand beyond the system boundaries (Enfors and Gordon 2007).

The generic sub-indicators of resilience selected by the GWAHS-CS project were: i) access to alternative sources of water; and ii) out-migration from the case study sites. These two sub-indicators relate to the persistence of the system of human dependence on groundwater; the collapse of this interdependent system would be captured by one of these two.

[5]Holling defined resilience as "a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables".

A series of other sub-indicators were also proposed that would capture the ability of the system to absorb changes. Adaptations within the system might be either physical or social. Existing adaptations would be captured by the following two additional sub-indicators: iii) groundwater-related infrastructure; and iv) institutional set-up related to groundwater management. The capacity of the system to adapt in the future through either of the above would depend on the existence and enforcement of legislation and policies related to groundwater management whose effectiveness will in turn be dependent upon the degree to which they are well-targeted. This will be determined by access to knowledge of groundwater degradation processes and groundwater management which is influenced by such access and the existence of and participation in social networks.
Each sub-indicator will be discussed in the context of the Beni Salama case study here.

Access to alternative sources of water: The introduction of an alternative source of water to the study area could permanently change the relationship between the population and groundwater, reducing resilience. Conversely, it could enable the population to supplement depleted or salinised groundwater supplies in order to sustain the function of the agro-ecological system, thereby increasing resilience. In reality, however, the potential for use of alternative sources of water other than groundwater in the study area is very low, and decreasing.

Various types of alternative water sources exist and include:

- *Rainfall:* Annual rainfall in the study area is less than 50 mm per year and highly seasonal. The name of the region indicates the presence of an ephemeral river, or 'Wadi'. No provision for capturing seasonal water flows was observed in the study area other than the natural processes of infiltration and storage in the soil. Some rain-fed farming was present in the study area in the past, but this is no longer possible due to the depleted water table.
- *Reuse of drainage water:* Use of water directly from drains is not apparent in the study area, although it is practiced in the surrounding area (e.g. at the Chinese Friendship Farm in Sadat City) and local people are gaining knowledge of this practice. The shallow Pleistocene aquifer itself may be considered a form of drainage water that could be reused more effectively, for example, by protecting the quality of the water and adding value to small-scale farm production. However, this would be improved groundwater use, rather than an alternative. This is discussed further below.

- *Surface water canal:* A project to bring water supplies close to the study area has been proposed. The environmental impacts of this project are anticipated to include increased recharge to the shallow groundwater and lakes in the study area (Attia et al. 2005, Attia et al. 2007). However, this would arrive through the shallow aquifer, supplementing groundwater recharge rather than representing an alternative to groundwater.
- *Lake water:* The lake water is groundwater that has discharged through springs into the lake. Therefore, it also is not a new alternative source of water. In the lake, salinity increases through continual evaporation and mixing with stored salts. Treatment would be required in order to use this water after it has entered the lakes (see Taher 1999a). Hence, it is considered more effective to capture the groundwater before it enters the lakes (Idris and Nour 1990).

For the moment, there appears to be no availability of alternative non-groundwater sources. There is therefore no negative effect on resilience associated with alteration of the system of groundwater dependence.

Out-migration: Out-migration from the village to the neighbouring urban areas of Wadi El Natrun and Resthouse for work or marriage was identified during the field investigations, as described in the previous section. If this migration breaks the relationship between the population and the groundwater that is under study, it represents a permanent change in the socio-ecological system, i.e. non-resilience.

Members of small-scale cultivating households in Beni Salama appear not to travel far away, and to return often when they do travel. Some younger men sometimes expressed the wish to migrate abroad, but appeared not to actually do so. Overall, the village is a vibrant, attractive place with a growing economy and strong social ties. Some out-migration is, however, known to occur.

On the other hand, the area around the village is characterised by high mobility. The farms belong to outside investors who are often absent, rather than out-migrating per se. There appears to be a high turnover rate as businesses succeed or fail. There is also considerable use of low-skilled, low-paid migrant labour in this area.

Groundwater-related infrastructure: The following infrastructure interventions can support adaptation of the system to cope with groundwater hazards:

- *Wells:* Deeper wells are frequently being dug where groundwater levels have dropped or become saline.
- *Pumping systems:* Pumping systems are being installed where wells were once artesian, for example the Beni Salama drinking water well.
- *Treatment systems:* Most village households do not have treatment systems other than the public system, which adds chlorine to the drinking water. Large farms and other enterprises have their own private treatment systems.
- *Sanitation systems:* Basic sanitation systems are installed and maintained by the residents of Beni Salama village.
- *Artificial recharge:* See above.

In theory, providing that sufficient funds are available, infrastructure can be constructed to maintain the system function in the face of any hazard. However, the effective construction of infrastructure relies on a thorough knowledge and understanding of the hazard, and of the potential environmental impact of the infrastructure. Both depend upon two factors: institutional arrangements for groundwater management and enforcement of legislation, and the existence of policies and legislation related to groundwater management.

Institutional set-up related to groundwater management: The institutional arrangements for groundwater management in the study area are evolving. During the year after the study was completed, a local groundwater management office was created in Wadi El Natrun. This office took over the tasks of groundwater management issues and well licensing that were handled by the General Office for Groundwater of the Ministry of Water Resources and Irrigation Office, located in the City of Tanta, over two hours away from the study site by private car and a considerably longer journey by any other form of transport.

Local environmental management and enforcement of environmental protection legislation is the responsibility of the Wadi El Natrun City Council. This is relatively weak due to the limited capacities and educational level of the environmental officials. They do not have the capacity to take a proactive role in the protection of groundwater, and spend most of their time coping with crises such as waste management problems, disposal of dead animals, and local disputes.

Policies addressing groundwater management have been described earlier. They are essential for the evaluation of potential future hazards and for enabling adaptation of infrastructure and institutions. However, policies can only be as good as the quality of information and knowledge on which they rely.

Inappropriate infrastructure can exacerbate hazards and increase, rather than reduce vulnerability. For example, digging deeper wells reduces the vulnerability of one farmer, but can increase the vulnerability of all the others. Malfunctioning sanitation systems have been observed to increase hazards in and around Beni Salama, until fixed by local people.

Access to information about groundwater management and social networks: The following types of information on groundwater management and social networks are available in Beni Salama:

- *Public information:* Concerning water use and management, information is not publicly available. Social networks addressing health issues include informal social networks and NGOs.
- *Information for small farmers:* Social networks are strong in the village where extended families are large and are interrelated through marriage. These networks transfer practical information of all kinds, including information on irrigation practices. No more formal source of information for small farmers was identified during the field survey.
- *Information for large farmers:* Concerning agricultural water management practices, some information is being provided by companies supplying drip and sprinkler irrigation systems and the Global Good Agricultural Practices certification programme.
- *Management information:* For the groundwater management authorities, information is generated by the Egyptian Groundwater Research Institute (RIGW). The last time RIGW had produced a report on the groundwater resources in the area was four years before this investigation, in 2006. This report may now be considered out of date. It is not available for public or scientific use.

Access to knowledge of groundwater degradation processes: Access to knowledge of groundwater degradation processes was considered by the study team to be the most relevant factor in determining the resilience of the local community to groundwater threats. This is required in the study area in order to enable the management of groundwater withdrawals and to minimise degradation effects. Local knowledge of groundwater degradation processes determines whether or not wells are used for drinking, and decisions concerning where and how new wells are dug.

Groundwater management decisions are currently based on two private studies that were conducted in the study area in 1995 and 2006. These studies are in need of review in order to take into account changes to the patterns of groundwater use and the state of the resource that have occurred over the past four years, and to more fully address the interactions between the study area and the interconnected regional hydrological systems of the Nile Basin, the Miocene Aquifer and the Nubian Sandstone Aquifer Systems on which it depends.

Local people have considerable knowledge of groundwater degradation processes from observations made during years spent living in the area, and from their experiences in digging wells on their own land and land owned by other people. Local people are knowledgeable about where wells have turned saline, and where they have not, where wells have been dug and abandoned, which crops have been grown where, and which have failed. Different individuals retain different pieces of knowledge. This knowledge is not systematically recorded for management use.

Groundwater knowledge has a high commercial value in the study area because it determines the value of land for investment. However, rather than enabling increased knowledge generation and sharing, this value appears to have encouraged the hoarding of groundwater data for private use and sale. The commercial value of groundwater knowledge differentiates access according to socio-economic status. As with information, local people can sometimes use social networks to circumvent the economic structure of access to knowledge.

Current data held by private enterprises, including drilling companies, farms, factories and government, is difficult to access, compile, and use in an independent scientific analysis for the generation and publication of knowledge. The scattered data could be far more informative if combined effectively in order to create improved knowledge and understanding, rather than used on a piecemeal basis.

The preceding sections of this report have established that there is a system of human dependence on groundwater in Beni Salama, which can be characterised in terms of health-related dependence for drinking water, socio-economic dependence for income-generating activities, and ecosystem dependence for the provision of ecosystem services supporting both of the previous aspects. The resilience of the system would therefore concern the maintenance of this relationship of dependence between the well-being of the human population and the groundwater system.

The resilience of the village of Beni Salama has been demonstrated to be as high as 85% up until now. Considerable changes in the surrounding population, land uses, and economy have had relatively little effect on the village and its groundwater-dependent cultivation systems. But the future management of the system is in the hands of institutions located outside the village that do not have effective information and knowledge management. There appears to be little scope for these institutions to understand local priorities, or to be guided by local knowledge.

2.4.5 Summary assessment of vulnerability in the Beni Salama case study

Overall, the findings of the case study show that exposure to groundwater hazards is high in Beni Salama. The hazards are greatest for users of shallow groundwater, and the smallest land users are the most sensitive to the hazards. Resilience is constrained by the lack of knowledge to inform responses in the form of infrastructure and institutional development.

In terms of differentiating human security amongst the community, the users with the smallest landholdings were found to be the most vulnerable. What is interesting is that in Beni Salama, the smallest land-holders have also been the most resilient in terms of their ability to remain in the area, continuing cultivation activities, and enjoying a high quality of drinking water and environmental amenities.

The differentiation between threats in deep and shallow aquifers requires further attention to the differentiation of hazard indicators, and also requires attention to the sensitivity indicators. Overall findings of the vulnerability assessment were quite varied for the different groundwater users. An essential point that was not properly captured in the assessment is that vulnerability of shallow groundwater users is affected by the behaviour of users of deep water users, but not vice versa.

The case study focused on the sensitivity of the community in the defined study area of the village. This was helpful to obtain a detailed picture of the conditions in the village, and it was also practical in light of the resources available to the project. However, the village exists in the larger context of the surrounding area which affects both the economic opportunities that are available to the population in the village and also the groundwater that is available in the aquifer systems. Groundwater management in the area surrounding the study site, particularly to the North and East, which is the direction of recharge inflow from the Nile Delta, play an essential role in the determination of groundwater availability and quality in the study area.

The assessment of hazard was designed to be based on available information. However, in this case study, available information was considered insufficient to make a fully comprehensive and forward-looking hazard assessment. The most significant knowledge gaps identified concerned estimation of total annual groundwater extraction. Although extractions for cultivation in the study area could be estimated, these calculations did not include water use by factories, water bottling plants, domestic urban water supplies, and health and leisure facilities that are also located in the study area because this data was not available.

The GWAHS-CS project framework highlights the importance of access to information and access to knowledge as indicators of resilience.

2.5 Assessment of Vulnerability: Synthesis and Discussion

The GWAHS-CS has endeavoured to develop a conceptual approach to the assessment of vulnerability in socio-ecological systems and to apply this through select case studies. Here, the applicability of the socio-ecological indicator framework for the ongoing assessment of vulnerability in Beni Salama is discussed. The socio-ecological approach to groundwater vulnerability assessment offers the advantage of taking future scenarios into consideration, both in terms of the way that it anticipates threats and added sensitivity due to human behaviours, and also because it includes consideration of management within the system.

The preceding sections have presented two approaches to the assessment of groundwater vulnerability – first, by considering the vulnerability of an aquifer, and second, by considering the vulnerability of the full socio-ecological system, including the aquifer and the human security-related dimensions of aquifer use and management. The review of hydrogeological information on the study area revealed some serious gaps in available data of the conditions and trends in groundwater availability, quality, and use that would need to be addressed in future assessments of hazards. These are likely to be further exacerbated by the effects of climate change in the region. When the groundwater-related hazards are viewed within the framework of the socio-ecological system, further practical and conceptual challenges emerge, as described in the preceding section.

The synthesis of findings on the effectiveness of the indicator approach for the assessment of groundwater resources vulnerability prepares the way forward for the concluding sections of this report which contain recommendations for the improvement of water use efficiency as well as policy recommendations and recommendations addressing capacity development needs and further research. Comparison between the findings from Beni Salama to those in different contexts may confirm whether or not the observations on the effectiveness of particular indicators may be generalised more broadly.

2.5.1 Effectiveness of the indicators

Conceptual, as well as practical difficulties were encountered when defining the components of vulnerability, for the former, and when determining the sheer number and complexity of indicators relating to sensitivity and resilience in the indicator framework, for the latter. These made it a challenge to generate, summarise, and communicate findings effectively. In order for the assessment of indicators to support improved groundwater management, the concepts, messages and presentation of the indicators need to be very clear. It has been suggested by Gunderson and Holling (2002) that "although the dynamics and behaviour of highly complex social-ecological systems are structured by the interaction of a large number of variables, the number of key variables is often somewhere between three and five".

Some of the GWAHS-CS indicators for vulnerability and sensitivity were found to be more essential than others. Most were found to be interrelated in some way. These were highlighted in relation to each subcomponent of vulnerability. In order to make an assessment of the vulnerability of the population of Beni Salama to groundwater-related hazards, it is possible to focus only on quantification of these indicators because they capture the effects of associated factors. For example, it is sufficient to examine the range of occupations of a household rather than to also attempt to account for the exact annual income that it generates. Measurement of income does not significantly add to understanding the sensitivity of the household, nor is it particularly feasible to ascertain accurately, despite the patience and sincerity of the survey participants with regard to this issue.

Taking the two most essential sub-indicators for each indicator of vulnerability (exposure, hazard, sensitivity, and resilience, as discussed in section 2.4.4.), we can quantify the scores for each sub-indicator. The simplest way to calculate vulnerability is to take the average value of the sum of the sub-indicators, which in this case would result in a vulnerability score of 57.5%. In this way, six indicators of vulnerability are reduced to one index value, thus allowing for comparability between different case studies. Other alternative approaches to the creation of an index score could include devices such as weighting of different parameters.

An alternative approach to synthesise the findings of the vulnerability assessment would be to further reduce the core set of indicators, observing that the percentage of economic sectors dependent on groundwater and household members without alternative income sources, respectively, are essentially two related dimensions of the community's economic dependence on groundwater. Similarly, groundwater balance and access to alternative sources of water are two related dimensions of water availability. Health status in relation to water quality, and water quality on its own are also closely related, even if this could be not proved despite this case study's dedicated environmental monitoring.

If we continue to reduce the indicators, we can observe that human security and vulnerability to groundwater hazards in Beni Salama are mediated by two essential factors: the use of deep or shallow aquifers (determining the hazard), and access to financial resources (determining the sensitivity). In the end, these two factors often coincide, since access to deep aquifers requires financial investments. The selected GWAHS-CS indicators led to this conclusion as a result of a bias towards socio-economic indicators within the selection of sub-indicators of sensitivity and resilience. It is notable that the GWAHS-CS project chose almost exclusively social indicators for sensitivity, although the Turner et al. (2003) model conceptualises sensitivity as including both social and ecological sub-systems. The lack of an indicator capturing an environmental dimension of the sensitivity of the exposed cultivated and natural ecosystems seems apparent in relation to the characterisation of exposure within the framework, which does adopt an ecosystems approach – but then the discussion of ecosystems is not carried through to consideration of sensitivity and resilience within the framework.

This leads to findings that would suggest that alteration of socio-economic constraints (i.e. poverty reduction) would alter vulnerability to groundwater-related threats, a finding which is already well known to policy-makers and groundwater users. A policy priority already exists to achieve poverty reduction, and every household is already quite aware of their needs to generate income. What is lacking is any new insight into how reducing vulnerability could be achieved. In light of this, this case study points to the need to adjust the framework in order to consider the ecosystem and the human population together in relation to each component of vulnerability. In order to do this, a deeper exploration of the sensitivity and resilience of ecosystems would need to be incorporated, and indicators would need to be selected to capture these. Such indicators could focus, for example, on biodiversity status.

When dealing with economic dependence on groundwater use for crop production, the diversity and tolerance of these crops to stresses associated with changing groundwater conditions are important dimensions of the sensitivity of the system. Increasing the resilience of the agro-ecosystems would involve the adaptation of cultivation patterns and produce to incorporate adaptations of life forms that have evolved to thrive in the gravel desert and salt-marsh ecosystems, either through breeding new species or by increasing human use of those that have evolved in the wild.

2.5.2 Outlook for future developments

From the review of available information on the selected indicators, as presented in this report, it is clear that scientific challenges remain to properly quantify and characterise groundwater-related threats for effective future planning scenarios. In order to do this, it will be necessary to take into consideration the effects of climatic and land-use-related changes on regional-level flows in three large and inter-related hydrological systems, including the Nile basin (affected by the regional climate system), the Nubian Sandstone Aquifer System, and the Miocene Aquifer System.

The GWAHS-CS Egyptian case study has reviewed available published data and tested the vulnerability assessment framework, recommending adjustments needed for the future, in particular the strengthening of indicator selection and definitions through an enhanced focus on the contribution of ecosystem services to resilience, and a more refined exploration of their sensitivity to groundwater-related hazards.

2.6 Groundwater Use Efficiency in Beni Salama Land Use Systems

This section will present a vision of the way forward for groundwater use in the study area. Water use efficiency has been identified by the GWAHS-CS project as a key priority in the management of groundwater resources. The options for managing groundwater use should therefore be examined in detail, as well as the effects of increasing or changing irrigation practices on water availability and quality.

Because the case study is located in an arid area, the efficiency of water use is a high priority both for cultivators at the field level and for decision-makers at the policy level. Although the study area contains a series of lakes, most of the available lake water and groundwater is highly saline. Salinity threats affect water use efficiency by causing large quantities of water to be required for leaching soils and by limiting plant-water uptake.

It is therefore necessary to integrate considerations of water scarcity and water salinity.

This section will first present an investigation of groundwater use across all ecosystem types in the study area, followed by a discussion on the productivity of these groundwater uses. Non-extractive, as well as extractive uses of groundwater are considered. The concluding discussion will examine water uses in the study area in relation to their productivity and ecological implications. Recommendations are presented concerning research needs to enhance understanding of the productive potential of shallow groundwater use.

2.6.1 Water use in ecosystem types of Beni Salama

The five ecosystem types of the study area have been described earlier (see Table 2.4). Saline lakes, salt marsh, and sand and gravel desert ecosystems rely on sparse rainfall, natural discharge from lakes, springs and water stored in the soil, and shallow water tables, where available. As observed by Zahran and Willis (2009), vegetation surviving without irrigation in the sand and gravel deserts are often ephemeral, appearing only in the late winter and early spring when there is sufficient water available in the environment to support them. Plants that remain in the sand and gravel environment year-round are highly effective at producing new shoots and branches when buried with sand. Some perennials have well adapted root systems to search for and access water stored in sand and soil (e.g. Phoenix dactylifera and Tamarix). Tamarix is also capable of excreting salt crystals onto the soil to absorb moisture from the air.

Although salt marshes and reed swamps do not require the extraction of groundwater, they still consume high volumes of water. Plants that are found in the dry salt marsh areas, such as Sporobolus spicatus, Cyperus laevigatus, Juncus acutus, Nitraria retusa, Zygophyllum album and Tamarix can tolerate dry spells and are productive under high levels of salinity.

In some of the agro-ecosystems, mature date palm trees survive without irrigation due to their extensive root systems. Other wild plants also grow in the agro-ecosystems around the irrigated areas. However, for the most part, the village gardens and other agro-ecosystems (small, medium-sized, and large farms) rely on irrigation by groundwater extraction and have varying irrigation water requirements according to cultivation type.

2.6.2 Productivity in the ecosystem types of Beni Salama

Table 2.7 shows a summary of the cultivation types and the nature of production of the different agro-ecosystems in Beni Salama village.

Table 2.7. Overview of cultivation types and general characteristics.

Farm size (feddan*)	Average well depth (m)	Type of pump	Most common irrigation methods	Chemical inputs	Most important crops	Use of produce
1-3	25	Diesel 3 inch 5 horse power	Flood	None except manure	Date palm, wheat, various fruits and vegetables	Home use
3-20	43	Diesel 8-10 inch†	Sprinkler flood and drip	Increasing	Alfalfa, beans, mango	Home use and local sale
20-100	114	diesel or electric 80-90 m^3/hr	Drip and sprinkler	Significant	Peach, grapes, citrus fruits (vegetables esp. medium-sized rented farms)	Local sale
100 +	146	Electric 110 m/hr	Drip	Some certified organic		Export or local sale

*feddan = 4,200 m^2 = 0.42 ha = 0.0042 km^2
†based on MWRI database

Irrigation water requirements for various crops in the agro-ecosystems can be calculated using the published FAO crop coefficients. These are multiplied by reference evapo-transpiration (ETo) to obtain the irrigation water requirement of each crop (ETc in mm) at each stage in the growth season (ETc = Kc × ETo). Where intercropping is practiced, as is the case in traditional oasis cultivation, the generic coefficients can be adjusted to allow for the effect of the canopy. Many of the crops that are grown commercially in the area are sensitive to salt. Salinity can inhibit the plants' ability to take up water and can thus reduce productivity.

As described earlier, shallow groundwater users are more vulnerable than deep groundwater users. Whereas shallow groundwater use effectively recycles drainage water as it flows towards saline lakes, pumping deep groundwater exacerbates the vulnerability of all users in the system. As shown in Table 2.7, well depths increased with the size of the farm. Therefore, the small farms and gardens were accessing shallow groundwater whereas wells on larger farms were tapping the Pliocene, and increasingly, the Miocene aquifers. The gardens were located in the village at low elevations around the lake, and small farms were also mostly in and around the village. Medium-sized and large farms were located further away from the village.

2.6.2.1 Crop production on large and medium-sized farms

For large (> 100 feddan) and medium-sized (20-100 feddans) farms, the choice of crops is an investment decision that involves analysis of the soil and water when establishing the farm to determine the most suitable crop choices. Depending on the growing conditions, the most profitable crops for farms of this size are often grapes (particularly banati or sperio varieties) and peaches. Tangerines and mangos are also very frequently grown on this size of farm. Dates, beans, onions, alfalfa, and wheat, which are the traditional crops grown on smaller farms and gardens in the study area, are still present. None of the farms visited in Beni Salama reported growing bananas, although this is understood to be highly profitable in the area.

Grapes and mangos are considered to be moderately sensitive to salts, while citrus and other soft fruits frequently grown on large and medium-sized farms are considered sensitive. These crops are not drought tolerant, and are also susceptible to climatic variations and pests. Fruit production, particularly for very popular crops such as grapes, requires a high degree of precision in the seasonal timing and amounts of water applied in order to support a good quality of productivity. Where problems arise with groundwater supplies on large farms, farmers have no choice other than to replace wells in order not to loose drought- and salt- sensitive crops.

2.6.2.2 Crop production on small farms

On small farms (3-20 feddan), a range of crops are grown that include fruits, vegetables, and alfalfa. Livestock, including camels, sheep, goats, cows, and poultry were also kept. Usually, part of the crop was for use by the farmers' households and animals, while the rest was for local sale. Popular crops for local sale include beans, wheat, and mango. Dates, olives, strawberries, and mandarins were also grown for local sale. One small farm belonged to an agricultural expert growing special varieties of mango to be showcased in exhibitions. An exotic weight-loss plant (referred to as Babaz) was also being experimented on this farm. Another small farm which was observed included a nursery growing seedlings for sale, including ornamental plants not otherwise observed in the study area. Crops grown most frequently (e.g. alfalfa) on the smaller farms are more salt tolerant.

2.6.2.3 *Crop production in gardens*

The produce grown in gardens (1-3 feddan) is usually for individual consumption, although they may be sold locally. Some gardens provide food for several households. Some locally adapted trees grown in the small gardens, such as the Ficus sycomorus L. (bitter sycamore), Ziziphus spina-chrisi (jujube), Morus alba L. (mulberry), are not commercially attractive at present. One Tamarindus indica L. (tamarind) tree was observed. Cultivators experiment with different varieties of fruit trees and vegetables. All gardens include Phoenix dactylifera L. (date palm). Ground crops are planted beneath the fruit trees. Planting patterns of ground crops continually change with the seasons.

2.6.2.4 *Salt marsh vegetation*

In Beni Salama, livestock graze on the saltmarsh and halfa grasslands around the drainage lakes. Plants are also used in the farms and gardens as fencing and building materials. Some are known to have potential for other industrial uses, such as paper and other fibre production. In addition to these uses, attempts to generate income from the amenity value of saline lakes and salt marshes have been pursued through ecotourism development since the 1990s. At the nearby Lake Hamra, a nature reserve and ecolodge were created. However, similar uses have not been proposed for the lake areas around lakes Fasda and Umm Risha in Beni Salama.

Zahran and Willis (as recently reviewed by Zahran and Willis 2009) recently reviewed the current state of knowledge of some of the productive uses of salt marshes and reed swamp plants. Some, such as the desert grass Panicum turgidum (Forssk), have been investigated in the growing literature on saline agriculture, while others have not (Qadir et al. 2008). Better understanding of these plants is needed, either to identify economic products for which they could be used directly in the agro-ecosystems as well-adapted alternative crops, or indirectly through adaptation of other crops and technologies using the mechanisms that these species have developed in order to survive under extreme conditions.

2.6.2.5 *Sand and gravel desert*

Although some of the plants of the sand and gravel desert systems are understood to have medicinal or cosmetic properties, these uses, and the associated marketing and distribution systems, are not well developed (El Bastawisy 2006). The Egyptian Desert Research Center has previously identified the strategic opportunity to grow medicinal desert plants at Wadi El Natrun. The National Water Research Centre (NWRC)/Water

Management Research Institute (WMRI) at Wadi Natrun has experimented with irrigated production of Aloe Vera, as well as salt tolerant crops and aquaculture. The location of the study area on the Desert Road close to Cairo facilitates the logistical dimension of production.

The natural habitats provided to wild animals in the sand and gravel desert support hunting and other recreational activities. Presently, other economic uses of the desert areas, besides land reclamation and irrigation, include construction of housing and leisure facilities, sand and gravel extraction, and solid waste disposal.

2.6.3 Assessment of water use efficiency

A range of definitions of water use efficiency is available depending on the objective of the water use (Seckler et al. 2003). The following discussion considers water use in the different ecosystem types of Beni Salama in relation to a series of different objectives.

Crop production per unit of groundwater is the most conventional calculation applied to assess water use efficiency. In this study, most of the farmed area is under drip irrigation, which is usually considered a relatively efficient use of water in terms of crop production per unit of water. Larger farms in the study area also use drip irrigation, and many of the smaller ones are also adopting this technique although some prefer to use sprinklers or flood irrigation which is still the cheapest method. This is why the water use per feddan is larger on the small farms than on the large farms.

Using drip irrigation, crops can be produced using less water than traditional flood irrigation systems. The capital investments and maintenance costs that accompany the increase in crop-water efficiency have induced economists to recommend an economic approach to the evaluation of this option, so that the investment costs can be factored into the crop-water efficiency calculation, to be weighed against the profits to be generated. This calculation assumes that crops are for commercial sale, and indeed the investment requires that revenue must be generated from the crops, if only to cover the cost of the investment. Therefore, farmers using efficient water delivery systems are obliged to grow the more profitable crops, such as grapes, mangos, and citrus fruits. As described above, if a hazard appears in the groundwater source, these crops are more vulnerable, and the farmer will be obliged to make further investments, for example on a new deep well, in order not to lose them.

Income generation per unit of groundwater (economic water use efficiency) represents the choices made by farmers in the selection of the uses of water that are anticipated to be the most profitable. Some large farmers in the study area have found soft fruits more profitable for export than dates, and therefore have considered removing date palm from their farms in order to use the water they have to irrigate fruit trees. Other farmers have observed that it could be more profitable to bottle and sell the groundwater than to use it to grow crops for sale. The efficiency of activities requiring large capital investments depends on both farmers' access to capital and the timeframe over which the financial calculation is considered. This is why farmers on short leases focus on vegetable production, as it brings a higher return sooner than other forms of cultivation.

An economic assessment of the options that are available in the study area indicated that the larger the farms and capital investments made in them, the more profit can be made from the use of groundwater (Yehia 2004). Most of the benefits of the largest farms in the study area go to external investors who do not necessarily have any long-term interest in the sustainability of the resources in the area. As a result, all of the profitable farms in Yehia's (2004) study were using chemical fertilisers to maximise productivity. The externality of agrochemical use does not appear in the farm-level economic efficiency calculation.

Local benefits per unit of groundwater, or social water use efficiency, or allocative water efficiency (social water use efficiency or allocative water efficiency - see Allan 1999), should also be taken into consideration. As indicated throughout this report when discussing groundwater dependence, the smaller farms and gardens in the study area play a particularly important role in supporting local families, while the large agribusinesses provide some local benefits in terms of employment for young men. However, these benefits to local people are not always well distributed, with some individuals benefitting more than others. Local people welcome external investors in the study area due to the anticipated creation of employment opportunities and other benefits for local intermediaries and advisors in the land purchase, registration, and development process. However, these benefits need to be weighed against the externalities that are caused by the resource use through the acceleration of groundwater extraction and risks of diffuse pollution with agrochemicals.

Ecosystem services per unit of groundwater (ecological water use efficiency) is another area for consideration. Some uses of groundwater contribute to maintaining ecosystem processes, including the provision of supporting, regulating, and provisioning services (e.g. cultivation and improvement of soils, sequestration of carbon, etc.), while others have a negative impact on ecosystem health (e.g. supporting types of industry and cultivation that require heavy use of chemical inputs that contaminate shallow groundwater sources elsewhere). Flood irrigation systems generate more benefits in terms of soil improvement and carbon sequestration than drip irrigation systems. They use more water, but the water that is used for flood irrigation in Beni Salama is shallow, renewable groundwater that would otherwise drain into Lake Fasda. Drip irrigation systems appear more efficient than flood irrigation systems, but they generate less ecosystem benefits in terms of soil improvement. Also, they frequently depend on the continued extraction of deep, non-renewable groundwater resources, affecting other groundwater users, and the future sustainability of the resource.

In order to assess the efficiency of groundwater use within the socio-ecological system, it would be desirable to take into account the full range of ecosystem services associated with groundwater use and management. For this to be done effectively, it would be necessary to monitor effects on geochemical cycling, and in particular, the flow of agrochemicals in the drainage lakes and shallow wells around Beni Salama village.

Food provision per unit of groundwater by the various ecosystem types are estimated in Table 2.8 on a per feddan basis, using information on amounts of irrigation, crop uses, and household occupations in Beni Salama. In contrast to the food security agenda, this calculation retains an emphasis on the local production of food for subsistence consumption, which has been demonstrated to be an important element of household budgets in the village of Beni Salama. The calculation differs from the self-sufficiency agenda that was prevalent in Egypt under President Nasser (1954-70), since it takes into consideration food purchases through income generation.

Table 2.8. Estimated irrigation use and food production per feddan in different ecosystem types.

	Calculated m^3/ feddan/ year	**Indicative average m^3/ feddan/ day**	**Food provisioning per feddan**	**Total % of household food needs**	**Food-provision efficiency of irrigation**
Large farm 100+	7,300	20	1% of households food purchases for each of 10 employees +30%	13	0.65
Medium farm 20-100	5,000-10,000	25	2% of 5 households food purchases +10% of two households food needs +30%	16	0.56
Small farm 3-20	5,000-10,000	30	4% of 3 household food needs + 10% of household food purchases	22	0.73
Garden 1-3	12,926	35	30% household food needs	30	0.83
Salt marsh	-	0	1% of fodder needs for all households in the village owning livestock	4	4
Sand and gravel desert	-	0	N/A (Very occasional hunting)	0.5	0.5

Table 2.8 calculates the efficiency of irrigation use and food production using the following equation:

Groundwater extraction and food provision efficiency =

$$\frac{\text{Household food provision}}{\text{Groundwater extraction } (\text{m}^3/\text{feddan/day}) + 1}$$

While food provisioning per feddan is calculated as:

$$\frac{\text{\% household food consumption from farm} + (\text{\% household food from farm income} \times \text{\# of employees})}{\text{Total number of feddan}}$$

For the gardens, we assume that a garden of 1 feddan produces 30% of household food needs.

For small farms, we assume that a farm of 5 feddan produces 20% of household food needs for 3 households, and 50% of the income for one household that sells produce.

For medium-sized farms, we assume a farm size of 50 feddan. Five permanent employees receive wages covering all of their food needs and one employee obtains 100% of his household food needs from the farm. Causal labourers, drivers, and other intermediaries add a margin of around 30% to the benefits.

For large farms, we assume a farm size of 100 feddan. Ten permanent employees receive wages covering all of their food needs. Casual labourers, accountants, and other services add a margin of 30% to the benefits.

The salt marsh is used for grazing sheep and cows by households living in the village, and the sand and gravel desert provide wild food only very rarely. Detailed investigations of owning livestock and use of wild food were not included in the GWAHS-CS survey, although the importance of livestock ownership became evident during observation of the lower income households' activities.

The estimated total annual irrigation application amounts are known to vary considerably within each cultivation type. These can therefore only be considered to be approximate estimates. For the moment, the groundwater uses of the salt marsh and sand and gravel desert systems is considered to equal zero, because groundwater is not extracted. Irrigation water uses are also the only uses that are considered in the assessment of the agro-ecosystems. This does not account for the use of water that enters the soil through the shallow water table, or as runoff, rainfall, or seepage from the lakes and springs.

2.6.4 Conclusions

Although it was not possible to estimate groundwater use efficiency in relation to the full range of ecosystem services affected by groundwater (provisioning, supporting, regulating, and cultural services), it was possible to consider groundwater use in relation to food provisioning to local households. In comparing the food provisioning benefits that are generated through extractive and non-extractive groundwater use in different ecosystem types, it is observed that positive benefits can be achieved through use of the salt marsh and sand and gravel desert ecosystems without any further increase in groundwater extraction.

If we assume any positive value for the benefits provided through non-extractive use of the groundwater in the salt marsh and desert ecosystems, no matter how little, it will always be an efficient use in relation to the (non) requirement for groundwater extraction as evaluated through the equation above. In order to improve efficiency in groundwater use, opportunities for improvement of the use of the well-adapted species of the sand and gravel desert and the salt marsh ecosystems might be considered a priority. Economic uses of these species may be underdeveloped, while the costs of further developing the use of irrigated crops will clearly increase due to the increasing vulnerability of the resource.

The assessment presented in this review incorporated consideration of the efficiency of groundwater extraction and use in a series of natural and agricultural land use systems that are present in Beni Salama. However, it is important to bear in mind that these are not the only possible configurations of land use systems. Other industrial, residential, and hybrid land use systems could also be considered.

2.7 Policy Implications

2.7.1 Groundwater management policies

The policy implications of the GWAHS-CS conceptual approach to understanding groundwater resource management as a socio-ecological question focuses on the need to address both physical and socio-economic issues, including development issues. This need for integration between development policies and water resources management policies is well recognised in current thinking concerning integrated water resources management (IWRM). This case study has highlighted two main areas where IWRM could be usefully strengthened:

i) Improved scientific understanding of environmental changes, including climatic changes affecting groundwater conditions and vulnerability. The current policy concerning scientific research on groundwater management issues is to maintain a dedicated government-funded research center for groundwater management research which generates research that is oriented primarily to the policy level. An important implication of this case study therefore concerns the need to consider a groundwater research policy that would engage with groundwater management knowledge at other levels, including the local level, and contribute to the generation of knowledge to improve groundwater management by groundwater users at the local level as well as policy-makers.

ii) The development and adoption of groundwater-use efficiency criteria to effectively manage social, economic, and environmental dimensions of groundwater use. This would require further investigation of social, economic, and human well-being related effects of groundwater extraction, and an effective framework for their evaluation. This report has explored the option of evaluating groundwater use in terms of food provisioning, which is a relatively limited scope of assessment in need of further development.

As an essential first step towards improving existing groundwater management policy, an environmental research policy addressing groundwater management through an ecosystems approach should be developed, building in a strong emphasis on capacity development. A strategy to focus and prioritise the necessary activities in research and capacity building is presented in the next section of this document.

Effective management of groundwater and ecosystems will require the continual generation, management, and use of environmental information. At present, the local government and dedicated government research centers do not have the capacity to fund and manage data collection and scientific activity on a scale that would be sufficient to fill all of the gaps in available information that are highlighted in this report. For this reason, it is essential that other stakeholders contribute to the process of knowledge development.

One of the most important policy instruments which already exists that enables this is the Environmental Impact Assessment (EIA) process, which requires developers to generate and publish scientific information as well as to undertake public consultation processes, through which further knowledge can be generated and evaluated. In this way, the burden of information generation to support decision-making that is currently placed on the public sector should be alleviated. Although this policy is in place, it requires skill and foresight for effective implementation.

2.7.2 Integration with economic development policies

Recommendations presented in this report so far have primarily addressed groundwater management policies, identifying opportunities for improved integration of social and economic dimensions. This would necessarily entail coordination with the economic development sector and a corresponding level of integration of priorities.

The recommendation already made to review criteria for evaluation of development activities according to groundwater use efficiency would have a direct implication for the economic development sector. In addition to this, further opportunities to promote economic activities that are less dependent on groundwater than cultivation, for example, increased processing of local produce, recycling of waste products, and harnessing natural energy sources, could be identified through attention to this issue at the level of economic development policy.

The appropriate mechanism through which to integrate environmental concerns and economic development needs is the EIA process, as indicated above. In addition, Strategic Environmental Assessment (SEA) of economic development policies, such as those determining land reclamation for agricultural or other uses, can also contribute to the integration of policy objectives for improved environmental management. Once again, careful oversight and transparency of information are needed to ensure that EIAs and SEAs do make a meaningful and lasting contribution to knowledge, leading to improved environmental management.

2.7.3 Integration of policies across scales

Policies relevant to the management of groundwater and human security in the study area are made at various levels. The three most significant levels of policy-making are described as follows:

National: At the national level, policymaking is approached on a sectoral basis. Agricultural policy and development policies are handled separately from water management policies. The main responsibility for management of groundwater resources remains with the national Ministry of Water Resources and Irrigation, through its offices based outside the region of Wadi El Natrun. Recognition of the need for integration of management efforts across scales has led to a decision to create a new local branch of the Office of Water Resources Management and Irrigation in Wadi El Natrun. This office will be responsible for reviewing and issuing permits to extract groundwater in the study area. Following the completion of this study, the office was created, and was able to remain in touch with the GWAHS-CS research team.

Governorate: The governorate of Behayra manages the land resources of Behayra from the capital in Damanhor. The system for obtaining a permit for groundwater use is integrated within the system of land registration within the Governorate. Much of the land held by small farmers in the study area is informally owned through the system of Wada` Yid, and is not yet formally registered in the Governorate. This limits the engagement of small landholders with the formal resource management system in the study area, and its relevance to their needs.

Local: The GWAHS-CS project has focused on local groundwater management issues, working primarily with the Environmental Affairs Office of the City Council of Wadi El Natrun. This is the scale at which the management of groundwater contamination threats and local economic activities take place. However, at this scale, information concerning the state of natural resources is partial and scarce. There are also considerable limitations in terms of human capacity and skills to address environmental management issues. This level seems to be appropriate for significant strengthening of public awareness, discussion of alternatives, and of possible water sharing/allocation agreements in order to slow down the over-exploitation of groundwater resources. Recommendations are proposed in the following section on capacity building.

Where institutional efforts to bridge the gaps between policy levels are continually taking place, strategic opportunities for capacity development interventions are created. Capacity development opportunities are described in the following section.

2.8 Capacity Development Programmes and Further Research

There is considerable scope for improved scientific research on the groundwater resources in the study area to support management efforts at a range of levels, not least because the area is very dynamic, continually undergoing land use and hydrogeological changes. In addition, the regional processes affecting groundwater vulnerability in the study area require studies connecting to work across a wide geographical area.

The GWAHS-CS project activities set out to review the available understanding of groundwater conditions. In doing so, several opportunities for ongoing research activities to improve available knowledge were identified:

i) Collection and analysis of historical (past) groundwater data

As described in the earlier section of this report on groundwater knowledge, there is a considerable amount of data available in the study area on previously observed groundwater conditions that could help to build an effective picture of the hydrogeological changes that are taking place. However, effort is needed to collect and analyse this information in order to generate knowledge of the effects of current management patterns on the resources. Many gaps in understanding the hydrogeological characteristics remain in relation to the individual aquifer properties, and also to their interactions, both within the study area, and also more widely. This knowledge can be improved through a compilation of all relevant data, and the improvement of existing groundwater flow models.

The GWAHS-CS project launched an effort to collect and review available data from farms and private laboratories on groundwater characteristics and change processes. If this work is continued, the collection and review of this knowledge would enable improvements in the available understanding of the changes that have been affecting groundwater resources in the study area. Opportunities to coordinate efforts and collaborate with other research institutions in the study area on this activity were identified through the GWAHS-CS project. Relevant institutions would include the American University (AUC) in Cairo and the Egyptian Desert Research Center. These institutions provided support to a follow-up study guided by the GWAHS-CS research team (Switzman 2013b, Switzman et al. 2015).

ii) Evaluation of groundwater use with groundwater users

Currently, groundwater monitoring activities are undertaken in the study area in order to ensure the quality of water for drinking and irrigation uses. However, systematic use is not made of the data generated for investigation of trends affecting the resource. This would require capacity that is not currently available in the institutions that are charged with day-to-day management issues. Coordinated monitoring and analysis activities with the responsible health and irrigation agencies could contribute to improving the management of knowledge and capacity. This would require bureaucratic coordination.

The GWAHS-CS project developed a summary assessment of groundwater use on farms of different sizes in the study area. This evaluation was developed collaboratively with local farmers and gardeners as a rapid assessment. Further research work on water use and productivity would be useful to improve the scientific validity of the information generated. In addition, and perhaps more importantly, the continuation of local collaborative research on water use issues should contribute to raising local awareness of management options.

Further investigation of water use efficiency with local groundwater users in Beni Salama should incorporate engagement with the economic, social, and environmental dimensions of water use efficiency, as outlined in the earlier section of this report addressing these issues. Priority topics identified by the project team would include economic and social water use efficiency in organic agriculture.

iii) Generation of alternative management scenarios

Generation and modelling of the effects of alternative management scenarios is an essential support to decision-making. Research is needed to support and institutionalise the process of scenario development, evaluation, and application in decision-making. This research activity would have an essential capacity building component, enabling decision-makers to learn to develop and evaluate management scenarios in a critical and effective manner.

At the present time, there is no groundwater flow model available that incorporates all of the four aquifers of relevance to the study area in order to enable the modelling of hydrological changes associated with the ongoing effects of land cover and climatic changes affecting the area. Because of this, it is difficult to accurately evaluate the potential impacts of the construction of new infrastructure in the study area or other alterations to the hydrological regime. The construction and dissemination of such a model for use by scientists and environmental impact consultants would be an important step towards improving the management of groundwater in the area. In the development of such a model, it is recommended to incorporate a particular focus on the uses of water within the well-adapted vegetation types of the study area. Ecosystem uses of water are often neglected in such models. In addition to the short-term goal of improving the accuracy of a needed hydrological model, research attention to the specific behaviour of the species in the study area could make a contribution of wider value to environmental science for the management of arid lands.

iv) Experimental investigation of alternatives to groundwater use for income generation

The GWAHS-CS project has observed the economic drivers of increasing groundwater use and resulting vulnerability that have been affecting the study area. The GWAHS Beni Salama case study team has identified opportunities for investigation of sustainable income-generating products from the processing of fibrous plants from the saline lake systems and of organic cosmetic products from the farms and gardens. A number of scientific contributions have been made to pursue the potential of such products at the international level (Jaradat 2003, El-Shaer and El-Morsy 2006), but considerable work remains to incorporate them into commercially viable products both in the village of Beni Salama, and more widely.

Economic activities that are less dependent on groundwater than cultivation, for example, increased processing of local produce, recycling of waste products, and harnessing natural energy sources require investigation to identify where viable opportunities may exist. Such activities continue to rely on access to groundwater, but could enable income benefits to be generated using a reduced volume of extraction.

In the short term, coordination with research activities addressing environmentally sustainable alternative income generating activities by the international cooperative research project on Sustainable Management of Marginal Drylands (SUMAMAD) is recommended. For the longer term, the creation of a dedicated research project in Beni Salama is proposed to investigate the opportunities listed above.

Capacity development requirements and opportunities identified by the study team during the project concern three major groups:

i) Officials responsible for water and ecosystem management

Capacity development is required for groundwater management engineers and officials to understand the hydrogeological processes that are taking place in the study area, and also to address the socio-economic drivers of groundwater use patterns. The GWAHS-CS project has begun a discussion of capacity needs with the General Office for Groundwater Management.

The main responsibility for the day-to-day management of environmental affairs in the study area belongs to the City Council in Wadi El Natrun. The GWAHS-CS has worked with the City Council and has identified a range of capacity needs for guidance and training at this level. The translation of the project findings for this group into a simple and accessible format to be available in Arabic is a high priority for the study team.

ii) Water and ecosystem users

Capacity development for groundwater users is required and should include awareness-raising on management options to increase water use efficiency. At this level, one can think of establishing a "boundary" organisation of all stakeholders.

iii) Young people

In order to have an effect on the future management of the area, it is essential to engage with young people. The study team identified the opportunity to build capacity amongst young people in the study area. Many of them took an interest in the research.

Three major opportunities for capacity development activities have been identified by the GWAHS-CS project:

i) As identified in the previous section of this report, the dynamic state of institutional development in the study area offers opportunities for capacity development activities to be introduced, particularly focusing on professional development. The most notable of these opportunities concerns the creation of the groundwater management office in Wadi El Natrun, which was done shortly after the field study was completed.

ii) The Department of Environmental Sciences at the University of Alexandria currently offers courses of Higher Education in environmental management issues of relevance to the case described in this report. Participation by young resource managers from the study area to pursue higher qualifications should be encouraged, both in order to increase resources management capacity in the study area, and also to improve the professional opportunities available to young people in this region.

iii) The GWAHS-CS project has been supported by several local schoolteachers in the study area. Their interest in contributing to educational and awareness raising activities was noted. Their collaboration in the design and implementation of such activities would be particularly valuable. The project team is convinced that environmental education should begin early in order to inspire children to use their creativity and curiosity to understand and safeguard the environment for their future.

2.9 References

Abdel Baki AA. 1983. Hydrological and hydrochemical studies on the area west of Rosetta Branch and south of El-Nasr Canaly. In Faculty of Science, Ain Shams University, Cairo

Abdel Mogheeth SMM, Khalifa AM, Elazizy IM and Ibrahim SMM. 2004. Depletion of groundwater in Wadi El Farigh and surroundings as a result of water resources mismanagement. Ain Shams University Faculty of Engineering Scientific Bulletin, 39, 495-512

Abdelkhalek A. 2013. Groundwater vulnerability assessment using modified DRASTIC GIS based index at the Western Nile Delta Region. Thesis submitted in partial fulfillment of the requirements for the Masters Degree in Integrated Water Resource Management (IWRM). In Faculty of Graduate Studies, University of Jordan & Institute for Resource Management and Technology in the Tropics and Subtropics (ITT) Cologne University of Applied Science Germany, 87. University of Jordan & Cologne University of Applied Science

Ahmed. 1999a. Geology and geomorphology of Beni Salama area at Wadi El Natrun. In Faculty of Science, 145. Ain Shams University, Cairo

Ahmed SAW E-SA. 1999b. Hydrogeological and isotope assessment of groundwater in Wadi El-Natrun and Sadat City, Egypt. In Department of Geology, Faculty of Science, 236, Ain Shams University Cairo

Al-Naqa A, Hammouri N and Kuisi M. 2006. GIS-based evaluation of groundwater vulnerability in the Russeifa area, Jordan. Revista Mexicana de Ciencias Geologicas, 23:277-287

Al Zabet, T. (2002) Evaluation of aquifer vulnerability to contamination potential using the DRASTIC method. Environmental Geology 43:203-208

Ali RR and Baroudy AAE. 2008. Use of GIS in mapping the environmental sensitivity to desertification in Wadi El Natrun Depression, Egypt. Australian Journal of Basic and Applied Sciences 2:157-164

Allan T. 1999. Productive efficiency and allocative efficiency: why better water management may not solve the problem. Agricultural Water Management 40:71-75

Aller L, Bennett T, Lehr JH, Petty RJ and Hackett G. 1987. DRASTIC: a standardized system for evaluating ground water pollution potential using hydrogeological settings. In: EPA Reports, 600/2-87-035 Washington DC.

Arabi NESE. 2012. UNESCO-IHP-Sub-component 1.1 Management of coastal aquifers and groundwater. The legal and institutional framework for coastal aquifers in Egypt. 56

Attia F, Fahmi H, Gambarelli J, Hoevenaars R, Slootweg R and AbdelDayem S. 2005. WDWCIARP drainframe analysis, Main Report. World Bank

Attia FAR. 2002. The Nubian sandstone aquifer system program basic information of the socio-economic survey. In: NSAS Socioeconomic Survey, 94

Attia FAR, Fahmy H, Eid MJH. and Slootweg R (eds). 2007. The West Delta Water Conservation and Irrigation Rehabilitation Project (WDWCIRP) Environmental and Social Impacts and a Frame work Management - Plan Part I: Environmental and Social Impact Assessment, Part II: Environmental and Social Management Plan - final draft. 86. Arab Republic of Egypt Ministry of Water Re sources and Irrigation and World Bank

Awad MA. 2002. Land use planning of Wadi El-Natrun Depression towards sustainable development. In Department of Environmental Sciences, 238. University of Alexandria, Alexandria

Ball J. 1939. Contributions to the geography of Egypt. Cairo: Government Press.

Boughriba M, Barkaoui A-e, Zarhloule Y, Lahmer Z, Houadi BE and Verdoya M. 2010. Groundwater vulnerability and risk mapping of the Angad transboundary aquifer using DRASTIC index method in GIS environment. Arabian Journal of Geosciences 3:207-220

CAPMAS. 1986. Population and Housing Census. Cairo: Central Agency for Public Mobilisation and Statistics, Arab Republic of Egypt

CAPMAS. 1996. Population and Housing Census. Cairo: Central Agency for Public Mobilisation and Statistics, Arab Republic of Egypt

CAPMAS. 2007. Population and Housing Census 2006. Cairo: Central Agency for Public Mobilisation and Statistics, Arab Republic of Egypt

CEDARE. 2001. Regional strategy for the utilization of the Nubian Sandstone Aquifer System (groundwater model). Cairo: Center for the Environment and Development for the Arab Region and Europe

Conway D. 2004. From headwater tributaries to international river: observing and adapting to climate variability in the Nile basin. Global Environmental Change 15:99-114

Daly D, Dassargues A, Drew D, Dunne S, Goldscheider N, Neale S, Popescu IC and Zwahlen F. 2002. Main concepts of the "European approach" to karst-groundwater-vulnerability assessment and mapping. Hydrogeology Journal 10:340–345

Dawoud MA, Darwish MM, El-Kady MM. 2005. GIS-Based groundwater management model for Western Nile Delta. Water Resources Management 19:585–604

Diab MS, Gad MI, Abdel-Baki AA and El Sheihk AA. 2002. Study the effect of new reclamation projects on the groundwater system in the area northwest Wadi El Natroun and south El Nasr by using mathematical modeling. In: Final program and Abstracts at the Third International Conference: Groundwater Level Control Inside Urbanized Areas. Faculty Engineering, Mansoura University, El Mansoura, Egypt, 17 – 19 December 2002

Ebraheem AM, Garamoon HK, Riad S, Wycisk P and El Nasr AMS. 2003. Numerical modeling of groundwater resource management options in the East Oweinat area, SW Egypt. Environmental Geology 44:433-447.

El-Fayoumy IF. 1964. Geology of groundwater studies in Wadi El-Natrun area. In Faculty of Science, 109. Cairo University, Cairo

El-Khouly AA and Zahran MA. 2002. On the ecology of the halophytic vegetation of the oases in Egypt. In: Proceedings of the International Symposium on Optimum Resources Utilization in Salt-Affected Ecosystems in Arid and Semi-Arid Regions, ed. DRC, 277-286. 8-11 April 2002, Cairo, Egypt: MALR

El-Shaer HM and El-Morsy MH. 2006. Potentiality of salt marshes in Mediterranean coastal zone of Egypt. In: Biosaline Agriculture and High Salinity Tolerance, 207-219

El Bastawisy IY. 2006. Social, economic and cultural perspectives of the western oases inhabitants ``El Wahataya`` on medicinal plants. Cairo University Journal of African Studies, Occassional Paper, 48

El Sayed MH, Mohamed RG. 2007. The possible impact of the depositional environments upon thE water chemistry of the Tertiary-Quaternary aquifers in the area northwest of Wadi El Natroun, Egypt. Assiut University Journal of Geology, V, 143-160

El Sheikh AEA. 2000. Hydrogeology of the area north and west of Wadi El-Natroun. In Faculty of Sciecne 177. Minufiya University, Minufiya, Egypt

El Tahlawi MR, Farrag AA and Ahmed SS. 2008. Groundwater of Egypt: "an environmental overview". Environmental Geology 55:639–652

Emberger L. 1955. Afrique du Nord-Desert, ecologie vegetale. Comptes rendus de Recherches. In Plant Ecology, Rev of Res: 291-249. Paris UNESCO

Enfors EI and Gordon LJ. 2007. Analysing resilience in dryland agro-eco systems: a case study of the Makanya catchment in Tanzania over the past 50 years. Land Degradation and Development 18:680–696

Fekry A and Salam MAE. 2002. Evaluation of groundwater development scenarios in Wadi El Natrun Depression. Water Sciences 31-38

Folke C. 2006. Resilience: the emergence of a perspective for socialecological systems analyses. Global Environmental Change 16:253–267

Foster S, Hirata R, Gomes D, D'Elia M and Paris M. 2002. Groundwater quality protection. A guide for water utilities, municipal authorities and environment agencies. 103. The World Bank. Washington, DC

Foster SSD. 1987. Fundamental concepts in aquifer vulnerability, pollution risk and protection strategy. In: van Duijvenbooden W and van Waegeningh HG (eds). Vulnerability of soil and ground water to pollutants. TNO committee on Hydrological Reserch, The Hague, Proceedings and Informaiton No 38:69-86

Foster SSD. 1997. Groundwater recharge and pollution vulnerability of British aquifers – a critical overview. In: Geological Society London Special Publications 130(1):7–22

Gallopin GC. 2006. Linkages between vulnerability, resilience, and adaptive capacity. Global Environmental Change 16;293-303

Gogu RC and Dassargues A. 2000. Current trends and future challenges in groundwater vulnerability assessment using overlay and index methods. Environmental Geology 39:549–559

Hammani A, Hartani T, Kuper M and Imache A. 2009. Paving the way for groundwater management: transforming information for crafting management rules. Irrigation and Drainage 58:S240–S251

Hamza MS, Aly AIM and Swailem FM. 1984. Groundwater recharge and pollution in Wadi El-natrun, Egypt. International Journal of Water Resources Development 2:39-44

Holling CS 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics 4:1–23

Holting B, Haertle T, Hohberger KH, Nachtigal KH, Villinger E, Weinzierll W and Wrobel JP. 1995. Konzept zur Ermittlung der Schutzfunktion der Grundwasseruberdeckung. Hannover: Heft

Ibrahim RGM. 2007. Hydrochemical study of groundwater in the area North-West of Wadi El-Natrun, Western Desert, Egypt. Minufiya University.

Ibrahim SMM. 2005. Groundwater Resources Management in Wadi El-Farigh and its Vicinities for Sustainable Agricultural Development. In Faculty of Engineering, Irrigation and Hydraulics Department, 152. Ain Shams University, Cairo

Idris H and Nour S. (1990) Present Groundwater Status in Egypt and the Environmental Impacts. Environmental Geology and Water Sciences 16:171-177

IFPRI. 1999. Egypt integrated household survey (EIHS): 1999 overview of the subsample of the EIHS 1997 households. 7. International Food Policy Research Institute Food Security Research Unit of the Agricultural Policy Reform Program in Egypt in collaboration with Ministry of Agriculture and Land Reclamation and Ministry of Trade and Supply Funded Under USAID Grant No. 263-G-00-96-00030-00.

Jaradat AA. 2003. Halophytes for Sustainable Biosaline Farming Systems in the Middle East. In: Alsharhan AS, Wood W, Goudie A, Fowler A and Abdellatif EM (eds). Desertification in the Third Millennium. Lisse / Abingdon / Exton (PA) / Tokyo: Balkema pp 187-203

Kaplan M. 2006. Questionnaire for household survey: land-use changes and mangrove conversion around Maduganga Mangrove Estuary. 18. Bonn: United Nations University Institute for Environment and Human Security Center for Development Research, University of Bonn.

King C and Salem B. 2012. a socio-ecological investigation of options to manage groundwater degradation in the western desert, Egypt. AMBIO: A journal of the human environment 41: 490–503

King C and Salem B. 2013. Assessing the cost of groundwater degradation in the urbanizing desert area of Wadi El Natrun. In: Simpson R and Zimmerman M (eds). The Economy of Green Cities: A World Compendium on the Green Urban Economy. Dordrecht: Springer pp. 295-311

Kwansiririkul K, Singharajwarapan FS, Mackay R, Ramingwong T and Wongpornchai P (2004) Vulnerability assessment of ground water resources in the Lampang Basin of Northern Thailand. Journal of Environmental Hydrology 12:1-15

Mohamed YA, van den Hurk BJJM, Savenije HHG and Bastiaanssen WGM. 2005. Hydroclimatology of the Nile: results from a regional climate model. Hydrology and Earth System Sciences 9: 263–278

Mukherji A, Shah T. (2005) Groundwater socio-ecology and governance: A review of institutions and policies in selected countries Hydrogeology Journal 13:328-345

Neshat A, Pradhan B and Dadras M. 2014. Groundwater vulnerability assessment using an improved DRASTIC method in GIS. Resources, Conservation and Recycling 86:74–86

Osborn NI and Hardy RH. 1999. Statewide groundwater vulnerability map of Oklahoma. In: Board Technical Report 99-1 79. Oklahoma Water Resources

Qadir M, Tubeileh A, Akhtar J, Larbi A, Minhas PS and Khan MA. 2008 Productivity enhancement of salt-affected environments through crop diversification Land degradation and development 19:429-453

RIGW. 1990. Hydrogeological Map of Egypt Scale 1:100 000 Wadi El Natrun. 11. Research Institute for Groundwater (RIGW), Ministry of Public Works and Water Resources

RIGW/IWACO. 1990 Vulnerability of Groundwater to Pollution, Cairo, Egypt. Cairo, Egypt

RIGW/IWACO 1991. Groundwater Potential in the Nile Valley and Delta. In Internal Report. Cairo, Egypt

Robins N, Adams B, Foster S and Palmer R. 1994. Groundwater vulnerability mapping: the British perspective. Hydrogeology 3:35–42

Robinson CA Werwer A, El-Baz F, El-Shazly M, Fritch T and Kusky T. 2007. The nubian aquifer in southwest Egypt. Hydrogeology Journal 15:33-45

Saad KF. 1962. Groundwater hydrology, in preliminary report on the geology, hydrogeology and groundwater hydrology of Wadi El-Natrun and adjacent area, Part 3. 61. Cairo, U.A.R.: Desert Institute, The General Desert Development Organization

Seckler D, Molden D and Sakthivadivel R. 2003. The concept of efficiency in water-resources management and policy. In: Kijne JW, Barker R and Molden D (eds). Water Productivity in Agriculture: Limits and Opportunities for Improvement. Wallingford: CABI Publishing and IWMI pp. 37-51

Sghaier M. 1984. Identification et analyse des systemes de production agricole dans les oasis de Nefzaoua. In: Memoire de Fin d'Etude de Cycle de Specialisation de l'INAT Economie Rurale, 147. Tunis INAT

Shaer HME. 2009. Potential role of Sabkhas in Egypt: an overview. In: Asraf M, Ozturk M and Athar HR (eds). Salinity and Water Stress Springer, Netherlands pp. 221-228

Stempvoort DV, Ewert L and Wassenaar L. 1992. Aquifer vulnerability index: a GIS-compatible method for groundwater vulnerability mapping. Canadian Water Resources Journal / Revue canadienne des ressources hydriques 18:25-37

Switzman H. 2013a. Groundwater, environmental change and conservation in north Egypt: the impact of environmental change and water conservation on dryland groundwater resources in Northern Egypt: modeling aquifer response using sparse data. A Thesis Submitted to the School of Graduate Studies in Partial Fulfilment of the Requirements for the Degree Master of Applied Science. 189. McMaster University, Hamilton, Ontario

Switzman, H. 2013b. The impact of environmental change and water conservation on dryland groundwater resources in Northern Egypt: modeling aquifer response using sparse data. In School of Graduate Studies, 169. McMaster University

Switzman H, Coulibaly P. and Adeel Z. 2015. Modeling the impacts of dryland agricultural reclamation on groundwater resources in Northern Egypt using sparse data. Journal of Hydrology 520:420–438

Taher AG and Soliman AA. 1999a. Heavy metal concentrations in surficial sediments fromWadi El Natrun saline lakes, Egypt. International Journal of Salt Lake Research 8:75–92

Taher AG and Soliman AA. 1999b. Inland saline lakes of Wadi El Natrun depression, Egypt. International Journal of Salt Lake Research 8:149–169

Turner BL, Kasperson RE, Matson PA, McCarthy JJ, Corell RW, Christensen L, Eckley N, Kasperson JX, Luers A, Martello ML, Polsky C, Pulsipher A and Schiller A. 2003. A framework for vulnerability analysis in sustainability science. In: Proceedings of the National Academy of Sciences of the United States of America 100 14:8074–8079

Vowinkel EF, Clawges RM, Buxton DE, Stedfast DA and Louis JB. 1996. Vulnerability of public drinking water supplies in New Jersey to pesticides. Fact Sheet FS-165-96, 3. Reston/USA: U.S. Geological Survey

Vrba J, Zaporozec A. 1994. Guidebook on Mapping Groundwater Vulnerability. Hannover: Heise Verlag

Yehia HALM. 2004. Land Resource Assessment for Sustainable Agriculture Development at Multi Spatial Scale: A Case Study for Behira Governorate and Wadi El Natrun District, Egypt. In Soil and Water Science, Faculty of Agriculture, 218. Alexandria: University of Alexandria p 218

Zahran MA and Willis AJ. 2009. The Vegetation of Egypt, 2nd Edition. Springer

Acknowledgements

Many people have provided inputs into the compilation of this report. They bear no responsibility for the final report, or any errors that it may contain. The study team wishes to express particular thanks to the following people for their advice and assistance:

The residents of the village of Beni Salama advised on the development of the field survey, and hosted numerous research visits with kindness and good humour.

Mr. Sayyid Khalifa, Wadi El Natrun, and Beni Salama ensured the smooth running of all the project activities in the field, including the GWAHS-CS international project workshop and site visits.

The Mayor of Wadi El Natrun and Officials of Wadi El Natrun City Council supported the scientific development of the project and welcomed the project activities in Wadi El Natrun.

Eng. Seyyid Serkis, Akram Fekry, and Fatma Abdel-Rahman Attia have provided essential advice on groundwater management provisions in Wadi El Natrun.

Colleagues at the Desert Research Center through their published and archived studies have provided essential scientific knowledge of the groundwater resources in the study area enabling this report to be compiled. To the best of our ability, we have referred to and acknowledged these works in this report.

The GWAHS-CS Project leaders and case study teams from other regions have provided stimulating discussions and support for the development of the Beni Salama case study.

Several anonymous reviewers have provided valuable comments for the finalisation of the case study report. Ahmed Abdelkhalek and Harris Switzmann have helped to check the references included and generated interesting follow-up work since this study was completed.

Ms. Olivia Dun and Ms. Evalyne Kataboro at UNU-EHS have ensured the smooth administration of the project, overcoming logistical and communication challenges with good humour and efficiency.

CHAPTER 3

The Effects of Groundwater Artificial Recharge on Human Security Iran Case Study

Mehrdad Mohammadnia[1], Gholamreza Chabokrow[1], Mohammad Hossein Ravanbakhsh [2]

[1] Fars Agriculture and Natural Resources Research Center, Shiraz, Iran
[2] Department of Soil Science, Shiraz University, Shiraz, Iran

3.1 Main Challenges of the Case Study Area

The study area of Shibkouh County is located in the south-eastern part of Fars province in the southern region of Iran. The area is representative of some 43 million ha in Iran with similar biophysical and socio-economic characteristics of arid and semi-arid regions. Shibkouh County is currently facing an over-depletion of groundwater, as well as depletion in its quality. The region has faced increasing pressure on the already scarce water resources and an increase in land degradation from various processes, among them the sedentarisation of nomadic pastoralists on marginal drylands. It is these characteristics, along with the presence of research, training, and extension services with over 30 years of experience on aquifer management, which led to the selection of Shibkouh County as a project site for Groundwater and Human Security – Case Studies (GWAHS-CS).

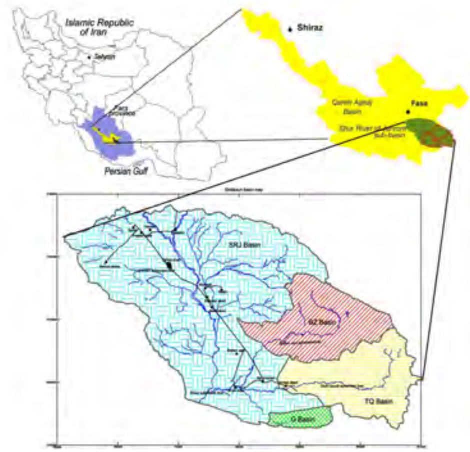
Classified as a hyper-arid environment, Shibkouh County is facing many challenges to its groundwater resources and therefore to the sustainability of the region and livelihoods of its people. An over-depletion of groundwater has increased the pressure on the already limited quantity of water available in the region, worsened by the illegal drilling of wells for groundwater extraction. The overuse of fertilisers on light textured soils, combined with spate irrigation and associated leaching of fertilisers has resulted in decreasing water quality; and the intrusion of brackish water as a consequence of aquifer depletion has resulted in the salinisation of groundwater and soils, thus compromising their use and dependence on them as a resource.

Given these challenges, the Shibkouh County case study took as its main objectives to:

- identify the constraints and limitations which reduce the quality and quantity of groundwater from the point of view of farmers, specialists, and local governors;
- assess farmers' attitudes towards drought and groundwater difficulties;
- study the social capital and ability of households to deal with the limitations caused by reduced quality and quantity of groundwater;
- assess the vulnerability of households to groundwater degradation and find ways to handle them;
- determine the awareness of rural households about risks in their area such as shortage in quality and quantity of groundwater;
- determine the degree of vulnerability using socio-economic indicators such as age, gender, training, education, poverty, employment rate, etc.; and,
- determine the coping capacities in the area and also the strategies applied to confront the socio-economic and environmental crises such as drought, poverty, out-migration, and crimes faced by rural households and local leaders.

3.2 Description of the Case Study Area

The study area of Shibkouh County (53º36'-54º13' E, 28º30'-28º51' N) is located 200 km southeast of Shiraz, Iran (Figure 3.1). Shibkouh County covers an area of 1,270 km^2 and is comprised of four sub-watersheds including the 675 km^2 Shur (salty) River of Jahrom Basin (SRJB); the 194 km^2 Bisheh Zard Basin (BZB); the 177 km^2 Tchah Qootch Basin (TQB); the 45 km^2 Gehrab Basin (GB); and the Gareh Bygone Plain (GBP) which covers an area of 179 km^2 (Kowsar and Pakparvar 2004).



Key

Yellow depicts the entire Fasa watershed; green depicts Shibkouh County (study area), which is divided into four sub-watersheds: SRJ = Shur River of Jahrom, BZ = Bisheh Zard, TQ = Tchah Qouch (including Gareh Bygone Plain),

G = Gehrab.

Figure 3.1. Location of Shibkouh County, Iran and its four sub-basins. (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009)

The climate in Shibkouh County is characterised by a very low and highly variable rainfall, averaging 243 mm annually with Class A pan evaporation of 3,200 mm, giving an aridity index[1] of 0.07. Temperatures can reach as high as 48° C, creating hyper-arid conditions (Fars Groundwater Authority 2011).

The majority of Shibkouh County's 25,500 inhabitants live in the town of Zahed-Shahr and the 14 surrounding villages. However, a few nomads also live in the County's marginal rangelands. The majority of the population has access to assets including electricity, tap water, mass media, education, and sanitation facilities. The main activities in Shibkouh County are agriculture, animal husbandry and service sector activities.

Prevalent land degradation further constrains agricultural development, which is the main source of income for rural inhabitants. Sedentarisation of pastoral nomads in marginal lands of Shibkouh County has exacerbated land and water degradation.

Groundwater degradation in many arid and semi-arid regions of Iran is associated with abandoned villages, increasing amounts of unemployed farmers due to water deficiency, and the rural young educated population seeking jobs in service or industrial sectors.

[1]The aridity index is defined as the long-term mean of the ratio of an area's mean annual precipitation to its mean annual potential evapo-transpiration, indicating a numerical value of the degree of dryness of the climate at a given location (Maliva and Missimer 2012).

Despite the problems posed by the above-mentioned issues, successful coping strategies from similar arid and semi-arid regions around the world exist. Artificial recharge of exploited aquifers using floodwaters and runoff followed by short duration rainfalls is one favourable strategy that is compatible with the climatic conditions of the country. Aquifer management projects (AMPs) implemented in different parts of Iran have been successful, and could be a further source of socio-economic information. As the GWAHS-CS project aimed to survey societal and environmental interactions affecting groundwater and human security, the outputs from this project could be helpful to these other studies and provide more practical experience enhancing the ability of decision makers and rural inhabitants to cope with insecurities throughout Iran.

3.2.1 Environmental characteristics

Ephemeral and flash floodwater is the most important surface water available in Shibkouh County for groundwater recharge in terms of both domestic and agricultural consumption. In addition, a few seasonal brackish seepage springs provide the surface water used by wildlife and some livestock.

The base flow of the SRJ, which drains the Fasa watershed covering an area of 4,530 km^2, is quite saline; the electrical conductivity ranges from 6 to 45 dS/m during the year. Although the salinity source has not been pinpointed as of yet, it is postulated that the dissolution of a hidden salt dome by the karstic waters, which probably discharge through a thrust fault on the western margin of the GBP, pollutes the groundwater in the area (Kowsar 2005). Over-extraction of the groundwater in the area also contributes to salinity increases throughout the aquifer. Overuse of chemical fertilisers pollutes the groundwater with nitrate as well (Mohammadnia 2010, Mohammadnia and Kowsar 2010, Mohammadnia et al. 2005). Since the general direction of groundwater flow in Shibkouh County is westward, a substantial volume of water, which is not extracted from the aquifer, eventually turns saline and seeps into the SRJ at the end part of the GBP.

The Bisheh Zard, Tchah Qootch, and Gehrab basins (Table 3.1) all drain into the GBP located at the eastern part of the study area, and their runoff is diverted for spate irrigation of food and forage crops, as well as for the artificial recharge of groundwater. The westward flowing Tchah Qootch river has deposited sediments in the GBP (the debris cone) in such a way that it slopes from east to southwest. The debris cone is terminated on its western extremity by the SRJ, an effluent, perennial stream that flows southward in the thalweg of the GBP.

Table 3.1. Geographical characteristics of the triple basins and a sub-watershed of the Shur River of Jahrom in the Shibkouh County.

Basin	Geographical coordinates		Area	Elevation above mean sea level (m)		Length of the longest stream (km)	Time of concentration
	Longitude	Latitude	km²	Max.	Min.		minutes
Bisheh Zard	53º55' - 54º11'	28º36' - 28º44'	194	1,582	1,170	28.5	282
Tchah Qootch	54º00' - 54º13'	28º32' - 28º39'	177	1,822	1,183	26.5	322
Gehrab	53º55' - 54º04'	28º31' - 28º35'	45	1,823	1,130	20.0	205
SRJ sub-watershed	53º40' - 54º01'	28º32' - 28º50'	675	1,247	1,153	13.1	----

Table 3.2. The stratigraphy of the Shibkouh aquifer (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

	Formation Name	Age	Descriptions
1	Qorban Formation	Paleocene	Thick-bedded bioclastic-sparite and chalky-dolomitic limestone and ferric low weathering marls.
2	Sachun Formation	Upper Paleocene	Thick to very thick bed of gypsum in alternation with thinly bedded dolomite, dolomitic limestone, and marls.
3	Jahrom Formation	Eocene	Uniform bedded intensive layer, unmmulite bearing cream limestone to grey ferruginous and dolomitic and marly limestone.
4	Asmari Formation	Oligocene	Massive, brown to grey weathering, bioclastic to biomicrosparite, thick bedded limestone, marly limestone with abundant micro fauna.
4	Asmari Formation	Oligocene	Massive, brown to grey weathering, bioclastic to biomicrosparite, thick bedded limestone, marly limestone with abundant micro fauna.
6	Upper part of Gachsaran	Miocene	Superficial chemical deposits gypsum and anhydrite, silty and marly limestone, ferrous and ferric marl, and gypseous bearing limestone.
7	Aghajari	Miocene-Pliocene	Feature forming, fine- to coarse-grain sandstone, diamictic and grit stone and mainly marls, marly sandstone, siltstone polymictic micro-conglomerate and conglomerate in top of portion.
8	Mishan	Miocene	Ferruginous marls with inter-bedded sandstone and sandy limestone.
9	Guri member	Miocene	Mainly hard reefal sandy limestone, marl and marly limestone.
10	Bakhtyari	Pliocene-Pleistocene	Polymictic, proximal, heterogeneous imbricate cherty conglomerate and low weathering lutite.
11	Quaternary system	Pleistocene-Holocene	Detrital fan, polygenetic, containing piedmont colluvial deposits consisting immature and clastic boulder to gravel-size clastic, clay and sand, polymictic conglomerate, alluvial and colluvial deposits of major intermittent watercourses and sheet washes.

Groundwater is the main source of both drinking and irrigation water for Zahed-Shahr town and 14 surrounding villages in the Shibkouh County. This town and the villages are highly vulnerable due to overexploitation and severe droughts which have occurred during the past decade (2000-2002; 2006; 2008-2010). The total water balance of the Shibkouh aquifers is negative (-46.21 Mm^3/year), leading to severe groundwater drawdown and human insecurity.

a) The Shibkouh County aquifers

A geological map of the Shibkouh County is given in supporting materials (SM, Figure 1). From a geological viewpoint, most formations of the Shibkouh County are related to the Cenozoic era and are divided into Paleogene, Neogene, and Quaternary systems (Table 3.2). In fact, the study area is a northwest to southeast syncline formed by the tectonic movement of the Zagros mountain ranges during the Mio-Pliocene period into the Agha Jari Formation. The Agha Jari Formation, one of the most widespread geologic formations in south/south-western Iran, ranges from the late Miocene to Pliocene period. This formation consists of rhythmically inter-bedded brown to grey, calcareous, feature-forming sandstones and low weathering, gypsum-veined, red marls, and grey to green siltstones. The Agha Jari Formation lies comfortably over the grey marls and limestone of the Mishan, which is from the early to middle Miocene age. Although the Agha Jari Formation is usually capped by the Plio-Pleistocene Bakhtyari Formation, severe erosion during the Quaternary period has left only small, scattered patches of the Bakhtyari Formation on the basins. The Bakhtyari Formation, which mainly consists of pebbles and cobbles of Cretaceous, Eocene, and Oligocene limestone and dark brown, ferruginous cherts, has provided the bulk of the alluvium in the study area; the Agha Jari Formation has contributed the rest. The Agha Jari Formation forms the major bedrock on which the alluvium has been deposited (Kowsar and Pakparvar 2004).

The westward flow of the Bisheh Zard, Tchah Qootch, and Gehrab Rivers has deposited a debris cone in the GBP in such a way that it slopes from east to southeast/northwest. This direction of flow in the above-mentioned rivers is consistent with the findings of Oberlander who, in 1965, established that although the folding trend of the Zagros Mountain Ranges is northwest to southeast, the rivers which drain the basins and recharge the groundwater in those ranges flow westward through the gorges and cut across the anticlines.

There are three different types of aquifers in Shibkouh County:

- calcareous alluvial that form the main body of the aquifer;
- karstic aquifer that is mainly located at the northern and southern boundaries of the county and that partially recharge the alluvial aquifer; and,
- conglomeratic aquifers located in the eastern part of the study area that also partially recharge the alluvial aquifer.

The Shibkouh County aquifer has an outlet for surface water flows and three natural recharge fronts. The first recharge front comes from northwest heights with unfavourable quality, originating from a neighbouring salt dome. The second recharge front emanates from the eastern heights of the Gar mountain. Thirdly, there is incoming groundwater emanating from upstream plains comprising Fasa and Nowbandegan.

Electrical conductivity (EC) and Chloride (Cl^-) in the groundwater from 1992-2007 reveal that their maximum concentration, are 10.27 dS/m and 1,597 mg L^{-1} respectively, as measured in the northwest part of the aquifer. However, minimum amounts of the above items were measured in Senan village located at the northern part, equal to 0.98 dS/m and 319 mg L^{-1} respectively. Due to groundwater overexploitation in the Shibkouh County, the area has been declared prohibited for use for agricultural purposes by the water organisation of Fars Province since 2002. Mean EC of the groundwater increased from 4.15 dS/m in 1992 to 4.8 dS/m in 2006, implying aquifer degradation (Fars Groundwater Authority 2011).

Groundwater quality degradation was the main indicator for prohibition of more extraction due to the following reasons:

- electrical conductivity increased by 2-3 dS/m in the northern and north west area;
- electrical conductivity increased by 0.5-1 dS/m in the central parts (Nasir-Abad and Koushk-e-Saadat villages); and,
- electrical conductivity increased by less than 0.5 dS/m in the northern and northeast parts (Senan and Khourangan villages).

Based on the Shibkouh hydrograph, the water balance exhibits both increasing and decreasing trends annually. When active agricultural activities begin from early December to late May, water levels begin to fall over the corresponding time period. However, water levels increase during the rest of the year depending on rainfall amounts and flood events.

Artificial recharge of groundwater occurs mainly through the Aquifer Management Project (AMP) implemented in the GBP of Shibkouh County, as described below, and plays a key role in the aquifer recharge during flood events. Alluvial depositions form the main part of the unconfined aquifer of the Shibkouh County with an extent of 270 km^2. Natural recharge of the aquifer mainly occurs through seepage from ephemeral streams during flood events. Floodwaters emanating from basins are the sole source of surface water available in Shibkouh County.

b) Groundwater-related problems in Shibkouh County

Issues such as rainfall deficiency, lack of permanent stream flow, groundwater overexploitation, and unsuitable cultivation patterns account for the main groundwater problems in Shibkouh County. The Shibkouh climate is hyper-arid, which cannot support current cultivation patterns in which highly intensive irrigation-dependent farms with unsuitable irrigation methods degrade groundwater. The overexploitation of groundwater beyond rechargeable thresholds is an unsustainable practice amongst desert dwellers. In addition, overuse of chemical nitrogenous fertilisers on the light texture soils (sandy to loamy sand) in the area followed by heavy spate irrigation causes high leaching of fertiliers into the vadose zone, and the aquifer as well.

Intrusion of brackish water followed by aquifer depletion creates a hazard for both drinking and agricultural sources of water, especially in the western part of the Shibkouh County where most of the inhabitants and populated centres are centralised. Due to the lack of scientific health surveying, no water-borne diseases have been documented in the area to date.

To address these problems, artificial recharge of groundwater through an aquifer management project (AMP) located in the eastern part of the Shibkouh County has been implemented in GBP since 1981 and provides a unique capacity for surrounding villages to cope with droughts through optimising floodwater harvesting (Lee and Schaaf 2008). The AMP has been established throughout the whole country (Kowsar 2005). The recharge of exploited and empty aquifers, where possible in wet years, and optimising the water use for sustainable production and development are the main goals of the AMP. In fact, the AMP is defined as the art and science of maximising the productivity of aquifers by whatever reasonable means, and optimising all resources which bear upon the continued usability of aquifers (Kowsar et al. 1996). Harnessing destructive floodwater and spreading it over permeable basins to recharge groundwater through floodwater spreading systems is the main component of an AMP.

The AMP in the Gareh Bygone Plain covers the Bisheh Zard Basin (BZB) which produces floodwaters; the Bisheh Zard Ephemeral River; and an alluvial debris cone overlaid by a sandy aquifer and located downstream of the BZB. Naturally floodwaters move from the BZB through the abovementioned ephemeral river into the floodwater spreading system (FWSS) located on the mid-part of the alluvial cone, to artificially recharge the Bisheh Zard Aquifer (BZA). Floodwater spreading systems occupy about one-third of the alluvial fan and consist of sedimentation basins (SB), which are partly forested with Eucalyptus camaldulensis Dehnh trees and the recharge basins (RB). Restricted non-anthropogenic activity areas located in the upper part of the alluvial fan, and two separated excessive farming areas located upstream and downstream of the FWSS, respectively, occupy the remaining areas in the GBP. Diverted floodwaters enter the FWSS and the remaining floodwaters leave the study area without passing through the farm fields (Mohammadnia and Kowsar 2010).

Inasmuch as aquifer capacity in the eastern part of the Shibkouh is large enough to serve and save 10,800 Mm^3 during wet years, it is expected that the AMP is capable of supplying sufficient and safe water for inhabitants during drought years. Moreover, the AMP provides better groundwater quality by recharging fresh floodwater into the vadose zone in comparison to non-recharged areas. Concentration of main groundwater ions and nitrate as the main pollutants are significantly lower in the recharged areas than in the western parts of the Shibkouh, which has higher rates of extraction and a lack of recharge systems.

3.2.2 Demographic features of Shibkouh County

Shibkouh County consists of 14 villages with a population of over 32,000. Eight villages were investigated in terms of social and economic aspects relating to groundwater use; these can be divided into two main groups: i) five villages with higher population levels and relatively good standards of welfare, and ii) three villages with lower populations and higher levels of poverty.

Based on the 2006 Iranian census, there are 5,828 households with an average household size of 4.4 persons/household. The population size and number of households in each village are shown in Table 3.3. Bishe Zard has the lowest population (1.3%) within the study area and the highest average household size (5.2 persons/household). Overall, data indicate that the household size in smaller villages is higher than the household size in larger villages. 50.2% of the population in the study area are male whereas 49.8% are female. 25% of the population are 0-14 years of age, 69% are 15-64, and 6% over the age of 65.

Table 3.3. Population and household size of villages in Shibkouh County (Statistical Center of I.R. Iran 2006).

Village/town	Population		Households		Average Household Size
	Total	Percentage of Study Area	Total	Percentage of Study Area	
Sennan	1,854	7.3	429	7.4	4.3
Miandeh	5,529	21.7	1,269	21.8	4.3
Nasir-Abad	1,616	6.3	349	6.0	4.6
Bisheh-Zard	410	1.6	78	1.3	5.2
Tchah-Dowlat	762	3.0	168	2.9	4.5
Fedeshkouyeh	4,690	18.4	1,115	19.1	4.2
Zahed-Shahr (town)	10,038	39.4	2,296	39.4	4.4
Rahim-Abad	601	2.4	124	2.1	4.8
Total	25,500	100	5,828	100	4.4

The population growth rate over the decade 1986-1996 was low (0.28%), while the rate for the following decade 1996-2006 was negative (-0.25%) indicating an out-migration from the study area towards urban environments and elsewhere. These rates are far below the provincial average of 1.28% and Iranian average of 1.59% for the 1996-2006 decade (Statistical Center of I.R. Iran 2006).

The population density of each village in Shibkouh County is presented in Table 3.4. According to this table, the average population density for the entire study area is 90 persons/km^2.

Table 3.4. Density of population in villages of Shibkouh County (Statistical Center of I.R. Iran 2006).

Name of village	Population	Area (km^2)	Population Density (people/km^2)
Sennan	1,854	7.19	257
Miandeh	5,524	18.33	301
Nasir-Abad	1,616	62.58	25
Bishe Zard	410	31.40	13
Tchah-Dowlat	762	45.54	16
Fedeshkouyeh	4,686	30.99	151
Zahed-Shahr	10,038	60.29	166
Rahim-Abad	601	24.87	24
Total/Average	25,500	281.19	90

3.3 Methodologies

3.3.1 Biophysical Assessment of the Study Area

Groundwater quantity parameters were determined through an input-output system, based on data provided by the Shibkouh Office of Water Affairs. A groundwater network of 33 observatory wells throughout the study area was used to provide fresh water samples for analysis. Electrical conductivity (EC), pH, Cl^-, and NO_3^- were measured for all samples in the field. However, in testing samples from the recharge areas, Na^+, K^+, Mg^{+2}, Fe^{+2}, dissolved O2, SO_4^{-2}, total hardness (TH), HCO_3^{-2}, CO_3^{-2}, NH_4^+ and total organic carbon (TOC) were measured using standard methods at the Fars Research Centre for Agriculture and Natural Resources' laboratories in Shiraz.

3.3.2 Social assessments

For the socio-economic assessment of the study area, two different methods were applied. The first involved a quantitative analysis of formal statistics published by the central government. The second involved a qualitative analysis with households in eight of the villages of Shibkouh County using methods such as Participatory Rural Appraisal (PRA) techniques, in-depth interviews with key informants, interviews with focus groups, and participant observation techniques. These methods are described below.

a) Quantitative methods

Given the relatively large study area, a sample of the population was randomly selected. Taking the biophysical, social, and economic conditions within the area into consideration, eight villages were selected as being representative of all 14 villages. In each village, a list of all households was provided by the local governor and households were randomly selected based on the sample size. A questionnaire was completed with the selected households using the assistance of trained interviewers. The questionnaire evaluated different socio-economic indicators such as household structure, facilities and access to assets, land ownership, education, access to credit, and activities which are related to vulnerability and coping with limitations on groundwater. In parallel, general information about the village was collected in another questionnaire by interviewing key informants. In addition, in each village, a group discussion with key informants provided related information about the villages under study.
Household Survey

Based on the method described by Lin (1977), 350 households were selected from a total of 5,828. The total number of surveyed households for each village are listed in Table 3.5.

Table 3.5. Sample size of each village (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

Villages	Number of households surveyed
Nasir Abad	18
Fedeshkoye	70
Zahed Shahr	150
Senan	34
Bishe Zard	3
Tchah Dowlat	5
Rahim Abad	4
Miandeh	66
Total	350

The questionnaires were completed by each household and facilitated by an interviewer. Farmers were asked questions related to: household structure, facilities and assets, education, land ownership, activities (agricultural and non-agricultural), credit (local and government), social capital (structural and cognitive), vulnerability and resilience, and coping with drought. Focus groups were asked to provide information on: roads, job opportunities, infrastructure, supporting organisations, groundwater limitations, coping with drought, and environmental issues.

b) Qualitative methods

A range of qualitative techniques were used, including participatory rural appraisal (PRA), focus groups, and interviews. Each is described below.

Participatory Rural Appraisal

Participatory Rural Appraisal (PRA) is an action research method. It is a collection of approaches, techniques and behaviours that help rural people to explain their opinions about conditions and facts and to plan their goals and evaluate the results (Chambers and Blackburn 1996). First, it was used to collect the required information from rural households, such as the history of drought in Shibkouh County, and the attitude of local households with regard to groundwater shortages and their options on how to overcome them. Second, it was used to empower the rural households to analyze the obstacles related to groundwater, such as improper laws, lack of financial support, lack of infrastructure, and weak social capital; and to subsequently find ways to deal with them.

Focus group method

Using focus group discussions approaches, three meetings and gatherings were organised with local governors to discuss issues in relation to the quantity and quality of groundwater, vulnerability, drought and their suggestions on how to address these issues.

The information collected during focus group sessions included: the quality and quantity of groundwater, coping with crisis, policies and legislation for water management, drought and diseases, drought and social security, drought and immigration, supporting NGOs, agricultural insurance, welfare in rural areas, and the training of villagers.

In-depth interviews with key informants

In-depth interviews were conducted by experienced interviewers with key informants in rural areas, such as heads of local councils, NGO representatives, governors, and local elders. Interviewees were asked to provide key information about different subjects including drought, groundwater, history of groundwater shortages, and disasters.

Photo 1. Participatory Appraisal.

Photo 2. Focus group discussions.

Photo 3. In-depth interviews with decision makers.

3.4 Results

3.4.1 Groundwater resources

3.4.1.1 Perspectives of the local households

The knowledge and opinions of rural people concerning groundwater-related problems were obtained via the household-level field research methods and PRA techniques described above. The majority of the surveyed households reported severe decreases in the changes of groundwater levels and availability of groundwater (Table 3.6).

Table 3.7 shows the perceived reasons for the reduction in the level of groundwater, based on farmer interviews. More than 60% believe that natural occurrences such as drought and low rainfall are the main reasons for reductions in groundwater levels, whereas only 33% indicated overexploitation as the cause for the decrease in groundwater quantity.

Table 3.6. Household opinions on changes in the quantity of groundwater in recent years (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

Type of Change in Groundwater Quantity	Number of households identifying this type of change	Percentage of households identifying this type of change
Serious decrease	279	79.9
Decrease	61	17.5
No change	9	2.6
Total	349	100

Table 3.7. Reasons cited by households for causes of groundwater level decreases (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

Reason for Groundwater Depletion	Number of households selecting this reason	Percentage of households selecting this reason
Natural factors	210	60.2
Overexploitation	114	32.6
Others	25	7.2
Total	349	100

Local households were also asked to forecast groundwater quantities in the future, in order to investigate changes in the quantity of groundwater. The results provided in Table 3.8 show that 17% of households believed that there would be no water in the future while 59% mentioned they could foresee a serious decrease, and just 0.3% (one household) declared a better situation.

Table 3.8. Household views on future rates of change in groundwater levels (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

Future change in groundwater level	**Number of households selecting this type of change**	**Percentage of households selecting this type of change**
No water	60	17.2
Serious decrease	204	58.5
Better conditions	1	0.3
No response	84	24.1
Total	349	100

Further, local households were asked their perceptions of the quality of groundwater (Table 3.9). Revealingly, no household indicated that the groundwater quality was in good condition, while around 72% mentioned an average condition and 28% a bad condition. Households indicated that salty tasting groundwater was the main reason for their conclusions about groundwater quality.

Table 3.9. Household views on the quality of groundwater in the study area (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

Groundwater Quality	**Number of households identifying this option**	**Percentage of households identifying this option**
Good	0	0
Acceptable	207	72
Bad	80	28
Total	287	100

The results from the PRA techniques indicate that during the last three decades the level of groundwater has decreased, with the maximum and minimum groundwater levels being reduced to 250 m and 30 m, respectively. In addition to reductions in quantity, the quality of groundwater has also decreased in recent years. Households state that groundwater is not drinkable because of excessive use of chemical pesticides and fertilisers. The results also showed that there is increasing salinity in the soils, and an increase in the number of legal and illegal wells in last three decades which further contributed to overexploitation of groundwater.

Through group discussions and interviews with local leaders, difficulties and limitations related to groundwater use were collected. The results confirmed the findings from the household interviews, with local leaders emphasising the overexploitation of groundwater as a main problem. Additional findings from the interviews with local leaders revealed that there are decreasing groundwater levels, increasing salinisation of groundwater, increasing groundwater degradation, and also a growing number of illegal wells.

3.4.1.2 Volume, storage capacity, and transmissivity of the Shibkouh Country aquifers

A groundwater monitoring network consisting of three alluvial well observatories and two Karstic wells was established in the study area by the Ministry of Power in 1971. In 1992, the network was extended to 30 wells with groundwater fluctuations being measured on a monthly basis. Due to severe droughts in recent years, 20 observation wells were surveyed as active observatory wells using the Thiessen method.

From these observations, the known thickness of alluvium which forms the main aquifer in the Shibkouh County, ranges from practically 0 metres on the eastern margin of the debris cone in the GBP to 90 metres in the central parts of the area. The depth to the water table ranges from 1.2 m in the vicinity of Kooshk-e-Saadat village to 76 m in the vicinity of Senan village. Considering the extent of the area (270 km^2), the average thickness of the watertable (40 m) and the coefficient of storage of the aquifer (10%), it is possible to store 10.8 billion m^3 of water in the aquifer. A representative geological log of the entire study area is depicted in Figure 3.2.

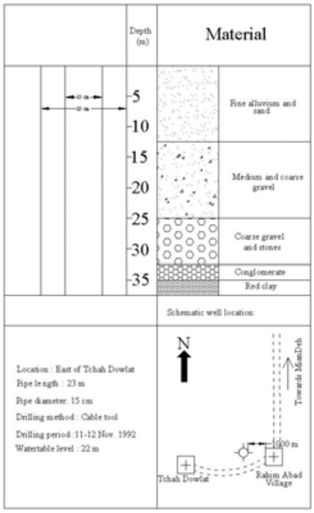


Figure 3.2. Geological log of a well in the Shibkouh County, prepared from well cuttings.

Source: Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009.

The estimated amount of water extracted annually from Shibkouh aquifer since 1980 equalled 10.45 billion m^3. This increased to 11.96 billion m^3 through 533 production wells in 2006. Groundwater depth in Shibkouh aquifer decreased at an average rate of 9.46 m annually during the period 1993-2002, while the average annual decrease was 0.73 m in the Shibkouh aquifer. The storage coefficient and transmissivity of the Shibkouh aquifer are calculated as 6-15% and 85-1800 m^2/day, respectively.

Transmissivity of the alluvium was determined in two wells using Jacob's method in 2003. The well in the northern part of the GBP was 29 m deep, with the water table at a depth of 22 m. The yield of this well was 15 litres per second (L s^{-1}). The well in the middle of the plain was 21 m deep, with the watertable at a depth of 14 m. The yield of this well was 11 L s^{-1}. Mean transmissivity (T) using the data acquired from these two wells was 790 m^2 per day, which is typical for a coarse-grained alluvium (Pakparvar 2015). Taking the width (W) and depth of the Shibkouh aquifer at 9830 m and 20 m, respectively, and the hydraulic gradient (i) of 0.0065, the yield (Q) is:

$$Q = WTi = 9830 \text{ m} \times 790 \text{ m}^2 \times 0.0065 = 50477 \text{ m}^3\text{day}^{-1} = 584.22 \text{ L s}^{-1}.$$

3.4.1.3 Renewable groundwater resources

The hydrogeological balance of the Shibkouh aquifer according to the Fasa District Water Affairs is presented in Table 3.10. Due to groundwater mismanagement and overdrafting, total balance of the aquifer is negative, leading to a great and serious threat in the area.

Table 3.10. The hydrogeological balance of the Shibkouh aquifer (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

Location	Area (km^2)	Aquifer type	Annual precipitation (mm)	Recharge million (m^3)	Discharge million (m^3)	balance million (m^3)
Plain area	438	Alluvial	209.4	34.0	90.4	-56.5
Mountains and hills area	832	Karstic	327.4	39.4	29.2	+10.2
Entire study area (Shibkouh County)	1370	Alluvial and Karstic		73.3	119.8	-46.25

3.4.1.4 Groundwater quality of the Shibkouh County aquifers

Since the general direction of the groundwater flow in the Shibkouh aquifer is westwards, a substantial volume of water that is not extracted from the aquifer eventually turns saline and seeps into the Shur River of Jahrum. Although the exact source of the salinity has not yet been identified, it is postulated that the dissolution of a hidden salt dome by the Karstic waters, which probably discharge through a thrust fault on the western margin of the GBP, pollutes the groundwater in that area. The base flow of the SRJ which drains the Fasa watershed covering an area of 4530 km^2, is quite saline; the electrical conductivity (EC) ranges from 6 to 45 dS m^{-1} during the year (Fars Groundwater Authority 2011).

The EC of groundwater ranges from 0.9 to 10.3 dS m^{-1} in the artificial recharge of groundwater (ARG) systems located in the GBP, and northwest of the area, respectively. However, maximum and minimum values of chloride concentration in groundwater range from 1597.5 mg L^{-1} to 319.5 mg L^{-1} in the same area. Obviously, mean EC of the groundwater increased around 0.6 dS m^{-1} during 1993-2006 in the Shibkouh aquifer. According to groundwater monitoring, EC decreased in the vicinity of the ARG system in the GBP. A possible reason for the high EC of the wells outside the influence of the ARG systems is an intrusion of saline water from a thrust fault to the southwest of the ARG systems. It is only through keeping a high head in the freshwater aquifer that encroachment of saline water into it can be hindered.

Increasing concentrations of NO_3^- in groundwater may degrade water quality and is a cause of concern both in shallow and deep aquifers. In fact, NO_3^- contamination of groundwater reduces the supply of relatively safe water and increases the costs of remediation treatment. High NO_3^- concentrations may cause methemoglobinemia in infants, and have been cited as a risk factor in developing gastric and intestinal cancers in adults (Flite III et al. 2001; Sakadevan et al. 2000). As NO_3^- is highly mobile and very soluble, the recharge events, either by rainfall or irrigation, may create infiltration pulses of downward flowing water and the entrained NO_3^- (Bauld 1994).

Nitrate is the main groundwater pollutant in the Shibkouh aquifer. Although incoming base flow of the groundwater contains geologic nitrate (<20 mg L^{-1} on average), agricultural activities dramatically increase its concentration more than 45 mg L^{-1} NO_3^- (the acceptable level permitted by the United States Environmental Protection Agency for health and safety regulations, Sparks (2003). Based on Figure 3.3, in 2007, nitrate concentration in the aquifer ranges from < 5 mg L^{-1} in the recharge area of the GBP to more than 85 mg L^{-1} in the vicinity of Nasir-Abad village.

Inasmuch as FWSS artificially recharge the aquifer in the GBP using decontaminated floodwater (through a phytoremediation process by an afforested filter zone of Eucalyptus trees), the aquifer under the AMP provides the best water quality in comparison with other parts of Shibkouh aquifer (Mohammadnia 2010, Mohammadnia and Kowsar 2010). The same process of decontamination happens by surrounding Karstic aquifers followed by natural aquifer recharge. Land use, depth of water table, farm mismanagement, groundwater shortage, sandy soil texture, and overuse of water are the main reasons contributing to groundwater degradation in Shibkouh County.

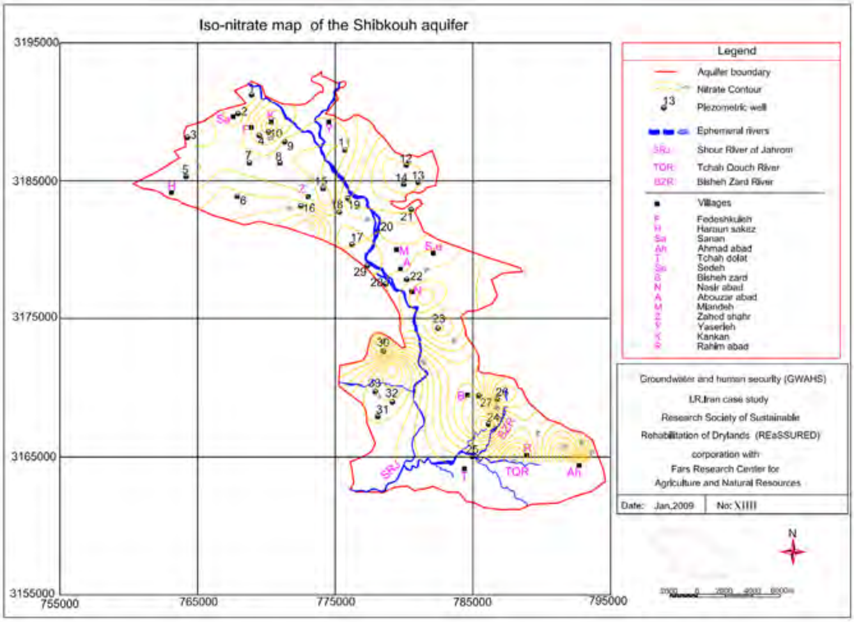


Figure 3.3. Groundwater iso-NO_3 map of the Shibkouh aquifer in 2007 (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

Groundwater contour lines (Figures 3.4 to 3.7) reveal the presence of two flow directions: the first relates to the artificial recharge of groundwater systems (east-west), and the second relates to the northwest flow direction of the Shibkouh. The groundwater level varies from -1195.03 m (between Zahedan and Fedeshkouyeh in the northern part of the area) to -1124.05 m (Rahim-Abad in the south-eastern part of the area). In general, the hydraulic gradient of the groundwater conforms the general slope of the plain, which is northwest to southeast, with a slight diversion towards southwest at the southern part of the area.

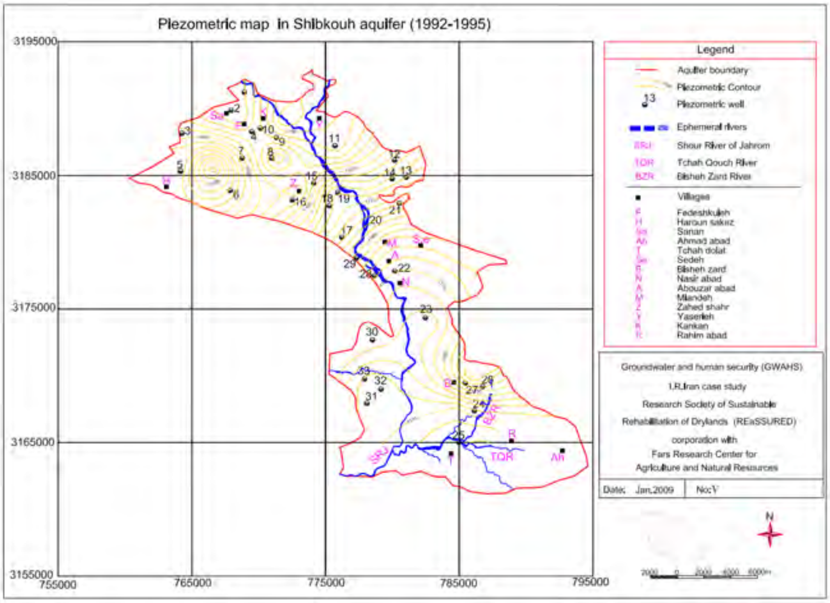


Figure 3.4. Groundwater iso-potential map of the Shibkouh aquifer (1992-1995) (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

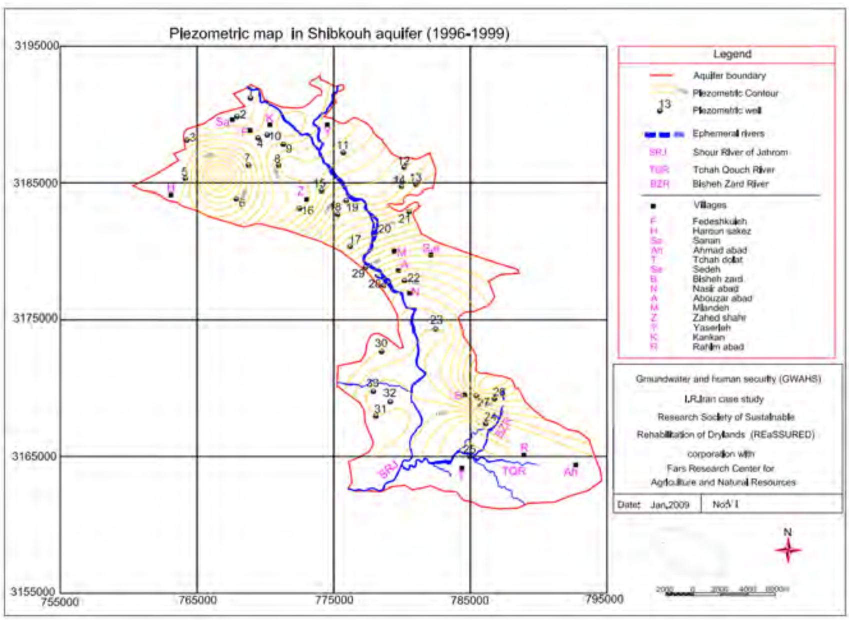


Figure 3.5. Groundwater iso-potential map of the Shibkouh aquifer (1996-1999) (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

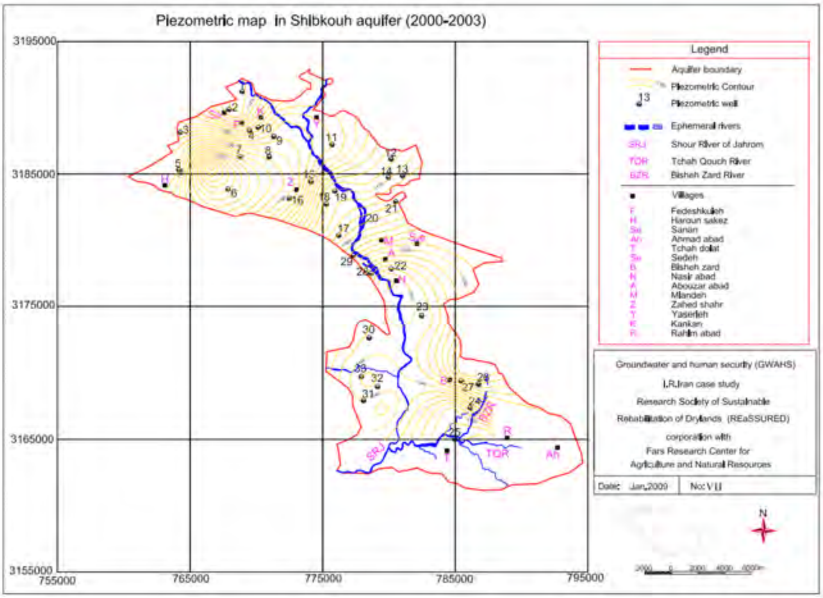


Figure 3.6. Groundwater iso-potential map of the Shibkouh aquifer (2000-2003) (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

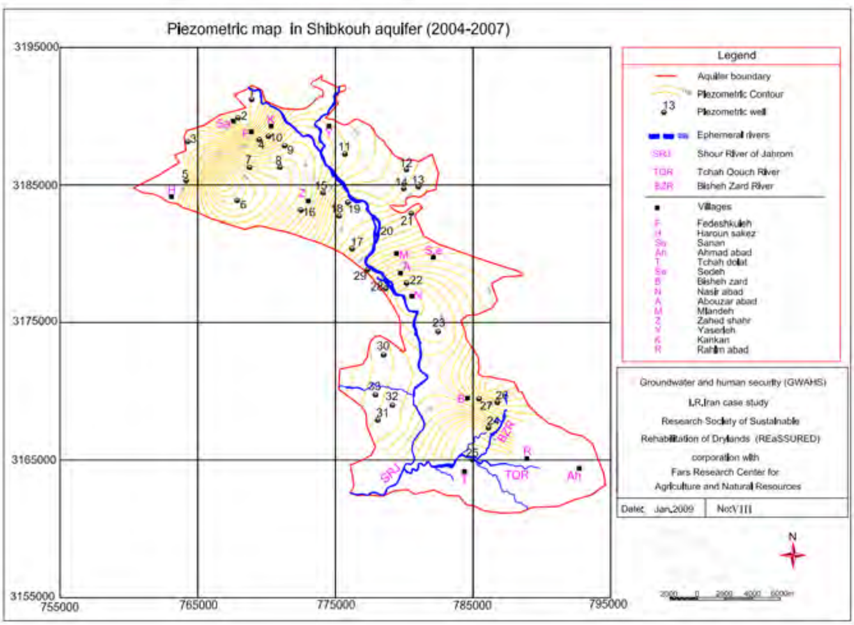


Figure 3.7. Groundwater iso-potential map of the Shibkouh aquifer (2004-2007) (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

3.4.1.5 Aquifer vulnerability

Groundwater and human security are inseparable in the lexicon of sustainable development of drylands. Overexploitation and degradation of the groundwater simultaneously increase the vulnerability of communities, especially in drylands.

There are almost 500 wells in the Shibkouh County. Assuming that 250 of the wells are each operated simultaneously at 20 L s^{-1}, this means that 5000 L s^{-1} of water are extracted from the aquifer, which is 8.56 times higher than that which can be sustainably supplied. Therefore, overexploitation results in salinisation, contamination and finally, drying out of the wells. Intrusion of salty water into the aquifer followed by overextraction makes agriculture impossible as the main source of income in the medium to long term. Therefore, aquifer vulnerability in the area has both groundwater quality and quantity dimensions. On the other hand, artificial recharge of the aquifer implemented in the eastern part of the GBP provides an opportunity for inhabitants to cope with droughts and decreases vulnerability of both the aquifer and people's livelihoods. As the study area has a slim chance of receiving adequate rain every year, the artificial recharge of groundwater systems must be designed and constructed in such a way so as to harness the largest possible flow of water that is technically practicable, environmentally sound, financially viable, and socially acceptable (Kowsar 2005).

As mentioned above, the depth of the water table in the Shibkouh ranges between -1.2m to -76 m in the mid-part and northern parts, respectively. However, water table drawdown ranges from 5-9 metres in the northern part to less than 2 metres for the southern parts of the area. Salty water intrusion following groundwater overextraction and nitrate leaching into the aquifer through overuse of fertiliers presents a high threat to local communities.

The vulnerability of the Shibkouh County aquifer can be divided into three distinctive zones (Figure 3.8). Zone one, located in the northern part of the area, faces the largest water drawdown and salty inflow intrusion, and is therefore classified as the most vulnerable zone. Lack of considerable recharge flow intensifies its vulnerability. The second zone, located in the mid-part of the Shibkouh County, is classified as moderately vulnerable, having the highest population but the least cultivated areas. The aquifer provides a bottleneck shape and a very low depth to bedrock in some points of that area. The zone of lowest vulnerability is located at the south-eastern part of Shibkouh including GBP and surrounding areas due to ARG through FWSS.

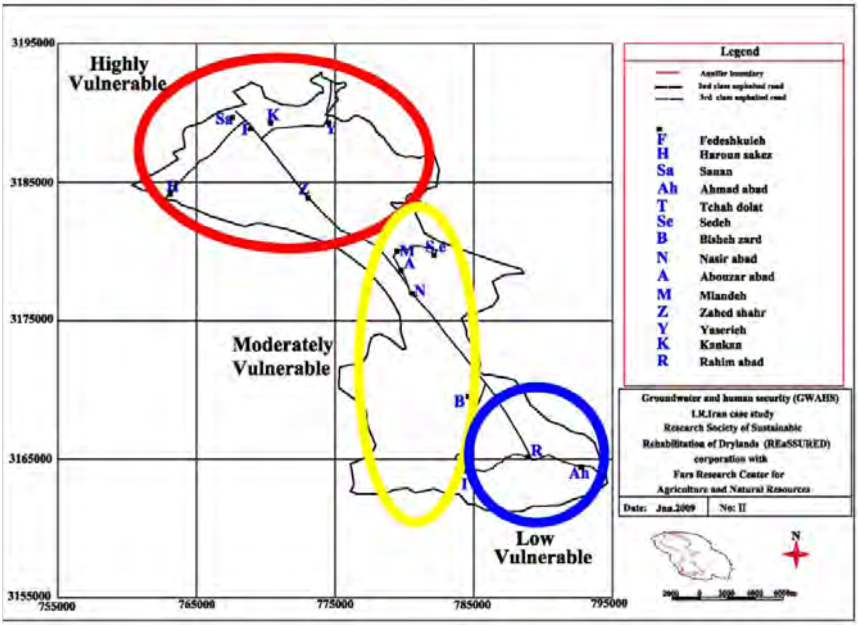


Figure 3.8. Aquifer vulnerability map of the Shibkouh aquifer (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

Implementing FWSS through AMP in the GBP has provided a suitable coping capacity to inhabitants to alleviate groundwater degradation and overcome severe droughts. Obviously, floods are a dilemma for human security of the Shibkouh region. If flood waters can be harnessed and used for recharge of the exploited aquifer, then they are considered a welcome gift; otherwise they are simply considered destructive and unwelcome by the local inhabitants.

3.4.2 Socio-Economic and institutional considerations

Agriculture is the mainstay of peoples' livelihoods in the study area, followed by the service and industrial sectors, respectively. The agricultural sector consists of two sub sectors: animal husbandry and farming. In this study, methods such as field research including interviews with local informers, governors, and villagers through questionnaires, interviews, and PRA techniques were used to obtain the necessary information about people's dependency on groundwater.

The results indicate that all eight villages are highly dependent on groundwater for their activities. Interviews with households reveal that during a drought, 10% of the farmers may migrate temporarily or permanently to neighbouring areas or larger urban centres, or may reduce their cultivated area because of a reduction and/or shortages in groundwater quality and quantity. Groundwater degradation clearly has deep impacts on the welfare and revenue of the farmers and so increases the rate of poverty in the study area.

Another indicator showing the dependence of farmers on groundwater is the increasing rate of new wells appearing in the area. According to the farmers and local leaders interviewed, there were only 188 wells in the study area (Shibkouh) less than three decades ago. In 2009, the number of legal wells has increased to 480. Based on interviews with local leaders, there are an additional 50 illegal wells in the study area. A five fold increase in the amount of new wells over the past three decades indicates the high degree of dependency of villagers on groundwater in the area.

A third indicator of dependency on groundwater is the changing depth of the wells in the study area. The groundwater level during the last three decades has fallen from 30-50 meters below surface level to more than 250 meters below the surface in most parts of Shibkouh County.

The results of interviews with local leaders also indicate that the main use of groundwater in the area is linked to farming since agriculture is the main activity within the study area. This suggests that the economic sector of the area is directly related to groundwater. Furthermore, many wells are dug to provide drinking water but several of them have become useless because of low water quality. Based on the results of the questionnaires, 80% of the households indicated that access to fresh drinking water is a serious problem in Shibkouh.

Based on the findings of the questionnaires and interviews with around 30 key informants including members of the rural council, local governors, and local NGOs, a shortage of groundwater in the area is associated with social and economic crises. Some of the calamities from the economic perspective are: low rates of revenue, a decrease in the employment rate, a shortage of agricultural products, a reduction in the rate of production of livestock products, and an increase in the rates of out-migration and poverty.

3.4.2.1 Pricing and subsidy policies of groundwater use

The main problem of groundwater management in Shibkouh County is how to achieve a balance between the demand for water and the available water supply. Water pricing can play an important role in this respect. Unrealistic water pricing and strict water allocations are two related factors that have played a significant role in the water crisis in Iran, and are controlled by the Iranian government in terms of planning and allocation to potential users. However, water is not rationally priced and it is heavily subsidised as a means to support the domestic agricultural production and the realisation of self-sufficiency in Iran. Moreover, farmers are not allowed to trade water with each other under the current strict water allocations through which water is distributed among farmers on the basis of cropping area rather than volumetric delivery. This suggests that there may be other mechanisms which would allocate water more efficiently to end users (Shajari 2005, Torkamani et al. 1999).

In general, groundwater has an economic value in all competitive applications and so is defined as an economic commodity. The price of water demonstrates its scarcity, and therefore policies on water management are connected to water pricing and market equilibrium. The results of this study indicate that groundwater shortage originates from weak management and inefficient water use. Water pricing is an issue that influences water use inefficiency. In most parts of Iran, the price of water is not determined according to its real worth; the water price in the study area is almost free. In any sector, including the agricultural sector, the price of water is directly related to the costs, of providing water, including the following: investment costs, institutional costs, implementation costs and maintenance costs. The real price of water must show all expenditures that farmers have to pay for accessing groundwater for farming purposes. The shadow price (real price) of water is different from the market price; it stimulates farmers to use groundwater optimally because real prices, which are always higher than market prices, will encourage farmers to use water more economically.

There are many factors that affect water pricing which should be considered when determining the real price of water, but the shadow price is not always considered by policy makers because of the desire to protect the agricultural sector, which means the government has to pay large amounts of water subsidies. Water pricing in Iran is more based on government protection rules than economic rules.

3.4.2.2 Government interventions, insurance policies, and credits

Iran, an arid and semi-arid area country, has a total water exploitation of 66 billion m^3, while water efficiency use is 32%. The agricultural sector currently uses 92% of all water exploited in Iran, but in fact can be maintained with only 21% (Agricultural Ministry of I.R. Iran 2008). The Iranian government contributes 7.5% of financial funding to support/subsidise the agricultural sector; this suggests a low priority attributed by the government to policies in the agricultural sector. It is worth noting that in water resources management and environmental policy, 'water demand management' and its enhancement refers to policies which control consumer demand for scarce and vulnerable water supplies. Therefore, effective water demand management in irrigated agriculture will hopefully lead to significant savings in the water sector.

Based on legislation in the Islamic Republic of Iran, surface water, groundwater, wastewater, seas, lakes, and springs all belong to the central government, and any utilisation of these natural sources should be based on common benefit. Any distribution, leasing, or supervising of water sources are allocated by the Ministry of Energy. The responsibility for water supply in the agricultural sector is allotted to the Agriculture Ministry. Moreover, the government is responsible for the general management of water sources taking into consideration a sustainable development approach in the agricultural sector.

3.4.2.3 Legal and policy frameworks

In a market mechanism, the real price of water is determined by supply and demand, and so there would be an economic efficiency in water utilisation (Shajari 2005). Non-market mechanisms for managing water distribution and allocation can lead to problematic situations in some irrigated agricultural areas.

To use water efficiently, in economic terms, it must be reallocated to its highest value uses. Water markets must be introduced by central governments as a measure to improve, in a decentralised manner, the allocation of water resources among its potential users and to reduce the effects of water scarcity. Thus, the main characteristic that justifies the introduction of water markets is its ability to reallocate water among various uses toward those with more value-added potential, while promoting more rational utilisation of the resource in every use. In Shibkouh County, as with many areas of the country, there is no water market, hence creating trends for inefficient use of groundwater.

In addition to high water use and low efficiency, environmental concerns are usually considered to be one of the main problems of the irrigation sector in Iran and in the study area. For example, excessive diversion of river water for irrigation (and other uses) brings environmental and ecological disasters such as excessive water depletion, water quality reduction, water logging, and salinisation of downstream areas.

High exploitation of groundwater, low productivity in the agricultural sector, and the difficulties of transferring water combined with increasing population growth rates and demand for food all put increasing pressure on water resources, especially groundwater in rural areas. Furthermore, the quality and quantity of groundwater have been decreasing in recent years, as evidenced through the interviews with the local households in the study area. Under these conditions, government interventions and policies from central government may lead to optimal utilisation of water sources. Some of these policies include: legislation for optimal use of water sources, institutional investment, and reform of authority and administration regulations.

Government intervention may ease the balance between supply and demand of water. The key factor to achieving this balance is an authoritative system with the following conditions (Shajari 2009, Shajari et al. 2005): confidence (a clear definition of "right" to water access and water use considering a few indexes such as quantity, quality, situation, and time); possibility of transformation; lack of external impacts; and existence of a competitive market (demand side and supply side). Without these conditions, government interventions are required in order to implement optimal water allocation. In developing countries, there are factors that affect pricing water under competitive conditions such as: external factors, water supplies, incomplete information, legislation, social limitations, and high costs of investment (Doppler et al. 2002, Torkamani et al. 1999). In the study areas and other parts of Iran, the government interferes in order to implement water allocation, but not via real prices. The result is non-optimal utilisation of groundwater with a reduction in both quality and quantity.

In the study area, water management consists of government and non-government management which are related to local development. National management is, on the one hand, connected to local management and local development, and on the other hand, related to macroeconomics and planning policies. In practice, water allocation is usually the combination of the following three patterns: political and institutional indicators such as installation of well contours, technical indicators such as land levelling, and economic indicators such as water pricing.

3.4.2.4 Patterns of water use in relation to existing enforcement practices

The rigidity of the existing arrangements to allocate water is based on cropping area. This, together with regulations which prevent water from being sold or bought at a given market price, result in some farmers using more water than necessary and others who are willing to buy the water but unable to do so. Therefore, the consequence of this policy is increasing demand for water that is not based on price signals, resulting in inefficient water use. It is argued that the rigid government water policy has contributed to the inefficiency of water use.

Based on the national water law, where the government provides water, all expenditures linked to supplying water (costs of management, maintenance, repair, and construction) must be paid by consumers to the government. In most regions of Iran, including in the study area, farmers do not pay for groundwater and its associated costs, and therefore the price of water is close to zero. Undoubtedly, the "free" water leads to overexploitation of groundwater which in turn leads to severe impacts on the quality and quantity of groundwater and the environment. In Iran, farmers must receive permission from the government to dig new wells or deepen old wells and must pay to obtain this permission. Currently, there is no enforcement to prevent the digging of illegal wells and this makes the situation worse, although the government does increase supervision during drought years.

3.4.3 Vulnerability of the socio-ecological system

3.4.3.1 Ecological vulnerabilities linked to groundwater

Depletion of groundwater storage induces changes in the hydrological system. Intrusion of salty water due to drawing down of the aquifers' water table causes changes in the rate and direction of groundwater flow. Lowering of the groundwater levels may also result in the drying up of perennial springs, changes in natural flora and fauna, and biodiversity reductions. The vulnerability of groundwater due to adverse impacts of droughts varies. Some aquifers are more vulnerable than others and as a consequence, some related communities are more vulnerable (Periera et al. 2009). In the Shibkouh region, the following adverse impacts and ecological vulnerabilities linked to groundwater overexploitation are possible:

- decreasing groundwater levels and aquifer storage;
- degradation of groundwater quality due to increasing levels and concentration of pollutants and brackish water intrusion;
- reduction in the discharge of springs which in turn adversely impacts natural flora and fauna in the region;
- reduction in biodiversity of natural flora and fauna;
- changes in the land surface due to subsidence. This event has intensified recently in the neighbouring areas of the Shibkouh;
- increasing energy consumption to compensate for water discharge through deepening production wells and digging new wells which are mostly illegal;
- increasing soil erosion caused by the removal and overgrazing of range plants species. Consequently, floods are extremely turbid, pollute downstream seasonal wetlands, and divert some small streams. However, in some cases, sedimentation of suspended

loads also provides suitable new cultivation areas;

- soil salinisation due to use of inferior water quality which seriously impacts soil quality and degrades native flora and fauna. Extracting degraded groundwater to irrigate farm lands, especially in the north and mid parts of the Shibkouh, has caused a reduction in agricultural production and has led to negative economic impacts for inhabitants; and
- lack of sufficient amounts of groundwater causes lower vegetative cover and enhances surface soil degradation and dispersion. Dust storms followed by soil erosion cause severe health hazards to in habitants.

Fortunately, Shibkouh County's aquifer system does not contain groundwater known as fossil water and can be replenished artificially using FWSS. This replenishment has already been successfully implemented in the GBP, located in the south-eastern part of Shibkouh County.

3.4.3.2 Dependence of ecosystem services on groundwater

Four main categories of ecosystem services can be recognised, including provisioning services, regulating services, supporting services, and cultural services (MA 2005). Many people, especially in rural areas, think that these services are infinite and should be free; unfortunately, as a consequence, they are not well managed at all. Table 3.11 provides an overview of the main groundwater-dependent ecosystem services in the study area based on the four above mentioned categories.

Table 3.11. Dependence of ecosystem services on groundwater in Shibkouh County (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

Ecosystem Services		**Degree of dependency on groundwater in Shibkouh County**		
		Low	**Moderate**	**High**
Provisioning	security, business, food, crops, wild food, fresh water, irrigation water, sanitation			■
Regulating services	climate regulation, carbon sequestration, waste decomposition, air purification, pest and disease control, biodiversity, desertification, poverty,		■	
Supporing Services	nutrient dispersal and cycling, seed dispersal, primary production	■		
Cultural Services	cultural, educational, intellectual and spiritual inspiration, recreational experiences (ecotourism), scientific discovery			■

3.4.3.3 Aquifer recharge and well density

Although the mid region of Shibkouh county, including Zahed-Shahr and Miandeh areas, has a higher population and shows greater well density than the northern part of Shibkouh County (Table 3.12), the groundwater hydraulic gradient is steeper in northern areas (the most vulnerable areas, based on Figures 3.4 to 3.7). The recharge of the aquifer through the ephemeral river's seasonal bed is the main reason for this discrepancy. Farmlands in the northern areas of Shibkouh County are mostly located farther from the seasonal river in comparison with those farmlands in the mid region. Natural recharge of the aquifer in the north is quite low, and as a consequence both groundwater quantity and quality are highly vulnerable. Moreover, the presence of coarse gravels beneath the river bed supports greater recharge of the aquifer for wells and villages located in the vicinity of the river.

The southern part of Shibkouh County has a lower population but greater well density. As mentioned above, the presence of three seasonal rivers and two artificial recharge projects located in the GBP and Bid-Zard provide suitable media underground for both natural and artificial recharge. Greater recharge volume of the aquifer in the southern part of Shibkouh also provides improved water quality. Despite greater well density in the south and mid regions of the study area, the aquifer seems more vulnerable to salty water intrusion in the northern parts of the study area. This is because of the lower recharge in the northern area in comparison with the two other regions

Overuse of chemical fertilisers on farmlands, especially nitrogenous types, followed by heavy spate irrigation, increases leaching of nitrate into the aquifer. A relationship between well density and nitrate pollution in the aquifers of Shibkouh County can be identified. Recycling of polluted groundwater in addition to annual use of fertilisers in farmlands with high well density has caused higher nitrate concentrations in the groundwater of the mid and southern regions of the Shibkouh aquifer (Figure 3.3).

Table 3.12. Registered wells' census in the Shibkouh County (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

Location	Village name	No. of registered Wells	Total No. of wells
North	Senan	12	50
	Fedeshkouyeh	26	
	Kouh-Ghebleh	2	
	Kankan	10	
Middle	Zahed-Shahr	80	168
	Miandeh	46	
	Ghasem Abad	26	
	Koushk-e-Mahkord	4	
	Houseyn-Abad	12	
South	Nasir-Abad	34	176
	Bisheh-Zard	33	
	Bid-Zard	28	
	Tchah-Dowlat	35	
	Rahim-abad	31	
	Ahmad-Abad	15	

3.4.4 Measurement of indicators

3.4.4.1 Hazards

Groundwater quality compared with drinking water standards

The groundwater quality of Shibkouh County for both recharged and non-recharged areas are compared to the baseline standards of the European Union and the World Health Organization (WHO 2004) (Table 3.13). All parameters in the non-recharged areas of Shibkouh County are in higher amounts than the baseline standards and over the safety range when compared with the same parameters of WHO's safe drinking water standards. However, groundwater quality in recharged areas fares better when compared to WHO standards, especially for nitrate as the main pollutant. Despite the existence of safe drinking water pipelines in the more populated villages of Shibkouh County, groundwater is the main source of water for both drinking and irrigation purposes in small and distant villages of the study area. Thus, in the recharge areas, people obtain their drinking water from production wells, which is safer to some extent.

Table 3.13. Comparison of drinking water quality to international groundwater standards (red boxes indicate amounts over range and green boxes indicate safe amounts in relation to WHO standards).

Parameters	Units	WHO[1] (drinking water standards)	European[2] groundwater baseline (mean)	Shibkouh County Groundwater (mean)	
				Non-recharged areas in the GBP	Recharged areas in the GBP
pH	-------	No guideline	7.53	7.37	7.00
DO	mgL^{-1}	No guideline	2.80	4.10	4.25
EC	µS/m	250	1150	**719**	**180**
Ca	mgL^{-1}	No guideline	65.80	266	82
Mg	mgL^{-1}	No guideline	24.40	209	49
Na	mgL^{-1}	200	146	**980**	**235**
K	mgL^{-1}	No guideline	11.40	17	7.41
Cl	mgL^{-1}	250	160	**966**	**171**
SO_4	mgL^{-1}	250	36.40	**1638**	**454**
HCO_3	mgL^{-1}	No guideline	288 (Lab)	348	260
NO_3	mgL^{-1}	50	50	**61.30**	**6.12**
TOC	mgL^{-1}	No guideline	6.02	16.54	1.64
Fe	μgL^{-1}	No guideline	1.35	2	<2
Hardness	mgL^{-1}	No guideline	No guideline	3055	385

[1]Lenntech Water Treatment Solutions, Drinking Water Standards. Available at: http://www.lenntech.com/applications/drinking/standards/drinking-water-standards.htm.
[2]Natural Groundwater Quality (Edmunds and Shand 2008).

3.4.4.2 Exposure

Two main indicators were considered for exposure. The first is percentage of population dependent on groundwater. The results from the discussion with local groups and key informants and the results from interviews with households indicate that 100% of people who live in the study area are directly dependent upon groundwater for farming and drinking water purposes. The second indicator deals with percentage of economic sectors dependent on groundwater. The main sector in the area is agriculture. The results of the present research show that 96% of this sector and also industry and services are dependent upon groundwater for their activities.

Therefore, an occurrence of any disaster will result in high vulnerability, especially in the agricultural sector.

3.4.4.3 Sensitivity

Sensitivity is a measure of the extent to which important outcomes change as a function of climate variation. It is in fact an indicator of elasticity to variable environmental stresses within its coping capacity. There are a few sub-indicators related to sensitivity; each will be explained briefly in this section.

Household dependency

The first sub-indicator describes the household dependency rate of the eight study villages considering the age as an index for dependency. The populations most at risk were studied; namely, those less than 15 years of age (29%) and those older than 65 years of age (6%). Table 3.14 shows the population structure based on age for each village. In total, more than 1/3 of the total population belongs to at-risk age groups. It means that in case of groundwater degradation or drought, 35% of households that are vulnerable may confront more hazards.

Table 3.14. Population structure based on age (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

Village Name	0-14 years		15-64 years		Over 65 years		Total	
	Number	%	Number	%	Number	%	Number	%
Sennan	264	25	1,275	68.8	115	6.2	1,854	100
Miandeh	1,548	28	37,044	67	276	5	5,529	100
Nasir-Abad	565	35	937	58	114	7	1,616	100
Bisheh-Zard	410	6	24	58	238	36	148	100
Chah-Dowlat	229	30	488	64	45	6	762	100
Fedeshkouyeh	1,407	30	2,955	63	328	7	4,690	100
Zahed-Shahr	2,815	28	6,616	65.9	613	6.1	10,039	100
Rahim-Abad	210	34.9	359	59.7	32	5.4	601	100
Total	7,386	29%	16,567	65%	1,547	6%	25,500	100%

Another sub-indicator is population density. In crisis situations such as drought and flood, areas with higher population densities may face more serious problems because of higher water consumption and job diversification. Based on the results of the study, the average population density for the study area is 91 persons/km^2, up to a maximum of 301 persons/km^2

and with a minimum of 13 persons/km^2, in Miandeh and Bisheh-Zard, respectively (Table 3.15). Since villages with higher population densities may face more serious problems because of higher water consumption in case of groundwater degradation or drought, villages such as Senan and Miandeh are in more danger, while Bisheh-Zard and Chah-Dowlat are at less risk.

Table 3.15. Population density (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

Village Name	$\textit{arithmetical density} = \frac{\text{total population}}{\text{total area (km}^2\text{)}}$
Sennan	257
Miandeh	301
Nasir-Abad	25
Bisheh-Zard	13
Chah-Dowlat	16
Fedeshkouyeh	151
Zahed-Shahr	166
Rahim-Abad	24
Average	91

Related to the population structure index is the average number of household members (Table 3.16). In the study area, the average number of household members is 5, with a minimum and maximum of 3 and 6, respectively. As mentioned above, households with higher populations (e. g. Miandeh and Chah-Dowlat) would be more affected by droughts and floods.

Table 3.16. Average number of household members (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

Village Name	Sample Size	Average of household members
Sennan	5	34
Miandeh	6	66
Nasir-Abad	5	18
Bisheh-Zard	3	3
Chah-Dowlat	6	4
Fedeshkouyeh	5	70
Zahed-Shahr	5	150
Rahim-Abad	5	4
Total	5	349

Occupation

In order to analyze this sub-indicator, information such as the number of people per household who are employed or have a second job, as well as the type of employment activity were collected. The results of the study indicate that in 81% of the households surveyed, only the head of the household is employed (Table 3.17). It means that for more than 80% of households, the rate of income is limited and so in case of drought, most households at the study area would be at risk.

Table 3.17. Number of employees per household (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

Village Name	Number of households with employees engaged in 1,2,3, or 4 occupations				Sample Size
	1	2	3	4	
Sennan	29	4	1	-	34
Miandeh	53	8	3	2	66
Nasir-Abad	16	1	1	-	18
Bisheh-Zard	2	1	-	-	3
Chah-Dowlat	-	2	-	-	2
Fedeshkouyeh	51	16	3	-	70
Zahed-Shahr	129	19	2	-	150
Rahim-Abad	3	1	-	-	4
Total	283	52	10	2	347

Agriculture is the main activity in Shibkouh County. However, the eight villages surveyed showed different levels of engagement in agricultural activities. For instance, in Zahedshahr, the main activity of households is agriculture (99.3%) due to the high rates of rainfall; whereas in Fedeshkoyeh, Miandeh, and Senan agricultural activities account for less than 50% of household employment (Table 3.18). Therefore, in case of drought, the households who live in Cheh-Dowlat and Zahed-Shahr are more in danger, since they completely depend on the agriculture sector.

Table 3.18. Agriculture as the main activity for households (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

Village Name	Is agricultural your main activity?					
	YES		NO		TOTAL	
	Number	%	Number	%	Number	%
Sennan	15	100	34	58.9	19	41.1
Miandeh	31	100	66	53	35	47
Nasir-Abad	10	100	18	44.5	8	55.5
Bisheh-Zard	2	100	3	33.3	1	66.7
Chah-Dowlat	3	100	3	-	-	100
Fedeshkouyeh	22	100	70	68.6	48	31.4
Zahed-Shahr	149	100	150	0.7	1	99.3
Rahim-Abad	2	100	4	50	2	50
Total	234	100%	348	33%	114	67%

The surveys indicate that all households engage in some non-agricultural activities. The studies showed that men are mostly engaged in agriculture/animal husbandry, with the exception of Miandeh village where men are also employed as drivers and as unskilled workers. The surveys showed that women are mainly engaged in carpet weaving.

Household wealth ranking

Based on the results of the household questionnaires, the wealth ranking of households in Shibkouh County is indicated in Table 3.19. Wealth ranking is determined by the financial conditions of households. Therefore, households with more equipments and facilities are wealthier. Based on this table, households either fall under average, poor, or very poor categories; no household is in the wealthy category. As we will see in section 3.5, a higher rate of vulnerability corresponds to a higher rate of poverty in Shibkouh County.

Table 3.19. Wealth ranking (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

Village Name	Wealth ranking of households
Sennan	average
Miandeh	average
Nasir-Abad	average
Bisheh-Zard	very poor
Chah-Dowlat	poor
Fedeshkouyeh	average
Zahed-Shahr	average
Rahim-Abad	poor

Access to savings/credits

Access to savings/credits is essential for households confronted with crisis situations. The survey results revealed that almost all households had no savings and all declared that they used governmental banks' credit for their agricultural and non-agricultural activities. There were no reported cases of access to credit via cooperatives, the private sector, or via kinship.

Duration of settlement in the area

The length of time that households have settled in the area is considered a proxy for the household knowledge of the environment and corresponding risks in the village. In the eight villages, the range of years since settlement was 43 to 54 years with an average of 49 years. The longer a household has been settled in an area may have positive impacts on the voluntary behaviour of households, since it motivates them to deal with crisis situations. In fact, over a longer period of time, households are able to motivate themselves to deal with crises such as droughts and floods.

Health status and social problems

In the study area, drought and low groundwater quality are associated with a few diseases such as Aleppo boil (Leishmaniasis). In some villages, the severe poverty which is caused by drought has resulted in malnutrition among women and children. Furthermore, the results of the field research using qualitative techniques indicate that low quality and quantity of groundwater is associated with social problems in the area such as drug addiction, smuggling, and robbery.

3.4.4.4 Resilience

Access to alternative sources of water

Alternative sources of water in the county are confined to very few perennial springs, with less than 2-3 L/sec discharge, located in the mountainous areas and far from populated regions. These sources of water are mainly used for animal herds which feed from range plants. The quality of these alternative water sources degrades during drought seasons, developing a brackish taste.

Access to information on groundwater degradation

The results from the household questionnaires concerning access to knowledge on groundwater degradation are shown in Table 3.20. Based on this table, more than 1/3 of households do not have access to information on groundwater degradation. Table 3.21 shows the ways that people have access to information on groundwater degradation. Based on this table, 45% of households declared that access to information is through television (TV), while 36% have no access to information on this topic. In general, it is possible to conclude that villages who are more informed on groundwater degradation would be less vulnerable as compared to other areas with no information on the subject.

Table 3.20. Access to information in the eight surveyed villages (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

Village Name	Access to information about groundwater degradation processes					
	YES		NO		TOTAL	
	Number	%	Number	%	Number	%
Sennan	22	64.7	12	35.3	34	100
Miandeh	39	59	27	41	66	100
Nasir-Abad	4	22.2	14	77.8	18	100
Bisheh-Zard	1	33.3	2	66.7	3	100
Chah-Dowlat	-	-	3	100	3	100
Fedeshkouyeh	56	80	14	20	70	100
Zahed-Shahr	100	66.7	50	33.3	150	100
Rahim-Abad	2	50	2	50	4	100
Total	224	64%	124	36%	348	100

Table 3.21. Ways of accessing information about groundwater degradation (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

Village Name	Ways of accessing information about groundwater degradation									
	TV		Radio		Neighbour		No access		Total	
	No	%	No	%	No	%	No	%	No	%
Sennan	14	41.2	2	5.9	6	17.6	12	35.3	34	100
Miandeh	30	45.4	5	7.6	4	6	27	40.9	66	100
Nasir-Abad	3	16.7	1	5.5	-	-	14	77.8	18	100
Bisheh-Zard	1	33.3	-	-	-	-	2	66.7	3	100
Chah-Dowlat	-	-	-	-	-	-	3	100	3	100
Fedeshkouyeh	54	77.1	-	-	2	2.9	14	20	70	100
Zahed-Shahr	51	34	29	19.3	20	13.3	50	33.4	150	100
Rahim-Abad	2	50	-	-	-		2	50	4	100
Total	155	44.5%	37	10.5%	32	9%	124	35.5%	348	100%

Coping strategies in response to possible groundwater degradation

In response to a question on how they would respond to groundwater degradation, close to 50% of households indicated a reduction in cultivated areas as their response, while 27% indicated they would change the crop pattern (Table 3.22).

Table 3.22. Type of decision-making in response to groundwater degradation processes (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

Village Name	Type of decision-making in response to groundwater degradation									
	Change type of crop		Reduce area of cultivated land		Find another job		Migration		Total	
	No	%	No	%	No	%	No	%	No	%
Sennan	15	15	9	26.5	6	17.6	4	11.8	34	100
Miandeh	13	13	30	45.4	15	22.7	8	12.1	66	100
Nasir-Abad	5	5	7	38.9	3	16.7	3	16.7	18	100
Bisheh-Zard	2	2	1	33.3	-	-	-	-	3	100
Chah-Dowlat	-	-	3	100	-	-	-	-	3	100
Fedeshkouyeh	16	16	19	27.1	17	24.3	18	25.7	70	100
Zahed-Shahr	41	41	102	68	4	2.7	3	2	150	100
Rahim-Abad	2	2	2	50	-	-	-	-	4	100
Total	94	94	173	50%	45	13%	36	10%	348	100%

Out-migration

During the last decade, out-migration has become a response to groundwater degradation. Out-migration occurred in six of the eight villages surveyed. This is associated with unemployment linked to groundwater degradation.

Participation in social networks for common goals

Participation in social networks such as local organisations, production cooperatives, and micro financing funds may be considered as an option to coping with a crisis such as drought or groundwater degradation. The results in Table 3.23 show that there is a low participation of rural households in social networks due to low levels of awareness and/or a lack of faith in collective activities, and therefore a low chance for coping with the emergency situations.

However, when households were asked about their participation in common goals, such as confronting drought and groundwater degradation or establishing local financing funds, the response indicted an average rate of participation of 59% (Table 3.24).

Table 3.23. Level of household membership in a society or group (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

Village Name	**Membership**					
	YES		**NO**		**TOTAL**	
	Number	%	Number	%	Number	%
Sennan	-	-	34	100	34	100
Miandeh	7	10.6	59	89.4	66	100
Nasir-Abad	14	77.8	4	22.2	18	100
Bisheh-Zard	-	-	3	100	3	100
Chah-Dowlat	1	33.3	2	66.7	3	100
Fedeshkouyeh	14	20	56	80	70	100
Zahed-Shahr	15	10	135	90	150	100
Rahim-Abad	1	25	3	75	4	100
Total	52	15%	296	85%	348	100

Table 3.24. Household participation towards common goals (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

Village Name	Level of Participation					
	HIGH		VERY LOW OR NONE		TOTAL	
	Number	%	Number	%	Number	%
Sennan	19	55.9	15	44.1	34	100
Miandeh	21	31.8	45	68.2	66	100
Nasir-Abad	16	88.9	2	11.1	18	100
Bisheh-Zard	2	66.7	1	33.3	3	100
Chah-Dowlat	1	33.3	2	66.7	3	100
Fedeshkouyeh	30	42.9	40	57.1	70	100
Zahed-Shahr	113	75.3	37	24.7	150	100
Rahim-Abad	3	75	1	25	4	100
Total	205	59	143	41	348	100

3.5 Discussion and Synthesis

Shibkouh County is an arid region where inhabitants have tolerated and coped with dry conditions for a long period (Lee and Schaaf 2008) in addition to being exposed to severe droughts over the last three decades. Drought, which is considered to be a temporary condition of natural water scarcity and may occur in all climatic zones and differs depending on zones of aridity (Priera et al. 2009), has made intolerable and non-renewable changes to the fragile ecosystems. Shibkouh County has experienced a combination of "meteorological drought", "agricultural drought", "water resources drought", and "economic drought", in which the water resources are insufficient to sustain local income-producing and recreational activities.

The groundwater in Shibkouh County is mostly dependent on recharge from seasonal floodwaters emanating from watersheds, and thus has been highly vulnerable to the more frequent droughts that have been occurring in the past decades. Farming areas irrigated with groundwater from the aquifers was subjected to soil degradation due to saline water intrusion into the alluvial aquifer, especially in northern and mid regions of the study area. Enterprises and activities in Shibkouh County which may be significantly impacted by drought are summarised in Table 3.25.

Table 3.25. Drought impacts on Shibkouh's main assets.

Drought impacts on Shibkouh's main assets		
Economic	**Environmental**	**Social**
Agriculture 1) Rain-fed crops suffered/failed 2) Irrigated crops decreased 3) Forestry suffered 4) Low-fertile soil increased 5) Pasture lands degraded 6) Apiculture suffered	1) Water quality degraded 2) Flora & fauna suffered 3) Wind erosion increased 4) Forest fires increased 5) Wildlife suffered 6)Biodiversity suffered	Urban/Rural 1) Access to water decreased 2) Households suffered 3) Water supply decreased 4) Landscape degraded 5) Recreation suffered 6) Health decreased
Industry 1) Agro-industries suffered 2) Water industry suffered 3) Tourism failed 4) Commerce suffered 5) Handicrafts suffered		Society 1) Farm incomes reduced 2) Unemployment increased 3) Reduced taxes 4) Livelihood suffered 5) Poverty/hunger increased 6) Conflicts increased

The environmental impacts of prolonged droughts in Shibkouh relate to, among others, a decrease in water quality, in which the concentration of salts and agricultural contaminants such as nitrate are increasingly present in groundwater. These conditions are aggravated by long periods of droughts.

Desertification, which has become a prominent environmental issue, can be considered the second consequence of social and environmental vulnerabilities to groundwater degradation in Shibkouh County. Environmental factors contributing to desertification vulnerability in Shibkouh County are provided in Table 3.26.

Table 3.26. Environmental factors contributing to desertification vulnerability in Shibkouh County.

Environmental factors contributing to vulnerability to desertification in Shibkouh County			
Climate	**Soil resources**	**Vegetation**	**Land and water**
Droughts Low and poorly distributed rainfall High evapotranspiration Wind storms Climate change	Poor soil productivity Water and wind erosion Low water holding capacity Salinisation	Fragile vegetation Risk of fire Vulnerability to climate change	Groundwater overdraft Degraded water quality Poor land use Misuse of land resources

It is important to emphasise the conclusion that groundwater is an incredibly valuable commodity in Shibkouh County, but that it is also the most limiting factor for the sustainable management of such dry ecosystems. Water insecurity represents a powerful risk factor for poverty and vulnerability which becomes twice as important in Shibkouh, where the inhabitants solely depend on a water-based economy for their livelihood. Consequently, water harvesting through implementing Aquifer Management Projects (AMP) is highly recommended to alleviate water shortages and human insecurity in that area (Lee and Schaaf, 2008). Positive effects of this intervention are still tangible in the southern part of Shibkouh, where Bisheh Zard Basin is located.

Socio-economic considerations

The main objective of this project was to study the impacts of groundwater degradation on human security in relation to social and economic aspects. It was further expected to identify the social groups and economic sectors that are exposed to the risks of decreasing quality and quantity of groundwater. The results of the research indicate that households in the area are highly dependent on groundwater for drinking, and so any reduction in quality may have serious impacts on their health. In addition, there is little or no job diversification in the study area. As agriculture is the main activity which is highly dependent on groundwater, any reduction in quantity and quality of groundwater will tend towards job losses and reductions in the main sources of household revenue. The results show that although all people in the study area may be negatively impacted by groundwater degradation, the elderly, women, and children are more at risk. The results of the field survey indicate that in more than 80% of households, with an average of five people in each household, there is only one person employed. Most of the population is at best poor, and so they are vulnerable to deteriorating environmental and social conditions. Most households have no savings, and the main source of financing is credit from the Agricultural Bank, with limitations on the amount of credit available and on the loan periods.

The results of the field research also point towards an increasing rate of disease and crime in the area due to a reduction in quality and quantity of groundwater. Groundwater degradation has serious impacts on the welfare of farmers by reducing their incomes; hence, the high rate of poverty in the area results in an increase in crimes such as smuggling and robbery. Disease prevalence has also increased as a result of poverty associated with droughts. With regards to access to information, the research indicates a relatively high rate of access to information on reduction in groundwater quantity. The survey respondents indicated that when faced with groundwater degradation, they will change crop pattern or may reduce the area under cultivation. They also may change their jobs or migrate to other rural areas in the city or countryside. The low membership rate in NGOs and participation towards common goals may indicate a risk of a lack of adequate coping strategies in crisis situations.

In general, the findings of the research indicate that a reduction in the quality and quantity of groundwater would be a serious challenge for rural households in Shibkouh County, and also for governors and local cooperation. A long-term and continuous control and monitoring system is needed to reduce the destructive impacts of groundwater degradation.

Based on Figure 3.9, Shibkouh County is divided into three main socio-economic areas, which are detailed in Table 3.27. With the exception of population growth rate, the rate of all indicators in regions A, B, and C are high, moderate, and low, respectively. For instance, when it is mentioned that the "rate of having a second job" in Region A is high, it means that in this region, compared to Regions B and C, the percentage of households with a second job is higher. Similarly, "wealth" in Region C is low, means that at this region the households are poorer. The main point of this study is comparing Figures 3.8 and 3.9. In fact, Regions A, B, and C in Figure 3.8 are very similar to the regions of high, moderate, and low vulnerability indicated in Figure 3.9. The decreasing rates of vulnerability from high to low in Figure 3.9 correspond to the decreasing rate of the socio-economic indicators, such as immigration rate, rate of access to information, wealth, and education. For instance, this means that Region A in Figure 3.9 matches with the region shown with a red circle in Figure 3.8. Therefore, a region with a high vulnerability has a higher rate of migration, access to information, education, rate of having second job, and rate of insurance coverage which all are related directly to vulnerability. This is also to mention that the main part of A is an urban area and the main job of households is not agriculture, so the rate of education and wealth in this area is high. Similarly, Regions B and C in Figure 3.9 match with regions which are shown with yellow and blue circles in Figure 3.8, respectively. It means that a region with a moderate and low vulnerability have moderate and low rates of the mentioned parameters respectively. In general we conclude that there is a relationship between rate of vulnerability and rate of socio-economic indicators in most regions.

Figure 3.9. Socio-economic map of Shibkouh County (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

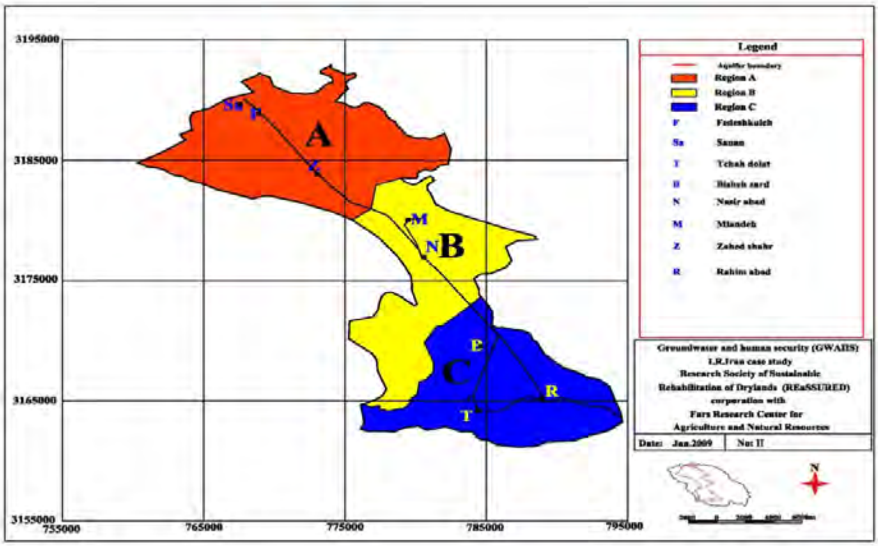


Table 3.27. Socio-economic vulnerability of Shibkouh County (Field research findings, Iran, Fars province, Fasa, Shibkouh County, 2009).

Indicators \ Region	A	B	C
Rate of having second job	High	Moderate	Low
Rate of occupation of household members	High	Moderate	Low
Immigration rate	High	Moderate	Low
Population growth rate	Low	Moderate	High
Population Density	High	Moderate	Low
Wealth	High	Moderate	Low
Rate of Insurance Coverage	High	Moderate	Low
Rate of access to Information and Participation	High	Moderate	Low
Education	High	Moderate	Low

3.6 Policy Implications and Recommendations

Iran is endowed with 42 million hectares of land covered with coarse-grained alluvium aquifers of good quality, ranging from 10 to 1,000 m in depth, with a coefficient of yield from 2-35%. Taking the mean depth and coefficient of yield at 100 m and 10%, respectively, 4,200 km^3 of water can be stored underground, equivalent to 10 times the country's mean annual precipitation. Furthermore, assuming zero population growth and water consumption equal to that of 2006, Iran can sustain a 40-year drought without being deprived of water if this subterranean reservoir is used (Kowsar 2008). Implementation of a national aquifer management concept in Iran to the largest possible extent is strongly recommended as a resilience tool to alleviate both social and environmental insecurity. Reverse migration into the GBP began in 1980 when the AMP was implemented; it has proven its effectiveness via the empowerment of the inhabitants to be self-supporting with the ability to sustain a livelihood in an abandoned desert (Mesbah et al. 2015).

In recent years, policymakers in drylands consider climate change as a threat. Thus, local and national policies concerning economic, social, and environmental investments built in response to these challenges. Nevertheless, the challenges of sustainable development in deserts such as Shibkouh County will need to include the potential impacts of climate change. Assuming that this phenomenon will increase the incidence of droughts and floods, the aquifer management projects will therefore play an important, if not vital, role in water resources strategies.

Increasing water use efficiency through scientific farm management and laser land levelling, which is highly pursued in Iran, positively affects the income of inhabitants and their social security in Shibkouh County. There is a need to seek new sustainable views on drylands and their security using "minimum groundwater dependent" policies. Developing handicrafts at household levels, apiculture, carpet weaving, greenhouse cultivation, improved traditional animal husbandry, collection of medicinal herbs, and processing are all types of income generation which can reduce pressure on groundwater resources.

In fact, from their experiences living in drylands, policymakers in the drylands should be ecologists par excellence, or, should genuinely seek local advice and knowledge (Kowsar 2008). An ecologist policymaker bases his/her ambitions for development on the sustainability of the available sources taking into account extreme climatic phenomena such as prolonged droughts and unusual flooding.

It seems that further attention should be placed on the implementation of water demand policies as an essential solution to problems such as environmental concerns, and water quality and quantity reductions, which are the main focus of this study. Such water demand policies should offer incentives for water conservation and resource reallocation in the direction of high value uses in agriculture.

3.6.1 Recommendations

Below are a few recommendations for the sustainable production, exploitation, consumption, and management of groundwater that have emerged from this study:

- determine a quota for water consumption;
- increase productivity in terms of water exploitation;
- re-evaluate water pricing;
- promote farmer participation;
- reduce the costs of water exploitation;
- invest in infrastructures;
- stimulate income generation from non-agricultural activities;
- introduce privatisation of water management;
- approve new rules for water exploitation;
- utilise wastewaters;
- achieve an equilibrium in the supply and demand of water in the agricultural sector; and
- control water pollution.

Groundwater policies should be evaluated at the following levels: local, national, project, and in the private sector.

In general, it is suggested that government policies related to groundwater in the study area should take into account the following:

1) Optimal allocation of water sources using development projects and spatial planning in watersheds.
2) Consideration of watershed boundaries as an important factor in local and provincial sustainable development plans.
3) Use of institutional and non-institutional activities; shift the position of crisis in groundwater to an equilibrium situation by controlling groundwater exploitation.
4) Increase the share of exploitation of surface water with respect to groundwater to achieve an equilibrium condition.
5) Improve the structure of groundwater utilisation by establishing an optimal pattern using new methods of watering.
6) Determine the real price of water in the area.
7) Strengthen the role of rural people and local organisations.
8) Modify the groundwater management and water quantity and quality assessment by collecting base information about water sources.
9) Cultural reform in water utilisation by introducing an optimal pattern.

10) Reorganisation of the utilisation of saline and wastewater sources.
11) Prepare an applied pattern for management of drought and flood.

Alternative sources of freshwater

Control and management of run-off emanating from watersheds as the sole source of surface water in the Shibkouh region seems inevitable. Flood-irrigated farming of barley and wheat has already been a common practice in the area, which is still partially useful in restricted parts of the region. As water use efficiency is quite low in Shibkouh County, increasing the efficiency might be a very useful tool to enhance water savings through the following practices:

1) Modern irrigation methods such as pressurised systems may increase water efficiency from 30% at present, to at least 60% in the farm fields of the study areas.
2) Water transfer canals from wells to the farms are mostly formed by soil with a very low efficiency rate equal to 30-40%. Using new pipelines or sealing their bed by cement may be useful in this regard.
3) Precision land levelling using laser-equipped instruments would facilitate better water distribution in the farms and also increase agricultural production.
4) Lack of any restrictions on groundwater extraction causes overexploitation of this vital source of water in the area. According to new rules, all production wells should be equipped by water meters to prevent any wastage or excessive use of groundwater.
5) A switch from current agricultural patterns which use high water-consuming plants, such as maize, to low water-consuming species and more drought-resistant plants would lessen demand for water and help ease pressure on groundwater resources.
6) Developing glasshouses or other protected cultivations would help to prevent large amounts of water use in open fields, resulting in better management of groundwater resources in the Shibkouh region.
7) Super absorbents are being used in high amounts, especially in glasshouse cultivations, to increase irrigation interval periods.
8) Water desalination using solar energy systems may provide new sources of water using brackish and degraded sources of water in Shibkouh, which has the benefit of receiving high levels of sunlight.

Pricing policy

Historically, in most countries, water costs have largely been, or still are, subsidised. In other countries and also in Iran, water is supplied for free. It is of importance to establish rate policies that emphasise greater user involvement in water conservation and saving. When users are charged appropriately for water services and these perform well, the water use, as well as the level of water wastage tends to decrease. In general, price should be related to consumption. There is often a desire to impose fixed standard charges in order to guarantee income to the water provider, but these generally do not assist in the conservation of water, and in fact, they may encourage wasteful use. Users must be billed correctly and be informed of the amount of their consumption. Increases and adjustments in prices must be clearly linked with the costs of water services. If they are not, prices may become subject to external influences (e.g. the need to raise tax revenue) and fail to be accepted by the consumers. In such cases, the consumers may react negatively to water saving programmes. In other words, water pricing must take into account the feasibility of the water user activities, and not lead them to be abandoned due to exaggerated costs.

The general results of the field study in Shibkouh County indicate a crisis situation, and continuing droughts will have serious impacts on rural households. The following policies may help to prevent, or at least decrease, the rate of destructive impacts of drought and groundwater degradation:

- government financial supports (i.e. loans with low interest rates and direct payments during droughts);
- income generation and job diversification;
- investment in infrastructure (i.e. rural roads, electricity, and canals);
- training and promotion about optimal and efficient use of groundwater;
- empowering local cooperation such as production, rural, and micro-finance cooperation;
- health care (i.e. vaccination, establishing rural clinics, and training);
- diversification of credit sources for farmers;
- determining the real price of water extraction/use/consumption;
- increase access to information on groundwater at the national and village level;
- promotion of efficient irrigation systems;
- establishing an organisation to study vulnerability in crises such droughts and floods; and,
- land levelling and land consolidation.

3.7 Capacity Development Programmes and Further Research

Establishing local NGOs to empower rural inhabitants to manage their own vital assets in Shibkouh is essential. However, people need to be informed of what is happening around them and in the world, including climate change and global warming, as people will be forced to deal with more water shortages and social insecurity in the face of these phenomena. In this way, loans and other funds from government and worldwide organisations in the area should be channelled towards increasing public awareness. Constructing big dams, if even possible, is not a priority in the Shibkouh County due to technical geological problems. Therefore, floodwater harvesting based on experience to recharge groundwater sources is a top priority.

People empowerment and water harvesting are two main results obtained in the first phase of the Sustainable Management of Marginal Drylands (SUMAMAD) project implemented in the Shibkouh County (Lee and Schaaf 2008). Floodwater harvesting by local NGOs should be of utmost concern to both decision makers and inhabitants in Shibkouh County in order to achieve a sustainable and secure sense of well-being. The presence of the Kowsar Floodwater Spreading and Aquifer Management Research, Training and Extension Station in Shibkouh provides a unique opportunity for exchanging traditional and scientific knowledge between inhabitants and academic scientists and researchers to achieve a combination of groundwater management and human well-being.

A link between the 2nd phase of the SUMAMAD project and a developed Groundwater and Human Security (GWAHS) model for Shibkouh County is strongly suggested as further research in the area. In addition to the present research, there are further useful activities that may be carried out in the future, including:

- exploring opportunities for job diversification and income generation in Shibkouh County;
- developing and implementing a comprehensive negotiated groundwater management plan;
- investigating opportunities to empower local cooperation to face future environmental crises;
- developing and applying a mathematical model to estimate all variables affecting human security in Shibkouh County; and
- forecasting the fluctuation of groundwater levels using statistical models.

3.8 References

Agricultural Ministry of I.R. Iran, Statistics Department, Annual Report, 2008

Bauld J. 1994. Groundwater contamination and control., Marcel Dekker Inc.: New York

Chambers and Blackburn. 1996. The Power of Participation, PRA and IDS Policy Briefings, Institute of Development Studies, University of Sussex, Brighton

Doppler W, Salman AZ, Al-Karablieh EK and Wolff HP. 2002. The impact of water price strategies on the allocation of irrigation water: the case of the Jordan Valley. Agricultural Water Management 55:171-182

Edmunds WM and Shand P (eds). 2008. Natural groundwater quality. Blackwell Publishing, Ltd, Oxford, UK

Flite III OP, Shannon RD, Schnabel RR and Parizek RR. 2001. Nitrate removal in a riparian wetland of the Appalachian Valley and Ridge Physiographic Province. Journal of Environmental Quality 30:254-261

Fars Groundwater Authority. 2011. Central grounds water data set. Fasa Water Office, Ministry of Energy of Iran

Kowsar SA, Mortazavi SM and Niazi Ardekani M. 1996. Eight -year performance of Eucalyptus camaldulensis in water spreaders in a sandy desert. Desert. Cont. Bull. (UNEP) 29:35-41

Kowsar SA and Pakparvar M. 2004. Assessment Methodology for Establishing an Aquitopia, Islamic Republic of Iran. In: Schaaf T and Lee C (eds). Proceedings of the 2nd International Workshop, Sustainable Management of Marginal Drylands (SUMAMAD), Shiraz, I.R. Iran, 29 November–2 December 2003. MAB Dryland Series No.3. UNESCO, Paris, pp. 40-55

Kowsar SA. 2005. Abkhandari (Aquifer Management): a green path to the sustainable development of marginal drylands. Journal of Mountain Science 2:233-243

Kowsar SA. 2008. Gareh Bygone Plain, Islamic Republic of Iran. In: Lee C and Schaaf T (eds). Sustainable Management of Marginal Drylands: Using Science to Promote Sustainable Development. SUMAMAD Project Findings from Northern Africa to Asia. UNESCO, Paris, pp. 105-125

Lee C and Schaaf T. 2008. Sustainable management of marginal drylands: using science to promote sustainable development. Project findings from Northern Africa to Asia. UNESCO, Paris. p 264

Lin N. 1977. Foundation of social research. McGraw Hill, New York

MA (Millennium Ecosystem Assessment). 2005. Ecosystems and human well-being: synthesis. Washington DC: Island Press

Maliva R and Missimer T. 2012. Aridity and drought. In Arid lands water evaluation and management Springer Berlin Heidelberg, pp. 21-39

Mesbah SH, Mohammadnia M and Kowsar SA. 2015. Long-term improvement of agricultural vegetation by floodwater spreading in the Gareh Bygone Plain, Iran. In the pursuit of human security, is artificial recharge of groundwater more lucrative than selling oil? Hydrogeology Journal 24(2):303-317

Mohammadnia M. 2010. Nitrate in groundwater: transport, attenuation and phytoremediation. Lambert Academic Publishing AG & Co. KG, Germany, p 208

Mohammadnia M and Kowsar SA. 2010. Eucalyptus Camaldulensis Dehnh: An Effective Remediator of Geologic Nitrogen in Ground water. In: Laughton RH (ed). Aquifers: Formation, Transport and Pollution. Nova Publishers Inc

Mohammadnia M, Fauziah Ishak C, Kanif Yosup M, Abu Bakar R and Kowsar SA. 2005. The Role of Eucalyptus camaldulensis Dehnh. Forest as a Nitrate Filter Zone in the Gareh Bygone Plain, Iran. In: Mousavee SF, Hajabbasi M and Kalbasi M (eds). Proceedings of the Human Impacts on Soil Quality Attributes, Isfahan Iran, 12 – 16 September 2005. IUT, Isfahan

Pakparvar M. (2015). Evaluation of floodwater spreading for groundwater recharge in Gareh Bygone Plain, southern Iran (Doctoral dissertation, Ghent University)

Periera LS. Cordery I and Iacovides I. 2009. Coping with water scarcity: addressing the challenges. IHP-VI-Technical Documents in Hydrology, Publication No. 58. UNESCO, Paris

Shajari S. Bakhshoodeh M and Soltani GR. 2005. Water use efficiency in wheat production under risky conditions in Iran, 5th International Conference of Asian Society of Agricultural Economists

Shajari S. 2009. irrigation water demand management, public participation and decision support systems in Doroodzan Dam irrigated areas. International Drought Conference, Shiraz University, Shiraz, Iran

Shajari S. 2005. Enhancing agricultural water productivity in MENA countries through adoption of improved irrigation technology under production risk: a case study. Economic Research Forum, 12th Annual Conference Egypt

Sakadevan B, Maheshvari L and Bavor HJ. 2000. Effluent irrigation and nitrogen availability in an agricultural soil. In: Proceedings of 2000 Nat. Conf. Exhibition., Water Essential for Life, Melbourne. 23-25 May 2000

Sparks DL. 2003. Environmental Soil Chemistry, San Diego, Ca: Academic Press

Statistical Center of I.R. Iran, Census Report, 2006

Torkamani J, Soltani GR and Asadi H. 1999. Effects of water price on optimum consumption of water. Journal of Agricultural Science and Technology 13(2):43-59

World Health Organization. 2004. Guidelines for drinking-water quality: recommendations (Vol. 1). World Health Organization

GWAHS-Iran Project Team Contact Details

Mohammadnia, Mehrdad (Team Leader)
Fars Research Center for Agriculture and Natural Resources
mmohammadnia40@hotmail.com

Chabokrow, Gholamreza (Team member)
Fars Research Center for Agriculture and Natural Resources
chabokrow@gmail.com

Kowsar, Seyed Ahang (Team member)
Research Society for sustainable rehabilitation of Drylands
kowsar@farsagres.ir

Ravanbakhsh, Mohammad Hossein (Team member)
Shiraz University, Iran
mhravanbakhsh@yahoo.com

Ghahhari Gholamreza (Team member)
Fars Research Center for Agriculture and Natural Resources
Ghahari@farsagres.ir

Majedi Seyed Masoud (Team member)
Fars Research Center for Agriculture and Natural Resources
majedi@farsagres.ir

Houseini Hamid (Team member)
Fars Research Center for Agriculture and Natural Resources
Houseini@farsagres.ir

CHAPTER 4

Tra Vinh Case Study – Vietnam: Vulnerability of Coastal Communities to Groundwater Depletion

Nguyen Van Sanh, Le Canh Dung and Vo Van Tuan

Mekong Delta Development Research Institute, Can Tho University, Can Tho, Vietnam

4.1 Main Challenges of the Case Study Area

The Mekong River Delta in Vietnam is the largest agriculture and aquaculture production region. As the furthest downstream region of the Mekong River bounded by both the East Sea (South China Sea) and the Gulf of Thailand, the Delta forms a large tropical wetland (Tuan and Wyseure 2007) (Figure 4.1). The bulk of the land in the Delta is just 2 m above mean sea level (Wassman et al. 2004). Historically and practically, the people have settled along the river and canal banks. Human life, agricultural and aquaculture production as well as domestic water supply in the Delta depend greatly on the changing water regime of the Mekong River. There are only two seasons in the Mekong Delta: the rainy season and the dry season. Due to the effect of the tropical monsoon, flood flows in the rainy season are about 25-30 times greater than dry season flows which occur between March and April (Öjendal 2000).

The Mekong Delta is known as the "rice bowl" of Vietnam. The Delta has a population of 20 million inhabitants living on 4 million hectares of land (Sanh et al. 1998, Be et al. 2007). The people living in the Delta depend completely on the water resources (mainly the surface waters of the Mekong River) for drinking and domestic purposes, crop irrigation, fish and shrimp farming, transportation of goods, and industrial production. As a general rule, any increase in industrial and agricultural activity upstream may affect water quality in downstream areas.

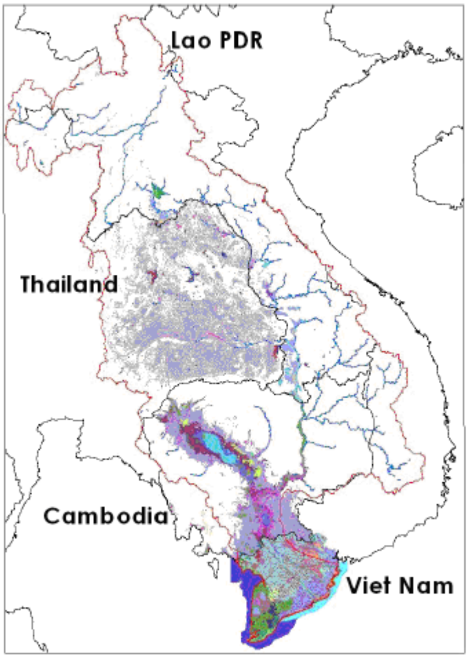


Figure 4.1. The Lower Mekong River Basin and the Mekong Delta (Source: MRC 2006).

Like many other regions in Vietnam, the Mekong Delta is confronted with severe water-related problems, of which pollution, drought, and flooding are increasingly becoming worse. Realising that the health of the people is one of several factors ensuring the sustainable development of the country, the Vietnamese government and international development agencies have implemented many water supply and environmental sanitation programs.

According to GSO (2013), about 98.1% of inhabitants in urban areas and 87.9% in rural areas in Vietnam had access to hygienic water. In recent years, several drinking water plants and wells have been built; however, most of them are located in cities, small towns, and suburban areas. In distant rural areas, farmers still access water directly from rivers, canals, ponds, or shallow wells. In Tra Vinh Province of the Mekong Delta, there is a high level of dependence on groundwater resources for both domestic and agricultural purposes. There is an overexploitation of groundwater with use estimated at approximately 65,000 m^3/day. This is leading to high competition amongst groundwater users for their daily activities including irrigation of crops, shrimp farming and processing, livestock production, and industrial development and services. The reduction in both quality and quantity of groundwater resources is a significant problem for sustaining people's livelihoods in the coastal Mekong Delta.

Climatic change is likely to result in higher water flow peaks in the flooding periods and higher air temperatures in the dry seasons. If the sea level rises 1m by 2050, the Delta may lose 31% of its land and damage around of 26.7% of its population (MONRE 2009). These adverse impacts could affect water resources and result in a socio-economic and environmental crisis in the Delta unless predictive and preventative measures are taken. Consequently, groundwater use will be a key issue for the socio-economic development of the Mekong Delta.

This study focuses on groundwater issues in two communes of Tra Vinh Province located in the Mekong Delta, Vietnam. The research was conducted in the Cau Ngang district of Tra Vinh province (Figure 4.2). This district regularly experiences drought, and groundwater resources are used for both domestic consumption and agricultural purposes. Increasing pressure is being put on the groundwater resources through pollution and salinity intrusion.

4.2 Description of the Case Study Area

4.2.1 Agro-ecological zones in the study area

The Tra Vinh sites in this study are representative of two of the seven agro-ecological zones of the Mekong Delta, namely the coastal zone areas and Ca Mau Peninsula (Sanh et al. 1998). The coastal zone occupies an area of about 600,000 ha. Agriculture depends on rainwater. Recently, the production of saline water shrimp has been rapidly increasing, however, this practice is now shifting to rice-shrimp farming systems. The Ca Mau Peninsula covers an area of about 800,000 ha of permanent and seasonally saline-affected soils, presenting a rich zone of mangroves and various rice-based farming systems under rain-fed conditions. Saline water shrimp production has also been rapidly developing, however, the monoculture of shrimp farming is now shifting towards the rice-shrimp farming system. The remaining zones of the Delta include the fresh water alluvial zone, the Plain of Reeds, The Long Xuyen-Ha Tien quadrangle, the Trans-Bassac Depression, and the high terraces (Sanh et al. 1998).

4.2.2 Physical conditions

The Mekong Delta was formed in the time between the Old-Tertiary Period of the Cenozoic (tens of millions of years ago) and the Pleistocene period

(Chiem 1993). Later, in the Recent (or Alluvial Epoch: 5,000 to 6,000 years ago) of the Quaternary Period, the Indochina region was affected by global sea expansion, and most of the present Mekong Delta was submerged. After this period, the Mekong Delta developed with rich sedimentation from the upper regions (Hori 1996). The depth of alluvial soil has a very wide range in the Mekong Delta, from several meters at Ho Chi Minh City to 20 m at Long An to 70 m at My Tho to 200 m at Bac Lieu and 260 m at Ca Mau (Thao 2001). The soils of the Delta are mainly constituted of alluvial, acidic, and saline soil groups (Figure 4.2).

Alluvial soils are found along the Tien and Hau rivers and cover an area about 1,100,000 ha (about 28% of the Delta). Acid sulfate soils occupy an area of 1,590,000 ha, mainly in the Plain of Reeds and the Long Xuyen-Ha Tien Quadrangle. These are classified into (i) potential acid sulfate soils covering 1,089,236 ha (28% of the Delta) and (ii) actual acid sulfate soils occupying 510,027 ha (13% of the Delta). Saline soils found along the coastal regions cover an area of 808,749 ha (21% of the Delta). The remaining soils are upland and mountainous peat soils.

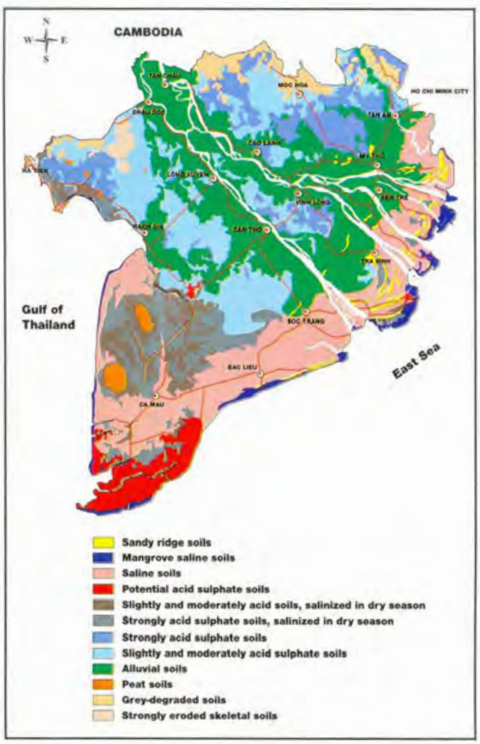


Figure 4.2. Soil characteristics of the study site (Source: Sanh et al. 1998).

The alluvial soil group is located in between two main rivers of the Delta and along the sides close to the rivers (Figure 4.2). This area still has some potential for acid-sulfate soil, but the continuous provision of freshwater and sedimentation keeps the soil in good condition. Such areas are therefore appropriate for farming in the Delta. The alluvial soils can be divided into two main groups: clay and sand (Figure 4.3). From this viewpoint, most of the points along the Tien River (Chiem 1993) have soft clay soils of around 20 m depth. Although Vinh Long has a very thin sandy top soil, almost the whole area has clay soil on its surface. The gravel layer exists less than 20 m from the surface, especially in upper area, and the border depth is around 30 m. According to Chiem (1993), the layer from 7 m to 28 m in the upper segment from Tan Chau to Vinh Long has middle or fine sand in the clay layer which can cause bank collapse. Lower points like Ben Tre, Mo Cay, and Ba Tri have sticky clay soil in the topsoil and sub-surface layers (Figure 4.3)

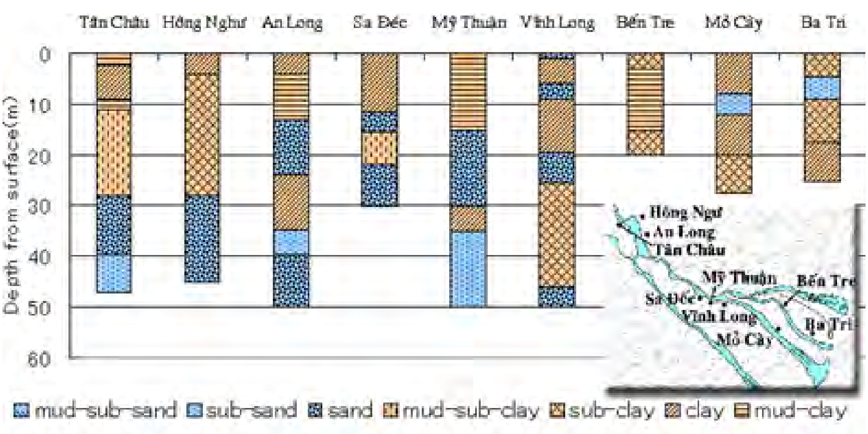


Figure 4.3. Cylindrical image of the geological status along the Tien River. Orange indicates clay components and blue indicates sand components (Source: Chiem 1993).

The acid sulfate soils are distributed widely as a result of former sea submergence, and this division occupies more than half of the whole Delta. Fe^{3+} and SO_4^{2-}, which originate from sea water, form pyrite (FeS_2) in soil under oxygen-poor conditions, and acid-sulfate soil is created when pyrite is recombined with oxygen through contact with water or agriculture. The types of vegetation able to grow on this soil are limited because of strong acidification, mainly Melaleuca or some kinds of reeds that have tolerance to such conditions. The saline soils are located along the coastal areas which undergo severe saline intrusion throughout the year; hence the soil characteristics are strongly dominated by the salinity of water. In Soc Trang, soil water was found to have 30% salinity with a soil pH of about 4.0. In addition, this area has the potential to develop acid-sulfate soils while the flushing effect of tidal movement presents a danger for agriculture (Department of Soil Science of CanTho University 2010).

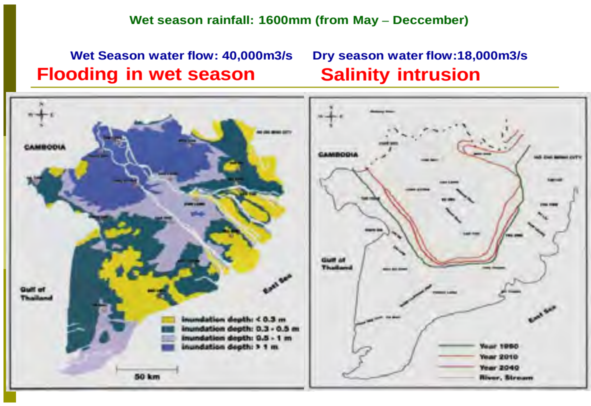


Figure 4.4. Maps showing flooding during the wet season and salinity intrusion during the dry season in the study site (Source: Sanh et al. 1998).

4.2.3 Water resources in the Mekong Delta

The annual rainfall, combined with the high flow of about 40,000 m^3/s of the Mekong River, results in regular floods of 0.3 to 3 m height during the wet season (May to November) in the poorly drained depressed areas of the Delta. In the dry season (December to April), the river flow is reduced to less than 18,000 m^3/s. As a result, salinity intrusion takes place during this period (Figure 4.4).

According to Tuan (2003), there are three sources of water in the Mekong Delta:

1) Rainwater is a favourite drinking water source, especially in rural and suburban areas. In urban places, rainwater serves as a minor source of drinking water, apart from that supplied through tap water. The quantitative range of annual average rainfall in the Delta is 1,400-2,200 mm. About 90% of total rainwater falls on the Delta between May and October. The dry season extends for 7 months, resulting in serious shortages of rainwater supply in many areas.

2) Surface water is considered a main source of water supply for agricultural and industrial purposes. Hydrological data records show that annually, approximately 500 billion m^3 (about 15,000 m^3/s) have flowed out to

the sea via the Delta. High rainfall combined with the high flow of the river results in yearly flooding. There is a significant difference in discharge between the wet and dry seasons. In the five months of the wet season (May to October), the River discharges two-thirds of the total annual flow. The remaining amount is distributed over 7 months (about 1,700 m^3/s) (November to May). The low discharge leads to salinity intrusion and becomes the major water use problem in the coastal lands.

3) Groundwater is widely used in the coastal areas. Sources of groundwater are plentiful and present all over the Delta. Groundwater is exploited and pumped at several depths: at 80-120 m principally for household wells and at 400-500 m for groundwater plants. The upper level water is extensively drilled and pumped out. Pumps supplied by a UNICEF project are commonly used, but there are many problems associated with pumping the groundwater such as high salinity and iron contents. Saltwater infiltration into groundwater is common in Tien Giang, Ben Tre, Ca Mau, and Kien Giang. Although many wells have experienced quality problems of some kind (pH, high iron content, salinity, and bad odors being most common), almost all plans for the future are based on increased groundwater withdrawal. The deeper water is of better quality, but is costly to exploit and can occasionally also be saline. Nevertheless, deep drilling of wells is often recommended although it could result in mining of fossil and non-renewable groundwater and in salinisation of deeper aquifers. Due attention should be paid to these facts to ensure the sustainable management of these aquifers.

4.2.4 Groundwater-related geological characteristics

It is estimated that groundwater resources in the Delta amount to about 1 million m^3/year, at depths varying from <100 m to more than 300 m (Figure 4.5). Tra Vinh province has groundwater available at various depths to more than 300 m. The various depths of the aquifers can be explained by the fact that several unconsolidated aquifers (coarse grained, sandy formations) of different age are separated by fine grained, clay/silt beds. Each aquifer potentially provides a groundwater source which can differ to the upper or lower one in terms of yield as well as groundwater quality (Wagner et al. 2012).

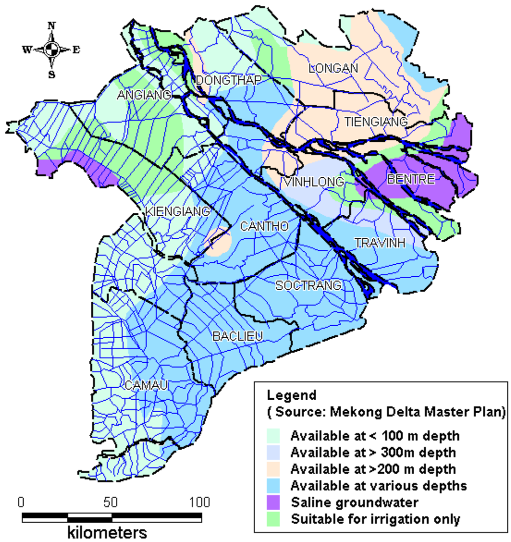


Figure 4.5. The Tra Vinh study area in the context of groundwater depth map of the Mekong Delta, Vietnam (Source: Thuan 2004).

4.2.5 Description of socio-economic activities

The role of the agriculture sector for the Mekong Delta‘s development is crucial and has important influences on economic development, changes of land use, food security, availability of agricultural and fishery products for export, and poverty reduction.

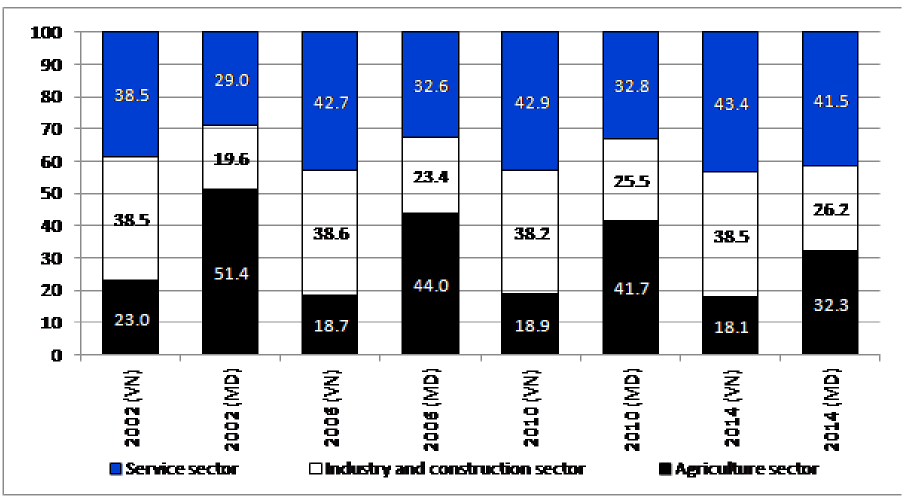
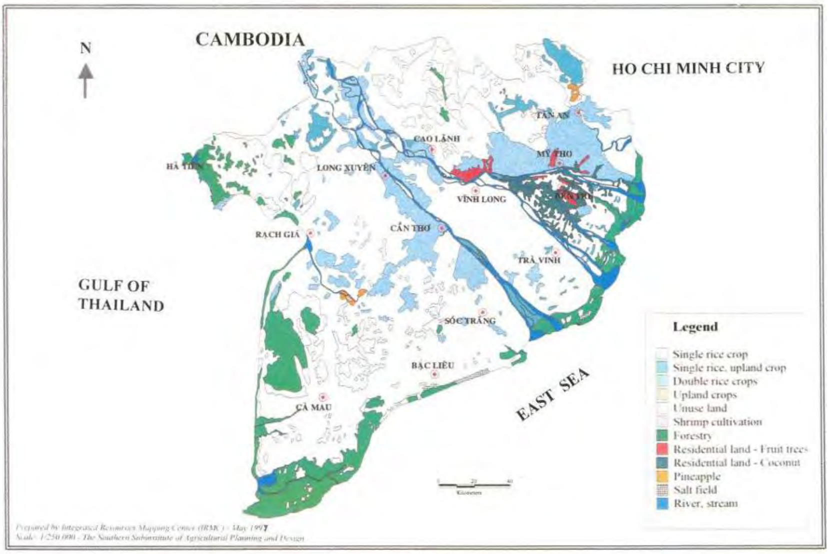
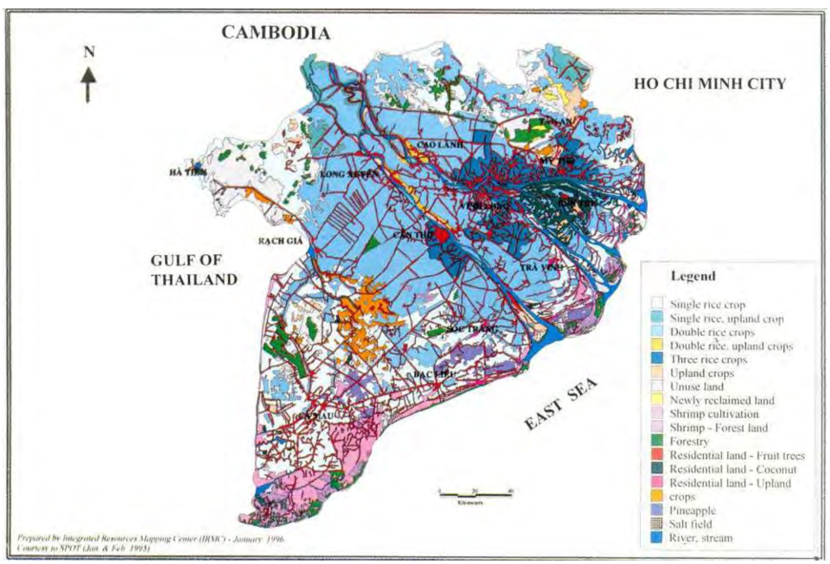


Figure 4.6. Economic structure transition in the Mekong Delta as compared to the country (Source: GSO 2002, 2006, 2010, 2014) (Note: VN: Vietnam, MD: the Mekong Delta).

Figure 4.6 shows that the percentage of the agriculture sector's contribution to the economy in the Mekong Delta was reduced from 51% to 32% between 2002 and 2014. However, compared to the country as a whole, distribution of the agriculture sector's contribution to the Mekong Delta economy was still high at 32%, followed by 26% from the industry and construction sector and 42% from the service sector, while the respective contributions for the entire country were 18%, 39%, and 43%.





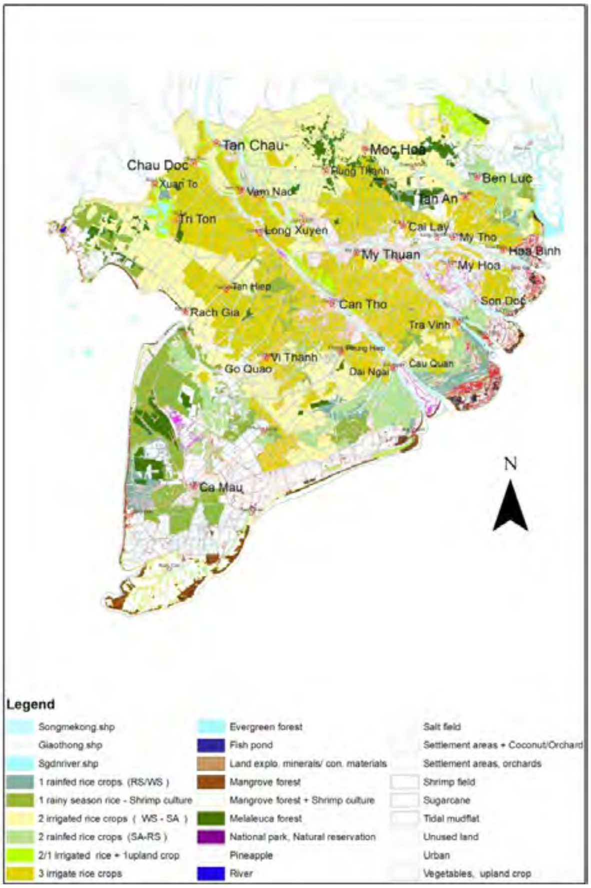


Figure 4.7. Land use changes in the Mekong Delta between 1976 and 2010 (Sources: Sanh 1998; Department of Soil Science of Can Tho University 2010).

Land use changes occurring between 1976 and 2010 (Figure 4.7) note that:

- more intensive rice production, with changes from 1 crop to 2-3 crops/year, is occurring in the provinces of Tien Giang, An Giang, Dong Thap, and more recently in Kien Giang province; mangrove deforestation for shrimp production is occurring in the coastal areas (Ca Mau, Bac Lieu, Soc Trang, Tra Vinh, and Kien Giang provinces); and
- aquaculture, focusing on catfish, is occurring along the main Mekong River Banks (An Giang, Dong Thap, Tien Giang, Can Tho City, Hau Giang, Vinh Long, Ben Tre, and Tra Vinh Provinces). Agricultural land use in the Mekong Delta is still high (64%) when compared to agricultural land use in the Red River Delta Zone (37%) and the country as a whole (31%) (Figure 4.8).

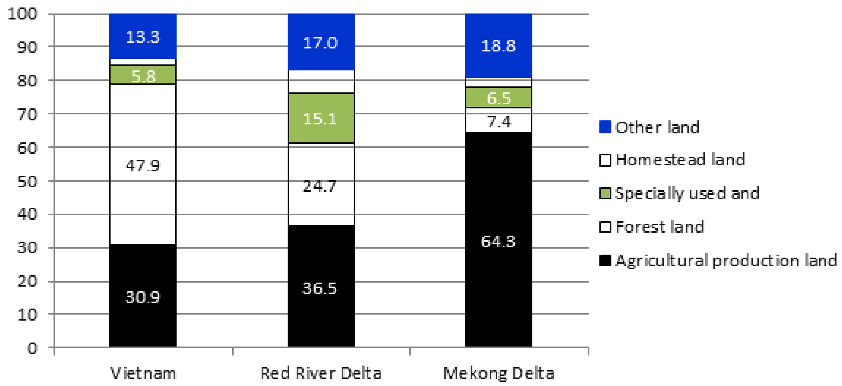


Figure 4.8. Percentage of agricultural land use in the Mekong Delta compared to the Red River and the Nation (Source: GSO 2014).

4.2.6 Prediction of the impacts of climate change in the Mekong Delta

While Vietnam generally has a high adaptive capacity, much of the country is subject to flood and drought risks as well as cyclones. For every meter of sea-level rise, 11% of Vietnam's population, 16% of its land area, and 7% of its agricultural area would be inundated (Carew-Reid 2007). In this context, the Mekong Delta is a hotspot for sea level rise (Dasgupta et al. 2007).

To assess the vulnerability of the agriculture sector to climate change, vulnerability indicators combining elements of exposure and sensitivity to climate change, and adaptive capacity need to be developed at the district level. According to MONRE (2009), an exposure can be reflected as the change in temperature and annual precipitation in 2050 or 2080 as compared to current levels. How those changes will affect agriculture, livestock, and fisheries in the Delta will depend on several factors such as crop type, CO_2 fertilisation, and multiple stressors. Sensitivity may be accessed through several variables such as rural population density, irrigated land, groundwater management, and agricultural employment. Likewise, several indicators can be used to measure adaptive capacity, such as poverty rates, access to credit, literacy rates, farm income, and agricultural GDP. More importantly, water management, particularly groundwater, will be an important issue in the socio-economic development.

4.3 Methodologies

4.3.1 Use of GWAHS vulnerability framework

The overall objective of this study is to address the threats to human security and well-being currently posed by water scarcity and water quality degradation in the Mekong Delta and the role of groundwater management and protection in alleviating these threats.

The conceptual framework of vulnerability assessment developed by UNU-EHS for the GWAHS-CS project (Chapter 1) was partially used for this study. Vulnerability indicators included hazard or disaster risk, viewed as the interaction between a hazard and vulnerability of exposed elements (Birkmann 2006). Vulnerability includes exposure, sensitivity, and resilience of the exposed elements (individuals, community, sectors, etc.) (Turner et al. 2003). Regarding the vulnerability assessment, indicators normally developed by specific disciplines were used to measure and compare vulnerability of exposed units to a certain hazard such as drought, water scarcity, or groundwater degradation. In order to identify indicators of hazard to groundwater resources by threats of overexploitation and changes in quality and quantity of groundwater associated with the exposure, estimates were made of the sensitivity and resilience of the population and socio-economic development at different levels: from the Delta region to the province, down to the community level of the two communes acting as the study sites. For each level, there were differences in approach and methods for data collection to support indicators of the vulnerability assessment.

The generic approach to the assessment of groundwater and human security was tested in the case study area of Mekong Delta and Tra Vinh case study by an interdisciplinary research team using the suite of generic indicators identified for this purpose by the GWAHS-CS project.

4.3.2 Review of secondary and national data

At the regional level, secondary data and national census data relating to physical conditions and human activities such as land use and socio-economic development were collected. At the provincial level, existing secondary data on institutions and management of groundwater resources in the Statistical Offices and in DONRE Tra Vinh were collected and analyzed.

4.3.3 Participatory rural appraisal, focus groups and household survey methods

At the community level, focus group discussions (FGD) and participatory rural appraisals (PRA) conducted by the multidisciplinary research team from Can Tho University and local staff were applied to probe qualitative data for the indicators, which also explored the main points of the research. In addition, the PRA and FGD further explained the household survey findings. At the household level, surveys were conducted to collect household data of different social groups with different livelihoods, vulnerability to water scarcity and groundwater degradation in the two communes studied.

Through the community's participation, including participation of different social groups, and commune leaders, PRA tools of ecosystem analysis, trends/timeline analysis, and seasonal and shock analysis were used to identify both vulnerability of communes to reduction in groundwater quality and quantity.

About twenty-five commune residents familiar with Long Son commune's resources of land, water, social activities, and farming systems were invited to participate in the PRA. Based on their interests and knowledge of the commune's resources, they were divided into four groups to develop four maps from a base map, namely: (i) a soil and irrigation map, (ii) a social map, (iii) a land use map and (iv) a transect map. These maps were related in terms of the ecology and human activities at the commune level. The results are discussed fully in the following section.

4.4 Results of the Assessments

4.4.1 Groundwater resources

According to NEDECO (1991), groundwater reserves amount to 92,128,000 m^3/day with a groundwater safe yield of just over 1 million m^3/day. In the Mekong River Delta, groundwater is found in the Upper Pleistocene with an area of 19,500 km^2 and a flow rate of 0.1 to 1.1 L/s. The Lower Pleistocene is distributed over 23,500 km^2, with a flow rate of 0.9 to 1.5 L/s. The Pliocene involves an area of 21,500 km^2 and a flow rate of 0.1-1.5 L/s. Finally, the Miocene consists of 28,300 km^2 and a flow rate of 0.2-0.9 L/s. The uppermost Holocene aquifer (above the Upper Pleistocene) can have some local relevance for domestic water supply, even if it is mostly saline, polluted and of low yield (Wagner et al. 2012). This is especially true for

sand ridges along the coastal zone, where the local people have used shallow groundwater to irrigate cash crops during the dry season.
The available groundwater reserves indicate that groundwater problems exist in the Mekong Delta. It is possible that the groundwater resources could decline more rapidly, in both quantity and quality, due to local over-exploitation and misuse of the resource. Specifically, rapid population and economic growth, the use of surface water for wastewater disposal, and the use of groundwater as a safe water source will each increase the pressure on this resource.

In many provinces, particularly in the coastal zone, underground water is mined to irrigate crops and to dilute saline water for coastal shrimp farming. The pervasive mindset that underground water is limitless has resulted in careless digging of bore wells whenever current wells are no longer adequate. The Ministry of Natural Resources and Environment (MONRE) estimates that the Delta residents use around one billion litres of groundwater every day. Tens of thousands of bore wells and pumps across the Delta are using the water from different depths. Most water supply companies in the area exploit water from depths of between 100 and 300 m, with residents in urban areas of Soc Trang, Bac Lieu and Ca Mau provinces using groundwater only for daily activities. Recently, more people are turning to groundwater because surface water is becoming increasingly contaminated (Danh 2007). The author found that available figures and evaluations about the water are inconsistent, insufficient, and inaccurate. Therefore, if there is no solution for managing the resource then there is a risk that it will soon become unusable and irreplaceable in the foreseeable future.

Within the last ten years there has been rapid economic growth in the Mekong Delta, resulting in an increase in domestic and industrial water demand. Surface water, which is often used for drinking water purposes, is highly polluted by agro-chemicals and other organic pollutants (e.g. inflow of untreated wastewater) (Nuber 2005). To deal with the problems of water quality, many households in the Delta have built their own groundwater wells despite the fact that they are living in freshwater areas. The situation in the coastal areas of the Delta is more complicated. People there rely mainly on rainfall water in the rainy season and groundwater in the dry season for drinking water. For other activities in the coastal areas, e.g. agriculture, aquaculture, and industry, groundwater is the main water source. Even though the potential of the groundwater resources in the Delta accounts for more than one million m^3/day (Nghi 1994), groundwater pollution and a decrease of the groundwater table have been observed due to improper exploitation of the groundwater source. Therefore, it is essential to evaluate the current exploitation of groundwater in the Mekong Delta.

The Mekong Delta in general, and Tra Vinh province in particular, is facing problematic levels of pollution of its groundwater resources. The pollution sources include contamination by agricultural activities, surface pollutants through incompetent drilling of wells, natural phenomenon such as arsenic pollution, and salinity due to over-extraction. Each of these is explored here.

First, in the modern input-based agriculture economy, water resources are seriously degraded. Along with rivers and canals, the groundwater aquifer is being polluted. The contamination by agricultural production is a consequence of the overuse of pesticides, fertilisers, and other chemical materials. Quyen (2005) reported that pollutants such as chlorides, sulfates, nitrate and nitrite, ammonium and phosphates, were found in many places with concentrations that were higher than the Vietnamese standards for drinking water (Table 4.1). These pollutants infiltrate groundwater through the extensive system of tube wells in the Delta. There are reports that more than 15% of private-dug wells in the Delta cannot be used because of improper drilling. The fact that well drilling is not performed by experienced technicians results in a large number of wells being rendered unusable. Consequently, these wells are discarded and can be polluted.

Second, dissolved arsenic in groundwater (which is limited to Holocene and upper Pleistocene aquifers) has been observed at many places in the Delta, which raises concerns about the health risks for residents. It is thought that arsenic can lead to skin cancer in humans. Long An, Dong Thap, An Giang, and Kien Giang are provinces where there is a very high possibility of arsenic pollution in groundwater. Detailed monitoring of groundwater and installation of small-scale filter systems are useful mitigation measures, and this work has been done by researchers from Can Tho University in Tra Vinh for households' drinking water supply; using alternative water sources is another option.

Finally, the salinity of groundwater due to over-extraction is another source of groundwater pollution. The variance of the water table between the rainy and dry seasons tends to increase over time. In some places, people can no longer use groundwater for domestic use due to the salinity, although they may have been able to in the past. Managing groundwater resources is considered as a measure to protect this invaluable natural resource. For example, groundwater extraction should be assessed and managed to sustainable levels in order to keep groundwater levels stable. In addition, pollution sources need to be identified and addressed according to current water policy. Policies that are implemented should be based on responses of the consumers who are directly affected by the quality of groundwater.

Table 4.1. Major characteristics of groundwater by season in Tra Vinh between 2003 and 2005 (Source: DONRE of Tra Vinh 2005).

Parameters	Dry season		Wet season		Allowable value1
	Mean	Standard Error	Mean	Standard Error	
PH	6.9	0.2	8.0	0.1	6.5-8.5
Cl^- (mg/l)	100.1	47.4	56.4	25.3	200-600
Hardness (mg $CaCO_3$/l)	259.6	25.0	225.7	15.1	300-500
Tubidity (NTU)	10.6	3.8	6.6	0.9	5-50
SO_4^{2-} (mg/l)	65.1	19.5	98.1	49.9	200-400
N-NO_3 (mg/l)	2.1	0.4	1.8	0.7	45
N-NH_4 (mg/l)	2.2	0.5	2.3	0.6	
DO (mg/l)	3.2	0.2	2.9	0.2	
COD (mg/l)	6.0	1.6	6.3	0.4	
BOD (mg/l)	2.6	0.7	2.7	0.2	
Al^{3+} (mg/l)	0.0	0.0	0.3	0.1	
Total Fe (mg/l)	0.8	0.2	0.6	0.2	1-5
Total Coliform (MPN/100ml)	613.6	279.8	982.6	281.9	3

4.4.1.1 Groundwater Users

According to Hoang (2008), the average number of groundwater users in the Mekong Delta has increased between 2002 and 2006. Most groundwater is exploited for agricultural use for growing crops, mainly vegetables, beans, and maize, and such use has seen increases from year to year, from 230,000,000 m^3/year in 2001 to 330,000,000 m^3/year in 2006. On the other hand, groundwater for livestock and household consumption is lower and stable at less than 30,000,000 m^3 annually. It can therefore be said that in general, farmers in the coastal Mekong Delta, and in Tra Vinh in particular, mainly use groundwater for agricultural production, particularly for irrigation during the dry season.

4.4.1.2 Over-exploitation and groundwater pollution in Tra Vinh Province

Tra Vinh is a coastal province where two-thirds of its surface water is affected by saline and acid water. The shortage of freshwater has a severe impact on the lives of the people in this area. Since 1999, Tra Vinh has used substantial financial support from the Asian Development Bank, the World Bank, and its own capital for carrying out centralised water supply projects (Trung 2005) to exploit groundwater for household consumption. The over-exploitation of groundwater in Tra Vinh is the result of the presence of 150 state-run pump wells and 41,000 small pump wells that withdraw around 65,000 m^3/day (Cuong 2006). Thus, competition for groundwater use stems from the fact that 80% of the population relies on it for daily activities, irrigation of vegetables, shrimp farming and processing, livestock production, and industrial development and services. This is exacerbated by natural hazards such as less recharge and droughts in the dry season with saltwater intrusions (Tra Vinh; DONRE 2005). According to Cuong (2006), the over-exploitation of groundwater in Tra Vinh for irrigation and shrimp cultivation has caused a decline in the groundwater level by about 8 m. In addition, according to the Tra Vinh Department of Science and Technology, a great number of wells are polluted by organic matter and chemical fertilisers, and approximately half of them have an iron content of around 1.2-4 times higher than the limit level recommended by the Vietnamese standard. The probable reason is that either these wells were not properly built, or the pipe systems have leaked (Hoang 2008). In general, groundwater resources have gradually degraded both in terms of quantity and quality, significantly affecting the livelihoods of local communities in the Delta, especially in the coastal area. Therefore, a vulnerability assessment of groundwater degradation in relation to different social groups is considered an urgent task in order to develop appropriate interventions to mitigate vulnerability to these hazards.

4.4.2 Development of ecological and social maps

4.4.2.1 Irrigation and soil map

Commune members participated in a group discussion in order to develop an irrigation and soil map (Figure 4.9). The group first identified the contours among their hamlets, and then identified the location of sandy banks which have a higher topography compared to the lowland areas in the commune and the location of lowland areas with brackish water. Through this exercise, they identified their commune's resources in relation to soil types and water availability for their agricultural practices.

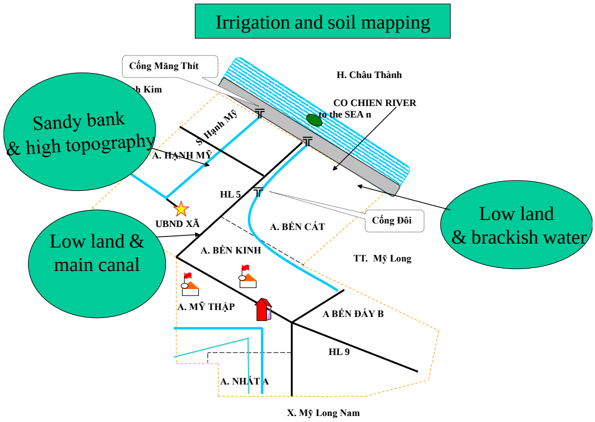


Figure 4.9. Irrigation and soil map of My Long Bac Commune (Source: PRA, Cau Ngang district, 2008).

4.4.2.2 Social map

After providing a base map, eight commune members who had experience and knowledge of the socio-economic conditions of their commune developed a social map (Figure 4.10). It was found that there are three ethnic groups living in the commune: Chinese, Kinh, and Khmer. The commune members also explained that the wealth or poverty of commune residents depends on the culture of the commune members' settlement and their business, their proximity to the road or main rivers, as well as their educational level and level of experience with farming practices. Those that are better off are usually from the Chinese ethnic group who settle near the market. The Kinh are usually average or better-off farmers and live among the main canals or rivers of the commune, while the Khmer usually occupy the sandy banks and isolated rural areas.

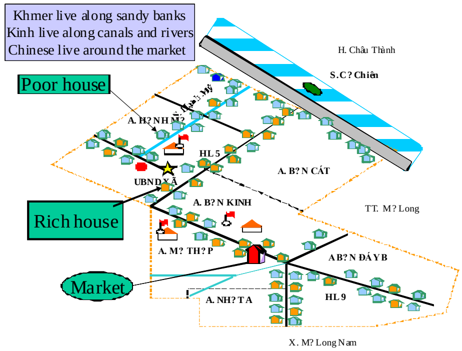


Figure 4.10. Social map of My Long Bac Commune (Source: PRA, Cau Ngang district, 2008).

4.4.2.3 Land use map

Between eight to ten commune members drew a land use map of the commune (Figure 4.11). The land use in the commune is closely related to the soils and water resources available, as well as the socio-economic conditions. There are three main cropping systems in the commune: (i) upland crop farming systems with maize, soybean, vegetables, and yams (practiced by Khmer farmers); (ii) shrimp farming (practiced mainly by Kinh); and, (iii) rice farming (practiced both by Kinh and Khmer).

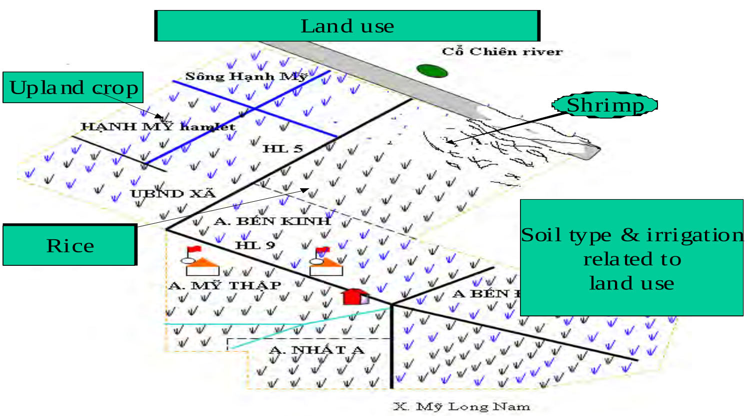


Figure 4.11. Land Use of My Long Bac Commune (Source: PRA, Cau Ngang district, 2008).

Commune members also explained that the culture of the settlement is related to farm activities and the farmers' status. The Chinese are mainly involved in service activities and work in small shops buying and selling products that the commune members need. They are usually wealthier than the other two ethnic groups of Kinh and Khmer. Due to their location along the river, the Kinh prefer rice or shrimp cultivation. They are average in terms of economic status, or better-off farmers. The Khmer living on the sandy banks have access to less land and water resources and therefore mainly grow upland crops; they are usually the poorest in the commune.

4.4.2.4 Transect map

Based on the land use map, eight commune residents were invited to a transect walk across their commune through the land uses of the three farming systems described above to identify resources related to the three types of farming systems. The results are presented in Table 4.2. The farming systems are very closely linked to soil and water conditions. The sandy bank and groundwater are mainly used for farming with upland crops. The loam soils and irrigated areas by canals are mainly used for rice farming and saline soils with brackish water are mainly for shrimp cultivation. Commune members also identified which of the crops and animals belong to each farming system. In the wet season, there is enough freshwater for these three types of farming systems.

In the dry season, groundwater problems for each farming system were identified. Extreme problems of competition and sharing of groundwater between the three types of farming systems result in a lack of groundwater for upland crops, a lack of groundwater supply for the beginning of the rice crop season, and a reduction in the degree of salinity for shrimp cultivation due to dilution with groundwater. These may lead to more complex problems if over-exploitation of groundwater continues in Tra Vinh province.

Table 4.2. Transect of My Long Bac Commune (Source: PRA, Cau Ngang district, 2008).

Resources	Upland crops	2 rice crops	Shrimp production
1. Soil	Sandy	Loam	Saline soil
2. Water	Groundwater	Groundwater & main canal	Groundwater & river
3. Crops	Beans, maize, vegetables	High yielding rice varieties	Brackish tree, e.g. nipa
4. Animals	Cows & pigs	Pigs, chicken & ducks	Tiger shrimp
5. Problems of groundwater	Lack of groundwater in dry season	Lack of water in beginning and at end of crops	Lack of groundwater in dry season

4.4.3 *Socio-economic assessments*

4.4.3.1 *Population and administration in the commune study sites of Tra Vinh*

Tra Vinh has eight districts with 102 communes covering an area of 2,240 km^2. The population exceeds one million people with a density of 465 persons per km^2 (Table 4.3). Two communes, namely Long Son and My Long Bac of the Cau Ngang district, were selected as the commune study sites for carrying out participatory rural appraisals and the standardised household survey because they are representative of the Tra Vinh ecosystems (e.g. sandy bank land, fresh water, and coastal land) and population characteristics with residents of Khmer, Kinh, and Chinese ethnicity, and different economic status.

Table 4.3. Population in the commune study sites of Tra Vinh Province (Source: Statistical Office of Tra Vinh Province 2007).

Administrative Units	Communes	Area (km^2)	Population	Population density (persons/km^2)
WHOLE PROVINCE	102	2,240.22	1,041,002	465
1. Tra Vinh City	10	68.04	92,172	1,355
2. Cang Long District	14	300.09	170,842	569
3. Chau Thanh District	14	334.86	145,137	433
4. Cau Ke District	11	243.25	124,661	512
5.Tieu Can District	11	220.39	112,588	511
6. Cau Ngang District	15	318.86	137,859	432
7. Tra Cu District	17	369.66	165,515	448
8. Duyen Hai District	10	385.08	92,228	240

4.4.3.2 *Problems encountered by farmers*

Although there is a rapid increase in the production and exporting of rice, fruit trees, and fisheries, farmers in the Mekong Delta remain poor due to low education levels, small farm size and low income with high expenditures (Table 4.4). These factors are explained further here.

Table 4.4. Household status with low education and low income in the freshwater and problem soils zones in the Mekong Delta (2008) (Source: Nhan and Sanh 2008).

Zoning	Average Income/ capita / year (Mil. VN D	Average expenditure/ capita/year (Mil. VND)	Rate of HH with saving (%)	Illiterate (%)	Elementary school (%)	Secondary school (%)	High school (%)
Fresh-water	8.2	6.2	68	2	26	39	32
Problems soils	6.4	5.0	47	20	55	21	4

Farmers have low levels of skills and training. Data from the General Statistics Office from 1996, 2000 and 2003 indicate that farmers' labour skills have changed little over time, with the number of farm labourers with no skills decreasing only slightly from 93% to 87%, with the majority having little primary training or skills. Thus, the improvement of labour skills for farming practices in the main agricultural and aquaculture sectors remains an urgent priority.

Based on results of the household survey carried out by Nhan and Sanh 2008) in three main agro-ecological zones of the Mekong Delta (freshwater, acid sulphate soils, and saline soil zones), the average income/household/year was low at 8.2 million Vietnamese Dong (VND)/household/year in the freshwater area and around 6.4 million/household/year in the area of problem soils (Table 4.4). However, annual expenditure is high, resulting in low savings rates. Of more importance, their education levels are low, and particularly there is a high rate of illiteracy and low education in the areas with problem soils.

Table 4.5. Farmers' income and expenditure in the Mekong Delta, 2007 (Source: Nhan and Sanh 2008).

Zoning	Family expenditure (Mil. VND)	Payment for farm inputs (Mil. VND)	Payment for loan interest (Mil. VND)	Payment for neighbour relationship (Mil. VND)	Total expenditure (Mil. VND)	Total income (Mil. VND)	Savings (Mil. VND)
Fresh-water	11	17	3.5	2	33.5	39	5.5
%	33%	50%	11%	6%			
Floods	9	11	3	1	24	25	1
%	32%	48%	125	4%			
Saline intrusion	16	83	12	3	114	125	11
%	14%	73%	10%	3%			
Average	12	37	6	2	57	63	6
%	21%	65%	11%	4%			

4.4.3.3 Household expenditure in different sub-zones in the Mekong Delta

The survey results of household expenditure in the three sub-zones (freshwater, salinity intrusion, and flood zones) in 2007 showed that the average annual household savings is approximately 6 million VND (Table 4.5). The lowest savings rate was found amongst households in the flood zone (1 million VND). The low savings rate per household is due to the ratio of high expenditures for farm input (65%) to small farm size. Also, there are high expenditures in relation to family expenses on education, health care, and daily food (21%), loan interest (11%), and neighbour relationships (4%). Therefore, it is not surprising that if even only one family member becomes sick or farm input prices increase, farmers are easily susceptible to poverty or to their children not attending school. These reasons also explain why farmers in the region are vulnerable to groundwater degradation problems.

4.4.3.4 Rapid increase in households with less land and small farm sizes

Figure 4.12 shows the various household farm sizes in the Mekong Delta. Households with a farm size of less than 0.2 ha increased from about 5% in 1994 to about 13% in 1997 and to 23% in 2001. In 2007, households with less than 0.5 ha accounted for around 50%. With the expected increase in population and lower rate of rural job creation, the number of households which are landless or have a small farm size will likely rapidly increase, making life for farmers increasingly difficult.

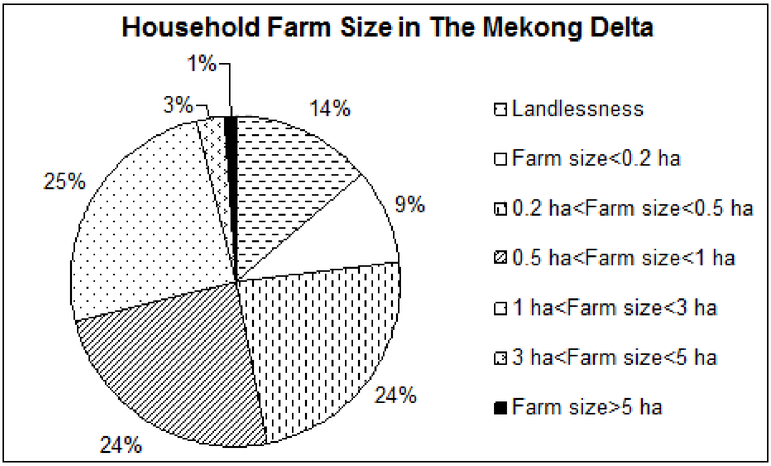


Figure 4.12. Mekong Delta farmers who are landless or have a small farm size (Source: GSO 2003).

4.4.3.5 Legal and policy framework for groundwater use and management

Centers of Rural Water Supply and Environmental Sanitation were established in each province of the Mekong Delta before the 1990s and were sponsored initially by UNICEF and by the Vietnam Central Government thereafter. These centers are responsible for providing clean water to rural communities. For urban areas, there are the Provincial Water Supply and Sewerage Companies.

A careful analysis was conducted to identify the case study's key stakeholders, an assessment of their interests, and the ways in which these interests affect the case study's risk and viability. Stakeholder analysis contributes to this research design through the logical framework in the initial stages, and by helping to identify appropriate participants. On the basis of information related to legal aspects, decrees, institutions of groundwater use, and management supplied by the Department of Natural Resources and Environment, the stakeholders in this research project consist of the three levels of government at the province, district, and commune levels. In addition, farmers groups were involved as a major respondent/beneficiary of the project.

The essential stakeholders include the provincial DONRE, the provincial Department of Agriculture and Rural Development (DARD), the district division of Agriculture and Rural Development, representatives of the commune people's committee, and social target groups (Table 4.6).

Table 4.6. Stakeholders and their roles and impacts in groundwater management (Source: PRA in Tra Vinh, 2008).

Level	Stakeholders	Method used for accessing information	Role and impacts in groundwater management
Provincial	- DONRE: Center of Rural Water Supply and Environmental Sanitation	- KIP (Key Informant Panel) - Documents and reports provided	- Check and update information - Management and use of groundwater - Strategy, planning
District	- Provincial Department of Agriculture and Rural Development: Center of Agricultural Extension	- KIP - Documents and reports provided	- Check and update information - Monitoring and management
Commune	- District Division of Agriculture and Rural Development: Section of Natural Resources and Environment - Agricultural Extension Station	- PRA (in-depth group interview)	- Follow up action plan - Implementation
Farmer	- Social Target groups: Vietnamese Poor group, Khmer Poor group, Vietnamese Non-poor group, Khmer Non-poor group, Women's groups	- PRA (target group interview) - Household (in-depth interview)	- Beneficiary - Profit - Vulnerability - Coping/Adaptation

Figure 4.13 provides a description of the challenges that exist with policy, organisations, and institutions. It was developed via a focus group discussion with the staff of the Tra Vinh Department of Natural Resource and Environment. A prohibitive groundwater management policy created complicated guidelines for groundwater use at the provincial level and led to a poor institutional and legal framework for groundwater management that further led to poor groundwater management planning. This also led to problems in making decisions to implement policies for groundwater management. As a consequence, many organisations were involved, but they were not effective in implementation, and there was a lack of human and financial resources for the monitoring and control of groundwater use from different stakeholders. These factors created problems of community participation in groundwater management at the local level.

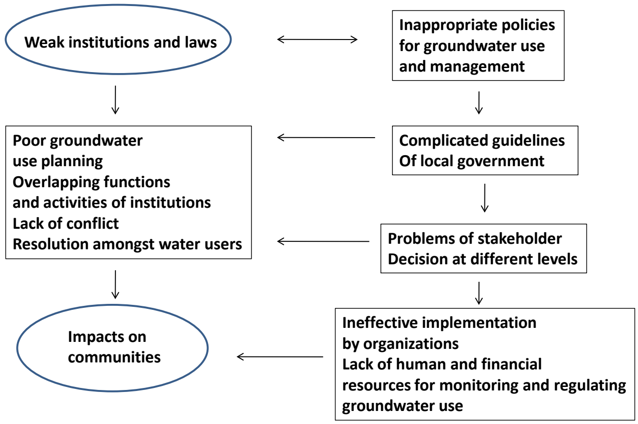


Figure 4.13. Problems of policy, organisation, and institution (Source: KIP with DONRE of Tra Vinh 2005).

4.4.4 Vulnerability of the community to groundwater depletion

In order to identify the vulnerability of the community to groundwater scarcity and to decreasing quality, PRA techniques of trend/timeline analysis and seasonal calendar analysis were used. The results are presented here. More senior commune members with experience of groundwater use in the My Long Bac commune were invited to complete the trend/timeline analysis (Table 4.7).

Table 4.7. Historic events in My Long Bac Commune (Source: Trendline Analysis , Cau Ngang district, 2008).

Trend/ timeline	Water use	Explanations
1975-1984	Rainfall mainly used for farm activities and less groundwater use for households	Practiced mainly on 1 rice crop/year
1985-1990	Use of both rainfall and irrigation for farm activities; shallow groundwater development for household use	Increased intensity of cropping systems; commencement of surface water pollution
1987-1993	UNICEF project invests in groundwater pumping wells for safe drinking water	Surface water pollution
2000-2003	Rapid increase of private wells and high competition for groundwater	Expansion and development of agricultural activities
2004-present	Villagers recognise both quality and quantity problems of groundwater	Increase of water pollution and scarcity of groundwater during the dry season

Following the Vietnam War, from 1975 until now, the trend in problems associated with groundwater resulting from intensive agriculture and surface water pollution were classified into five periods. From 1975 to 1984, rice was grown once per year during the rainy season. There was little use of groundwater for household consumption. From 1985 to 1990, with an increase in intensive farming systems, farmers used both rainfall and irrigation for their farm practices. With the development of surface water pollution, farmers began to use shallow wells (20 m depth). From 1987 to 1993, due to surface water pollution, UNICEF invested in pumping wells to provide drinking water in this area. As agricultural activities expanded, the use of private wells developed rapidly and high competition of groundwater use was identified between 2000 and 2003. From 2004 until now, due to an increase in water pollution and a scarcity of groundwater resources for agriculture and aquaculture in the dry season, the commune elders recognised problems of both quality and quantity of groundwater use and management.

Three groups of farmers representing the three types of farming systems were invited to present their seasonal cropping calendars and share their experiences of difficult times in the year. The results from these interviews are presented in Figure 4.14. Almost all farmers for these farming systems have faced difficult times during the dry season, from January to May, due to a lack of groundwater supply for their farms. However, the most difficult time for farmers with upland crops was from January to March; for farmers with two rice crops and one cash crop, it was from April to May; and for farmers with shrimp cultivation, it was mainly from February to the middle of March. In addition to difficult times resulting from a scarcity of groundwater resources, the commune residents also identified a lack of money for their farm investments from April to May, together with unemployment and low income during the months of April, July and August.

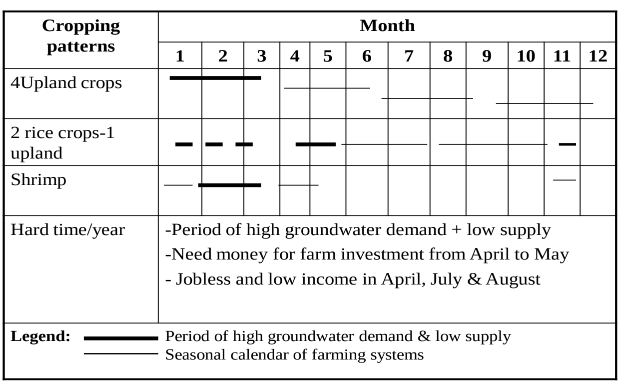


Figure 4.14. Seasonal calendar and community groundwater vulnerability (Source: PRA, Cau Ngang district, 2008).

Further, results from the PRA technique yielded the following conclusions:

- there is a close relationship between physical and biological attributes based on soil type and water resources;
- there is a relationship between culture, physical/biological attributes, and water use within the different social groups;
- the Khmer people live on the sandy banks of higher topography with upland crops and cows as their main farming activities, and as a result have a high level of groundwater use;
- the Kinh people living along the river and lowlands have rice, shrimp, and live stock as their main farming activities; they use higher amounts of groundwater during the dry season;
- the main activities of the Chinese people living around the market are agricultural services and supply of goods, and mainly use groundwater for their household's domestic consumption;
- community members recognise the problems of lower quality and reduced quantity of groundwater, and perceive it to be caused by increasing agricultural activities and surface water pollution; and
- the poor are more disadvantaged by problems of groundwater use because of their limited capacity to invest in private wells.

4.4.5 Socio-environmental indicators of groundwater vulnerability by household survey

Based on the conceptual framework of the livelihood approach, the classification of livelihoods and their indicators were described (Table 4.8). In order to identify sensitivity and resilience, the socio-environmental indicators of groundwater vulnerability were classified into five assets or capitals to be surveyed at the household level, as described in the table below.

Table 4.8. Indicators reflecting sustainable livelihood assets.

Livelihood Capital	Indicators
Human capital	- Health status and capacity to cope with their health - Labour skills and education
Social capital	- Self organisation to deal with groundwater problems - Community organisation and networks
Natural capital	- Land use and farm activities related to water resources and management
Financial capital	- Income and expenditures, savings, capacity to access credit supply
Physical capital	- Types of houses, farm equipment, and infrastructure

4.5.1 Results of the household surveys

The five assets described in Table 4.8 formed the basis for the questionnaires. According to a ranking by commune members and commune statistics of Long Son and My Long Bac communes, there was a total of 237 farming households representative of households of varying economic status. Different farming systems were investigated to identify further details about the socio-environmental indicators of groundwater vulnerability (Table 4.9). A total of 241 households were surveyed using the questionnaire. However, four of these households were working in non-farm based activities and so were not included in the household type classification (Table 4.9).

Table 4.9. Summary of household types surveyed in Tra Vinh Province (Source: Household survey, Cau Ngang district, 2009).

Land use patterns	Households: higher economic status	Households: lower economic status	Total
1. Upland farming	52	82	134
2. Rice farming	32	52	84
3. Shrimp farming	4	15	19
Total	88	149	237
4. In which woman is head	28	14	42

Household types were classified based on the income share from the major farming components. Rice farming household types are identified where household income from rice accounts for more than 50% of the total farming income. A similar definition of household type classification is given for upland farming and shrimp farming households, where their income share from upland crops or shrimp accounts for more than 50% of the total household farming income.

4.5.2 Human assets

Human assets at the household level, including general information about household head and labour skills in the households, are outlined in this section. Table 4.10 provides information concerning the head of each household surveyed. The average age of the household head is 50 years old. The household heads have a low level of education, which is roughly the beginning of secondary school. In these two communes, the number of female-headed households was fewer than 14%.

Table 4.10. General information on household head surveyed.

	Unit	Long Son	My Long Bac	Total
Household surveyed	Household	121	119	241
Age of household head	Years	49	50	50
Education of household head	Years of schooling	5.64	5.85	5.75
Woman as household head	Household (%)	20 (16.53)	22 (18.49)	42 (17.43)
Avg. household size	Member	4.4	4.6	4.5

Table 4.11 presents the major occupations of family members. Almost all commune residents are farmers, with farming work accounting for 45% of occupations. Next are students, while off-farm jobs such as workers (people not working on farms), government staff, and services account for less than 15%. Dependents, including retired people and children, totaled around 10%. Daily labourers comprised around 9%.

Table 4.11. Major occupations of family members in each commune (Source: Household survey, Cau Ngang district, 2009).

Major occupation/ activity	Long Son commune (% of people in occupation/activity, n=477)	My Long Bac commune (% of people in occupation/activity, n=483)	Total (% of people in occupation, n=960)
Farmer	46.12	43.89	45.00
Wage Labour	3.35	1.66	2.50
Worker	8.39	8.90	8.65
Officer	5.66	5.38	5.52
Service	1.68	1.24	1.46
Retailer	2.52	1.45	1.98
Resource Exploiter	0.00	0.62	0.31
Student	17.61	22.98	20.31
Children	6.29	4.76	5.52
Retired	2.31	6.63	4.48
Others	6.08	2.48	4.27
Total	**100.00**	**100.00**	**100.00**

4.5.3 Physical assets

Physical assets involved identifying different types of houses, the time of settlement, farm equipment, as well as social and economic infrastructure. It was found that almost all commune residents are long-term settlers

(87%), while around 9% of residents are migrants from neighbouring communes. These results indicate that farming has been a stable and predominant source of livelihood in the region.

Table 4.12 presents the distance from homestead to the main roads of the communes. In general, most homesteads are located near hamlet or commune roads, while fewer homesteads settled near district or provincial roads. Most settle in close ethnic groups. For example, Khmer groups live in the sandy bank of the communes and Kinh occupy the main canals which are parallel to the road.

Table 4.12. Relative distance from homestead to roads by commune (Source: Household survey, Cau Ngang district, 2009).

		Unit*	Long Son Commune	My Long Bac Commune	Total
National road	Household	HH	1		1
	Distance	m	120		120
Provincial road	Household	HH	43		43
	Distance	m	211		211
Commune road	Household	HH	37	56	93
	Distance	m	451	642	566
Commune centre	Household	HH	7	39	46
	Distance	m	1,357	1,248	1,265
Hamlet road	Household	HH	33	25	58
	Distance	m	238	664	422

*HH= household; m=metre

Because of the long-term settlement in the area, there is a high distribution of concrete houses (50%), while 30% of houses are of semi-concrete construction, and fewer than 20% of houses were in poor condition in both communes.

In Long Son and My Long Bac communes, groundwater is the principle water source for agriculture and domestic use. Almost every household has a deep well for exploiting groundwater. Table 4.13 shows that 204 out of 241 households own at least one deep well; 35% have two deep wells, and around 8% of households own three deep wells. The increase in number of wells owned may be due to the fact that large farm sizes require several deep wells for water supply. It indicates that large farm households exploit groundwater for agriculture much more than smallholdings do.

Table 4.13. Number of deep wells owned by households surveyed in the communes (Source: Household survey, Cau Ngang district, 2009).

Number of Deep Wells	Long Son	(%)	My Long Bac	(%)	Total	(%)
1	51	54.26	56	50.91	107	52.58
2	29	30.85	44	40.00	73	35.43
3	9	9.57	8	7.27	17	8.42
4	4	4.26	2	1.82	6	3.04
5	1	1.06	0	0	1	0.53
Number of households	94	100.00	110	100.00	204	100.00

In addition to owning a deep well to exploit groundwater, water storage is a major concern for local people coping with water scarcity. However, it was found that only 25% of households own water tanks for storing water. Table 4.14 shows that the richer the household, the more water tanks are owned.

Table 4.14. Number of water tanks by group and by commune (Source: Household survey, Cau Ngang district, 2009).

Number of water tanks	Long Son commune (%)			My Long Bac commune (%)		
	Poor	Non-poor	Total	Poor	Non-poor	Total
No tank	33.33	25.00	28.10	38.78	15.71	25.21
1-5	64.29	48.21	58.68	40.82	42.86	42.02
6-10	2.38	23.21	11.57	18.37	34.29	27.73
>10	0.00	3.57	1.65	2.04	7.14	5.04
Total	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**

4.5.4 Natural Assets

Natural assets of households include farm land resources and farm activities related to water resources and management. Table 4.15 shows the area land use by farm household. Farm size was small, averaging 1 ha, of which rice cropping was the highest contribution at around 0.7 hectares (more than 50%), followed by cash crops at 0.15 ha, and aquaculture at around 0.11 ha.

Table 4.15. Area of land per household by commune (Source: Household survey, Cau Ngang district, 2009).

	Unit	Long Son	My Long Bac	Total
Rice land	m^2	8,066	5,655	6,865
Cash crop land	m^2	2,000	1,013	1,509
Aquaculture land	m^2	2,040	214	1,131
Residential land	m^2	1,386	959	1,173
Other land	m^2	298	33	166
Total	**m^2**	**13,789**	**7,874**	**10,844**

Farm size differed between poor and non-poor households (Table 4.16). The farm size of the non-poor households is double compared to those of poor households, 1.36 ha and 0.63 ha respectively. Rice land accounts for the highest distribution amongst the different farm sizes. Even though there are different farm sizes between poor and non-poor households, farmers usually divide their land for diversification of farm activities such as rice, cash crops, and aquaculture regarding water supply.

Table 4.16. Area of Land per Household by Household Group in Long Son Commune (Source: Household survey, Cai Ngang district, 2009).

	Unit	Poor	Non-poor	Weighted Mean
Rice land	m^2	3,788	8,732	6,865
Cash crop land	m^2	1,018	1,806	1,509
Aquaculture land	m^2	552	1,482	1,131
Residential land	m^2	857	1,365	1,173
Other land	m^2	66	227	166
Total	**m^2**	**6,281**	**13,612**	**10,844**

Further, the gap between farm sizes was very large in Long Son commune, where there is a high distribution of the Khmer group. There is up to a threefold difference in farm size between poor and non-poor farmers, with 0.63 ha for poor household and 1.7 ha for the non-poor farm (Table 4.17).

Table 4.17. Area of land per household by household group in Long Son Commune (Source: Household survey, Cau Ngang district, 2009).

	Unit	Poor	Non-poor	Weighted Mean
Rice land	m^2	3,369	10,563	8,066
Cash crop land	m^2	1,300	2,372	2,000
Aquaculture land	m^2	714	2,744	2,040
Residential land	m^2	954	1,616	1,386
Other land	m^2	48	430	298
Total	**m^2**	**6,385**	**17,725**	**13,789**

Where residents of My Long Bac commune are mostly from the Kinh group, the gap in farm size between poor and non-poor farmers is about 1.5 times, at 0.6 ha/household and 0.9 ha/household respectively (Table 4.18). The rice land also has the highest distribution, accounting for 70% of the total farm land.

Table 4.18. Area of land per household by household group in My Long Bac Commune (Source: Household survey, Cau Ngang district, 2009).

	Unit	Poor	Non-poor	Weighted Mean
Rice land	m^2	4,148	6,694	5,655
Cash crop land	m^2	776	1,177	1,013
Aquacultured land	m^2	412	77	214
Resident land	m^2	775	1,086	959
Other land	m^2	82	0	33
Total	**m^2**	**6,192**	**9,036**	**7,874**

4.5.5 Financial assets

Financial assets are determined by farm household income and expenditure, the amount of savings per household, and the capacity to access a form of credit. Table 4.19 presents a summary of net farm income in the two communes surveyed. The annual average net household income is 45.6 million VND. This is mainly derived from on-farm activities, which contribute 65% of total income, while income from off-farm activities contributes about 27%, and income from family labour was about 5%. Because of the larger farm sizes in Long Son commune, the net household income of this commune is higher than that of My Long Bac commune, at 49.5 million VND and 41.7 million VND respectively.

Table 4.19. Household net income (VND/household) by commune (Source: Household survey, Cau Ngang district, 2009).

Source of income	Long Son commune		My Long Bac commune		Weighted Mean	
	Income	(%)	Income	(%)	Income	(%)
Agriculture	33,946,372	68.48	25,331,896	60.70	29,602,939	64.89
Hired labor in agriculture	1,856,356	3.74	1,942,125	4.65	1,899,601	4.16
Non-agriculture	12,507,034	25.23	12,420,117	29.76	12,463,210	27.32
Total	**49,573,830**	**100.00**	**41,730,305**	**100.00**	**45,619,111**	**100.00**

Table 4.20 shows the income distribution between poor and non-poor farmers. The non-poor households have double the farm income of the poor farmers. Annual household income of non-poor households is 56.1 million VND compared to 27.6 million VND of poor households. The income from agriculture and aquaculture is the major factor in explaining the difference between the income of poor and non-poor households. For example, 68% of income for non-poor farmers comes from agriculture while this only accounts for 54% of income for poor households. However, off-farm income was more important for the poor at about 31% compared to 26% for the non-poor.

Table 4.20. Household net income (VND/household) by household group (Source: Household survey, Cau Ngang district, 2009).

Source of income	Poor		Non-poor		Total	
	Income	(%)	Income	(%)	Income	(%)
Agriculture	14,915,450	53.99	3,8219,599	68.04	29,602,939	64.89
Hired labor in agriculture	3,066,250	11.10	1,215,167	2.16	1,899,601	4.16
Non-agriculture	8,644,045	31.29	14,703,787	26.18	12,463,210	27.32
Others	1,000,568	3.62	2,036,333	3.62	1,653,361	3.62
Total	**27,626,314**	**100.00**	**56,174,886**	**100.00**	**45,619,111**	**100.00**

As shown by the above results, if groundwater is a common asset, the non-poor farmers with a larger farm size gain more benefits from using the groundwater for their farm income. This might increase the income gap between non-poor and poor farmers, and an unfair disparity in commune resource use will become more pronounced in the future.

The household income structure in Long Son commune is somehow different from the general income figures of the total households surveyed.

In the poor households in Long Son commune, income earned from selling labour comprised a large proportion at 15.6%, while in the non-poor group, this type of income only accounts for 1.2% (Table 4.21).

Table 4.21. Household income (VND) by groups in Long Son commune (Source: Household survey, Cau Ngang district, 2009).

Source of income	Poor		Non-poor		Total	
	Income	(%)	Income	(%)	Income	(%)
Agriculture	15,917,645	49.50	31,829,056	85.18	25,331,896	70.61
Hired labor in agriculture	2,168,980	24.59	1,785,563	7.40	1,942,125	14.42
Non-agriculture	9,251,143	23.55	14,607,155	1.80	12,420,117	10.68
Others	862,245	2.36	2,846,338	5.61	2,036,167	4.28
Total	**28,200,012**	**100.00**	**51,068,112**	**100.00**	**41,730,305**	**100.00**

Agriculture with upland crops, rice, and livestock is quite an important component of household income in Long Son commune. However, the importance of these constituent components is different between poor and non-poor household groups. Upland crops play a very important role in poor households, contributing 58% of total household income (Table 4.22). On the other hand, upland crops make up only 38% of total income in non-poor households. This difference in income structure also implies that the poorer households might rely more strongly on groundwater exploitation, since upland crops require more groundwater per unit of land compared to other crops like rice, or livestock.

Table 4.22. Household income (VND) from agricultural activities by group in Long Son Commune (Source: Household survey, Cau Ngang district, 2009).

Source of income	Poor		Non-poor		Total	
	Income	(%)	Income	(%)	Income	(%)
Rice	3,175,347	32.11	8,945,437	16.92	6,589,317	23.12
Cash crop	11,376,278	58.54	16,502,070	61.45	14,409,038	60.26
Fruit	-	0.00	-	0.00	-	0.00
Livestock	963,980	8.70	5,599,859	17.93	3,706,875	14.16
Aquaculture	402,041	0.65	781,690	3.71	626,667	2.46
Total	**15,917,645**	**100.00**	**31,829,056**	**100.00**	**25,331,896**	**100.00**

In My Long Bac commune, agriculture plays an important role in livelihoods and accounts for 70% of total household income. Table 4.23 below indicates that agriculture is quite essential for non-poor households. In other words, agriculture is a principle income source for allowing this household group to access more income. The poorer household groups only own a small amount of land and they tend to work in other sectors such as labour or non-farm activities. Agriculture makes up 23% of total income in this poor household group.

Table 4.23. Household income (VND) by groups in My Long Bac Commune (Source: Household survey, Cau Ngang district, 2009).

Source of income	Poor		Non-poor		Total	
	Income	(%)	Income	(%)	Income	(%)
Rice	3,104,692	22.73	11,524,646	26.21	8,741,780	25.75
Cash crop	7,955,206	58.25	15,230,258	34.64	12,825,792	37.78
Fruit	30,769	0.23	-	0.00	10,169	0.03
Livestock	1,524,744	11.17	11,195,759	25.47	7,999,407	23.56
Aquaculture	1,040,872	7.62	6,012,335	13.68	4,369,225	12.87
Total	**13,656,283**	**100.00**	**43,962,998**	**100.00**	**33,946,372**	**100.00**

Table 4.24 shows the importance of upland crops in the agricultural sector of My Long Bac commune, contributing to 60% of agricultural income.

Table 4.24. Household income (VND) in agricultural activities by groups in My Long Bac commune (Source: Household survey, Cau Ngang district, 2009).

Source of income	Poor		Non-poor		Total	
	Income	(%)	Income	(%)	Income	(%)
Agriculture	13,656,283	50.76	43,962,998	72.35	33,946,372	68.48
Hired labor in agriculture	4,193,590	15.59	702,532	1.16	1,856,356	3.74
Non-agriculture	7,881,282	29.29	14,790,633	24.34	12,507,034	25.23
Others	1,174,359	4.36	1,308,354	2.15	1,264,068	2.55
Total	**27,626,314**	**100.00**	**56,174,886**	**100.00**	**45,619,111**	**100.00**

Generally, income from on-farm activities shows only a slight decline from the year 2000 to the present time (results not shown). There is a small increase in dependence on natural resources exploitation in Long Son commune, however, this is almost unchanged in My Long Bac commune. The households tend to seek income from non-farm activities far from their settlement. This can be considered a common phenomenon since impacts of urbanisation in Tra Vinh town and the development of service sectors occurs outside Tra Vinh province.

4.5.6 Social assets

Social assets were defined as participation in a self-help organisation or a community's own organisation, or participation in community organisations (such as farmers' associations, women's associations, or Youth Union) on which a network of households and the community could potentially rely on to deal with groundwater problems. Table 4.25 shows the participation level of household heads in rural community organisations. The number of household heads without involvement in rural community organisations was high, about 66% from the Long Son commune, and 72% from the My Long Bac commune. The remainder included farmers' organisations and veterans.

Table 4.25. Rate of household heads participating in local institutions (Source: Household survey, Cau Ngang district, 2009).

Institution	Long Son (%)	Institution	My Long Bac (%)
Missing	6.6	Missing	2.5
Do not participate	66.1	Do not participate	71.7
Farmer's union	9.1	Farmer‘s union	5.0
Farmer's union/women	1.7	Farmer's union/women	0.8
Women	0.8	Women	1.7
Youth	1.7	Veterans	14.2
Veterans	5.0	Veterans and officers	0.8
Officer	5.8	Veteran	2.5
Other	3.3	Other	0.8
Total	**100.0**		**100**

Table 4.26 shows the economic losses caused by drought between the non-poor and poor households among the two communes. When comparing the poor's losses from serious drought (a drought that could damage the farming crops) and ordinary drought (lack of water over a short period of time), the former created about double the amount of losses in both communes; about 5.9 million and 3.1 million VND of loss in the Lon Son Commune, and about 6.55 million VND and 3.8 million VND of loss in My Long Bac Commune. More importantly, the non-poor households experienced a greater loss due to drought when compared with the poor, and serious droughts created more losses than those of ordinary droughts, in

the amount of 12.4 million VND and 3.7 million in the Long Son Commune respectively, and 6.86 million in My Long Bac as compared to those of 3.1 million VND in the My Long Bac Commune.

Table 4.26. Economic loss (VND/household) due to drought occurrence, by groups and by communes (Source: Household survey, Cau Ngang district, 2009).

	Long Son		**My Long Bac**	
	Poor	Non-poor	Poor	Non-poor
Ordinary drought	3,121,875	3,708,750	3,865,600	3,107188
Serious drought	5,946,250	12,443,939	6,548,462	6,862162

It was found that drought can occur annually in the surveyed areas. The ways local people in Long Son commune cope with drought are generally similar between poor and non-poor household groups (Table 4.27). Most people store water in small jars and tanks to withstand drought. Some secure water from their neighbours. Regarding agricultural and livestock production, many people have started to change to crops and animals that require less water in order to cope with drought occurrences. For example, they grow hybrid corn instead of rice crops, or they change from raising duck to chicken farming. Other solutions include digging deeper wells in nearby rice fields or buying machines for pumping during electricity stoppages, etc. Table 4.27 indicates the various adaptation options. Most people try to build deeper wells rather than rely on what they have currently used. A significant proportion of local people have used tap water from a common water supply station as a good means of adaptation.

Table 4.27. Coping mechanisms and adaptation strategies to drought by poor and non-poor households in Long Son Commune (Source: Household survey, Cau Ngang district, 2009).

	Coping		**Adaptation**	
	Strategies	**(% of households)**	**Strategies**	**(% of households)**
Poor households	Storing water	71.43	Building water tank	42.86
	Getting water from neighbour's deep well	26.19	Building dug well	42.86
	Changing livestock	11.90	Building deep well	66.67
	Changing crops	33.33	Using tap water	42.86
	Others	38.10	Other	4.47
Non-poor households	Storing water	63.29	Building water tank	49.37
	Getting water from neighbour's deep well	22.78	Building dug well	36.71
	Changing livestock	24.05	Building deep well	77.22
	Changing crops	45.57	Using tap water	39.24
	Others	34.18	Others	5.06

In My Long Bac commune, ways of coping with and adapting to drought are almost the same as those in Long Son commune. There is not much difference between poor and non-poor people's response to the occurrence of drought. Most people rely on storing water. Some change crops and animals to those requiring less water. For adaptation, people mostly look to building a new deep well rather than relying on what they have already owned (Table 4.28).

Table 4.28. Coping mechanisms and adaptation strategies to drought by poor and non-poor households in My Long Bac commune (Souce: Household survey, Cau Ngang district, 2009).

	Coping		**Adaptation**	
	Strategies	**(% of households)**	**Strategies**	**(% of households)**
Poor households	Storing water	38.78	Building water tank	26.53
	Getting water from neighbour's deep well	24.49	Building dug well	34.69
	Changing livestock	4.08	Building deep well	75.51
	Changing crops	30.61	Using tap water	28.57
	Others	51.02	Others	6.12
Non-poor households	Storing water	66.20	Building water tank	38.03
	Getting water from neighbour's deep well	7.04	Building soil well	14.08
	Changing livestock	8.45	Building deep well	92.96
	Changing crops	23.94	Using tap water	29.58
	Others	42.25	Others	4.23

Groundwater is gradually declining both in quantity and quality. There are many reasons to explain this situation. About 48.5% of total respondents interviewed stated that there has been a decline in groundwater quantity due to its over-use for upland crops over the last several years (Table 4.29). Other reasons include using it for rice and domestic purposes.

Table 4.29. Local people's perception on the quantity status of groundwater (Source: Household survey, Cau Ngang district, 2009).

As compared to the last 5 years (%, n=241)		**Looking forward to the next 5 years (%, n=241)**	
Very serious decrease	0.83	Exhausted	13.69
Serious decrease	6.22	Fast decrease	46.89
Decreased	41.91	No change	37.34
Unchanged	42.32	Missing data	2.07
Don't know	7.47	-	-
Missing data	1.24	-	-
Total	**100.00**	**Total**	**100.00**

With respect to the quality of groundwater, not many people stated an observed decline, however, there is a certain proportion of local people who said groundwater quality has decreased over the last five years (Table 4.30). No scientific documentation is available about the reduction in quality of groundwater. Local people perceive the decline in groundwater quality to be a normal process as groundwater is being used for many purposes without security measures from local authorities.

Table 4.30. Perceptions on the quality of groundwater over the last 5 years (Household survey, Cau Ngang district, 2009).

Quality status	**Percent (%)**	**Reason for quality change**	**Percent (%)**
Better	5.39	Natural	17.43
Unchanged	75.10	Chemical used in agriculture	12.86
Worse	17.01	Multiple uses	11.20
Others (no idea or the same)	0.41	Misuse of deep well	6.64
-	-	Don't know	63.07
Missing	2.07	Missing	2.49
Total	**100.00**	**Total**	**100.00**

4.5 Synthesis and Discussion

4.5.1 Vulnerability Assessment

From the viewpoint of the indicators at the regional level, there are hazards to groundwater in that it is vulnerable to over-exploitation, salinity intrusion, and therefore reduction in groundwater quantity and quality is a reality. Changes in land use and intensive agriculture, human activities, and surface water pollution are major factors creating the vulnerability of groundwater in the region. This situation may be aggravated by climate change impacts in the future.

The indicators at the provincial level reveal over-exploitation of groundwater with a high density of small pump wells and large state-run pump wells. Furthermore, there is high competition between groundwater users that rely on the supplies for daily activities, agriculture and shrimp cultivation, and also for industrial development and services. More importantly, salinity in groundwater caused by over-extraction is another source of groundwater pollution in the province. The variation of the water table between the rainy and dry seasons gradually increases. Less groundwater recharge in the dry season, drought, and salinity intrusion are also major natural hazards to groundwater in Tra Vinh province.

Through participatory rural appraisals, relationships were recognised among physical features and biology on the basis of soil types and water resources, as well as the relationships between culture, physical features, and biology, and water use of the different socio-economic groups. Khmer people living on the sandy banks, in a high topography with upland crops and cows as their main farm activities, record higher groundwater use because of upland crops. These crops create a high demand for water in the dry season, which is mostly supplied from groundwater. Kinh people living along the rivers and in lowland with rice, shrimp, and livestock as their main farm activities record relatively high uses of groundwater in the dry season but can also more readily access surface water. Chinese people living close to the market with their main activities of providing agricultural services rely mainly on groundwater as a good drinking water supply. Moreover, community perception of groundwater and recognition of problems of quality and quantity by increasing agricultural activities and surface water pollution were also identified. The poor face greater problems accessing groundwater for use because of their restricted capacity to invest in private deep wells.

4.5.2 Capacity of households to cope with groundwater problems

The sustainable livelihoods framework developed by DFID (1999), with its emphasis on human, social, natural, financial, and physical assets, was applied to the Tra Vinh case in order to undertake a livelihoods analysis according to the situation of agricultural activities and opportunities of economic development due to groundwater use and reduction. Livelihood development depends on the results of a vulnerability assessment, and is concerned with shock, trends, and seasonality that affect the livelihoods assets of local people. The framework emphasises that, in particular, the transforming structures in the governmental system or private sector and respective processes (e.g. laws, culture) influence the vulnerability context, and determine both the access to and major influences on livelihood assets of people. The approach underlines the necessity of empowering local marginalised groups in order to reduce vulnerability effectively. The approach views vulnerability as a broad concept, encompassing livelihood assets and their access, and vulnerable context such as shocks, seasonality, and trends, as well as institutional structures and processes that are described by the vulnerability assessment above.

Two hundred and forty-one farm households were interviewed to identify more details of socio-environmental indicators of groundwater vulnerability and livelihood approaches to dealing with groundwater problems. The interview included components on human, physical, natural, financial, and social assets, as described in the section above. Some of the constraints and opportunities which were identified through these results for coping with groundwater problems are as follows:

- households whose head is elderly or has a low level of education may hinder technological applications of water management and farm practices;
- the high occurrence of concrete and semi-concrete house structures indicate that there is high potential for practicing and stimulating rainfall harvesting techniques, especially for coping during periods of drought. Some wealthier households already practice rainfall harvesting in storage tanks, and share this water for drinking with poorer households; however, only 25% of house holds practice rainwater harvesting;
- in order to avoid risks and cope with droughts, both poor and non-poor farmers use highly diversified farm activities that re quire less water;

- income from agriculture and aquaculture provided the most important components of the differing levels of income between poor and non-poor households;
- when groundwater is a common asset, non-poor households benefit more from using groundwater for their farm income. This may lead to a widening of the gap between poor and non-poor households, and may lead to a higher level of disparity in communal resource use;
- self-help organisations and community networks may be one way of dealing with groundwater problems, and around 20-25% of commune residents are already members of an organisation;
- recent overuse of groundwater for cash crops has led to a decrease in groundwater quantity;
- it is locally perceived that groundwater quality is also decreasing due to its wide use for multiple purposes, with little oversight or effective regulation from local authorities; no scientific documents recording a reduction in groundwater quality are available; and finally,
- a significant proportion of local people have begun using tap water from a common water supply station for drinking water as an adaptive strategy.

4.6 Policy implementation

The increasing water scarcity, particularly in groundwater, will threaten the sustainability of the region without further means to control and improve water supplies. There is a need to balance water supply and demand based on economic, social, and environmental objectives, maximising net benefits of water use and groundwater trading, where possible.

Although the amount of water in the Mekong Delta is large compared with that in other regions of the world, surface water pollution has increased year after year, and the demand for water use has been increasing due to a growing population, industrialisation, urbanisation, and higher living standards. Providing a clean water supply from groundwater and its management will therefore be a major issue for policy debate and implementation.

Immediate and long-term solutions for sustainable management of groundwater resources in the Mekong Delta in general, and Tra Vinh in particular are necessary. First, in order to improve the situation and ensure effective and sustainable use of groundwater, systematic surveys and assessments of groundwater resources should be immediately undertaken to formulate appropriate management policies. Second, the calculation of recharge and withdrawal rates at different scales should be undertaken in order to come up with a reasonable solution to using groundwater over specific scales. Third, groundwater exploitation should be reduced through alternatives such as increasing rainwater storage, artificial recharge, and slow sand filtration (KIP methods of the study team 2008).

On a regional level, because groundwater has no boundaries which align with provincial administration boundary lines, a regional approach to setting uniform regulations for groundwater use and management among the provinces in the region is highly recommended. Linkages and coordination with the economic development sector are needed with a corresponding level of integration of priorities of groundwater users.

Commune residents now recognise the important value of groundwater for their livelihoods and their daily activities. Therefore, at the national level, policy makers have the opportunity to involve communities in groundwater use and management. The interaction and development of linkages between the Ministry of Agricultural and Rural Development and the Ministry of Natural Resources and Environment to implement regulations of groundwater use and management is strongly recommended.

A decentralised water supply for rural communities is recommended. The development of many small drinking water treatment plants inside or near communes or districts may be provided at a low cost as a simple means of distribution and for ease of management. Local knowledge and community participation opportunities for groundwater management should be practised annually at the commune level. In this way, commune residents will identify their common resources related to groundwater use and management and will be more aware of groundwater management according to their local conditions, which will facilitate implementation of the policies for groundwater resource management.

It is also important to enhance the ability of government agencies and local governments to manage groundwater resources as well as to raise public awareness on the issue. Groundwater monitoring and integrated water resource management involving community participation should be applied.

4.7 Capacity Development Programmes and Further Research

The GWAHS-CS project highlights the advantages of providing good networking opportunities for groundwater users and managers to share experiences and lessons learned. The present study has also highlighted some areas where further research could be undertaken and include the following:

- There are many definitions of vulnerability that depend on the purpose and nature of the research on groundwater use and management.
- PRA methods and livelihoods approaches are suitable for engaging community participation in groundwater resource management and identification of capacity at the household level to cope with groundwater problems. Such methods are strongly recommended.
- In the case of Vietnam, research on institutions, organisations, and policies for groundwater management are recommended.
- The roles of groundwater in the context of climate change impacts in the Mekong Delta should be a priority subject for further research.
- Short training courses on the efficiency of groundwater use and management should be implemented at the commune level.

4.8 References

Be TT, Sinh BT and Fiona M. 2007. Literature analysis challenges to sustainable development in the Mekong Delta: regional and national policy issues and research needs. Bangkok: The Sustainable Mekong Research Network Retrieved from: www.sumernet.org

Birkmann J. 2006. Measuring vulnerability to promote disaster-resilient societies: conceptual frameworks and definitions. In: Birkmann J (ed). Measuring Vulnerability to Natural Hazards: Towards Disaster Resilience Societies. UNU Press

Carew-Reid J. 2007. Rapid assessment of the extent and impact of sea level rise in Viet Nam. Climate Change Discussion Paper No. 1, International Centre for Environmental Management, Brisbane

Chiem NH. 1993. Geo-pedological study of the Mekong Delta. Southeast Asian Studies, Vol.31, No.2, September 1993, Kyoto University

Cuong V. 2006. Dong Bang Song Cuu Long: co noi nuoc ngam tut xuong toi 14 m. Nong Thon Viet Nam [in Vietnamese]

Danh VT. 2007. Economic value of groundwater protection in the Mekong Delta. Project Report (CAULES-DANIDA Project)

Dasgupta S, Laplante B, Meisner C, Wheeler D and Yan J. 2007. The impact of sea level rise on the developing countries: a comparative analysis. World Bank Policy Research Working Paper 4136

Department of Soil Science of Can Tho University. 2010. Land use map of the Mekong Delta 2010

Department of International Development (DFID). 1999. Sustainable livelihoods guidance sheets. Retrieved from: http://files.ennonline.net/attachments/871/dfid-sustainable-livelihoods-guidance-sheet-section1.pdf

Department of Natural Resources and Environment (DONRE) of Tra Vinh. 2005. Planning for natural resource use from 2005-2010 in Tra Vinh Province. Workshop by the Tra VInh ‘s DONRE, Un published

General Statistical Office (GSO). 2003. Statistical Yearbook. Ha Noi, Statistical Publishing House

General Statistical Office (GSO). 2002, 2006, 2010, 2013 and 2014. Statistical Yearbook. Ha Noi, Statistical Publishing House

Hoang H. 2008. Tra Vinh: Can xiet chat quan ly nguon tai nguyen nuoc ngam. Department of Water Resources Management, MONRE

Hori, H., 1996. The Mekong: The Development and its Environmental Effects. KOKON-SHOIN Publishing, Japan.

MONRE (Ministry of Natural Resources and Environment of Vietnam). 2009. Climate change and sea level rise scenarios for Vietnam (internal report)

MRC. 2006. Flood areas of the Vietnam Mekong Delta. MRC lower basin Mekong Planning, 2006

NEDECO (Netherlands Engineering Consultants). 1991. Master Plan for the Mekong Delta in Vietnam (VIE/87/031). Groundwater and Water Supply. Working Paper No.2. NEDECO, 1991

Nghi VV. 1994. Assessment of groundwater resources in the Mekong Delta. Ha Noi, Journal of Geology (3-4):36-46 [in Vietnamese]

Nhan DK and Sanh NV. 2008. Vietnam Mekong Delta with high values of agricultural product exports, but poor farmers. Internal Report

Nuber T. 2005. Appraisal of drinking water resources of the Mekong Delta, Vietnam. University of Bochum

Öjendal J. 2000. Sharing the good models of managing water resources in the Lower Mekong River Basin. Department of Peace and Development Research, Gothenburg University, Sweden p 297

Quyen TTH. 2005. Current situation of groundwater uses and quality and management in CaiRang District, Cantho City, Vietnam. Unpublished Bachelor Thesis. Cantho University

Sanh NV. Xuan VT and Phong TA. 1998. History and future of the farming system in the Mekong Delta. In: Xuan VT and Matsui S (eds). Development of Farming Systems in the Mekong Delta of Vietnam. HCMC, Ho Chi Minh City Publishing House, pp. 16-80

Statistical Office of Tra Vinh Province, 2007. Statistical Yearbook. Tra Vinh, Provincial Statistical Office

Thao LB. 2001. Territory and regional geography of vietnam. World Publishing House

Thuan TM. 2004. Multi-objective management of saltwater intrusion groundwater: optimization under uncertainty. PhD Thesis. Wagenninge University

Trung VT. 2005. Tra Vinh: feasible measure for clean water supply in the rural area. MONREDONRE [in Vietnamese]

Tuan LA. 2003. An overview of the drinking water supply situation in the Mekong River Delta, Vietnam. Can Tho University. Internal Report Tuan LA and Wyseure G. 2007. Organic matter distribution of the root zone in a constructed subsurface flow wetland. Communications in Agricultural and Applied Biological Sciences. 72(1): 297-300

Turner BL, Kasperson RE, Matson PA, McCarthy JJ, Corell RW, Christensen L, Eckley N, Kasperson JX, Luers A, Martello ML, Polsky C, Pubsipher A and Schiller A. 2003. A framework for vulnerability analysis in sustainability science. Proceedings of the National Academy of Sciences 100(14):8074-8079

Wagner F, Tran VB, and Renaud FG. 2012. Groundwater resources in the Mekong Delta: availability, utilization and risks. In: Renaud FG and Kuenzer C (eds). The Mekong Delta System: Interdisciplinary Analyses of a River Delta, Springer pp. 201-220

Wassman R, Hien NX, Hoanh CT and Tuong TP. 2004. Sea level rise affecting the Vietnamese Mekong Delta: water elevation in the flood season and implications for rice production. Climatic Change 66(1-2):89-107

Acknowledegments

The Chapter is an output derived from the field survey, including in-depth interviews, focus group discussions and standardised household survey in 2008 under a framework of the GWAHS-CS Project. We would like to express grateful thanks for the assistance of Dr. Fabrice Renaud (UNU-EHS) and other experts from the project. We also appreciate the valuable support from local specialists and farmers during our field survey in the coastal area of Tra Vinh Province. We would like to thank the research team members of the Mekong Delta Development Research Institute, including Dr. Le Ngoc Thach, Mr. Nguyen Ngoc Son, Mr. Nguyen Cong Toan, Mr. Pham Hai Buu, who participated in the field research in Tra Vinh.

CHAPTER 5

Vietnam – Binh Thuan Case Study: Example of Aquifer Recharge

Bui Tran Vuong[1], Doan Ngoc Toan, Pham Van Hung, Do Thi Thanh Hoa, Pham Van Sinh, Nguyen Thi Hoi,

Division for Water Resources Planning and Investigation for the South of Vietnam

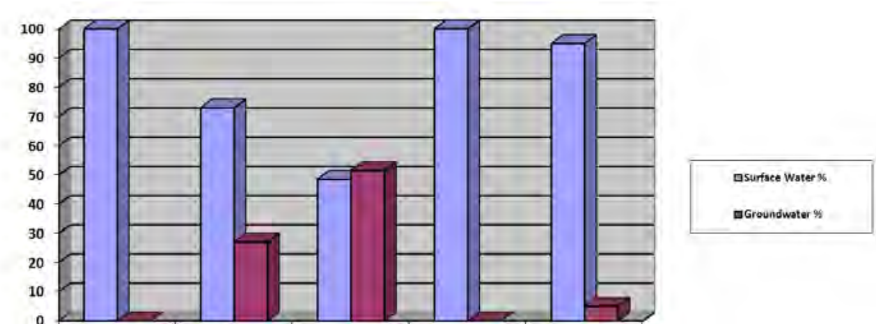
5.1 Main Challenges of the Case Study Area

Binh Thuan province covers the coastal plain of southeast Vietnam and has an area of approximately 8,000 km² with a population of about 1 million people (Figure 5.1). The province is planned as one of seven economic development regions in Vietnam and is therefore of strategic importance. The main development sectors are agriculture, forestry, fisheries and associated industries, processing industries based on agriculture, and minerals, and timber. The relative value of agriculture is expected to decrease as the economic focus is expected to shift away from agriculture towards the tourism and processing industries. At the same time, there is an increasing trend to diversify from rice production to more cattle- and goat-raising for meat production, with an attendant need to irrigate pastures. These trends, together with plans to move industries into rural areas, are expected to increase the demand for rural water supply, and agricultural development in these areas will require part of these supplies to be of high quality.

Figure 5.1. Location map of the study area: Binh Thuan province (Thoa et al. 2010).

A peculiarity of the region is the appearance of a small lake over the last 30 years as a result of direct infiltration into the sand aquifer due to the removal of land cover in 1975. The Bau Noi Lake was formed in November 1999 due to the elevation of the piezometric head of the aquifer (Figure 5.1). Since the water occurrence is perennial, only slight level changes during the wet and dry seasons are observed. Bau Noi was chosen as a case study site because of its close proximity to Hong Phong Villages which have been affected by longstanding and recurrent water shortages, and the potential for improving the quality of water through pumping at reasonable rates and at a sufficient distance from the lake in order to provide adequate residence time in the aquifer for pathogen removal (Thoa et al. 2006).

The freshwater used for irrigation purposes is derived almost entirely from surface water sources. For domestic water use in urban areas, 73% of the freshwater supply is surface water and 27% comes from groundwater sources. In rural areas, the equivalent domestic water sources are 48.5% and 51.5% respectively, indicating the higher dependency of rural communities on groundwater resources. Freshwater supplies used in the aquaculture sector derive only 5% of their total water usage from groundwater sources (Figure 5.2) (Department of Water Resources Management 2008).



	Irrigation	Urban	Rural	Hydro Powe	Aqua Culture
Surface Water %	100	73	48,5	100	95
Groundwater %	0	27	51,5	0	5

Figure 5.2. Ratio of surface and groundwater use by economic sector in Binh Thuan Province (Department of Water Resources Management 2008).

To exploit groundwater resources in a sustainable manner, the following aspects and challenges need to be considered:

i) Effects of existing water use on spring waters

Groundwater resources are not used extensively through abstraction from wells over the main body of the aquifer. However, the natural discharges from these aquifers through a series of springs around the periphery support a significant amount of rural irrigation and crop production. Therefore, any development of groundwater resources must be managed to ensure that these spring flows are not reduced to an unacceptable level. Alternatively, supplementary water supplies could be developed for use. These could be provided from the main aquifer with appropriate engineering and management.

Design and planning of the layout of wells will be crucial in determining the potential effects of abstraction on spring discharges; the wells should be properly sited so that their drawdown effects on the springs are minimised. This will require a good understanding of hydraulic characteristics of the aquifer and an ability to predict the extent of drawdown for production wells.

ii) Salt water intrusion

Both the Phan Thiet and Bac Binh aquifers discharge to the ocean through a salt-/fresh- water interface located within 1 km of the coast. Exploitation of the groundwater resources is likely to result in landward intrusion of the interface if this discharge is reduced, with a consequent lowering of the potentiometric head in the vicinity of the interface.

Preliminary studies have mapped the saline interface via electrical resistivity techniques and some well census information. This mapping needs to be confirmed using wells constructed to accurately determine the location and configuration of the interface and to allow for future monitoring of any movement.

Clearly, the well field should be located and managed in a manner that will ensure that salt water intrusion does not present a threat to its long-term operation. Some modeling of the drawdown effects of alternative well field and pumping scenarios can be utilised to design the optimal layout.

iii) Environmental effects

The primary environmental concerns with the aquifers are related to wetlands located within the northern area and to environmental systems associated with the spring discharges. These ecosystems need to be evaluated in order to determine the extent of their dependence on groundwater resources and their value either as a source of water supply or for their social or ecological value. They should also be assessed in terms of the water quantity and quality regimes necessary to ensure that these ecosystems are not damaged; these regimes should then be set as the management constraint criteria. Techniques are available to ensure ecosystem resilience and sustainability while enabling significant groundwater abstraction rates. The primary tool for evaluating alternative development and operational strategies for any well field is a hydraulic model of the groundwater, as will be discussed below. Techniques to maintain wetland ecosystems can be employed using techniques such as artificial recharge.

iv) Land use and water quality protection

According to a 2008 survey conducted by the Department of Water Resources Management under a project on water resources planning of the Nam Trung Bo area, land use in the province consists of 260,000 ha of unused land and 95,000 ha of agricultural land, of which 78,000 ha is under perennial crops, the majority of which is rice (Department of Water Resources Management 2008). Most of the land overlying the two aquifers in the region, the Bac Binh and Phan Thiet aquifers, is sandy, infertile, and consequently vacant. This suggests that the water quality is not subject to a high degree of risk of contamination from human activities. Care needs to be taken at the extreme north of the Phan Thiet aquifer where an extensive cemetery and rubbish disposal area provide considerable potential for local groundwater contamination. If any aquifer development is to take place, it is recommended that the area close to the cemetery and disposal area not contain production wells. That is, no production well should be

sited north of the military camp immediately south of Phan Thiet.
The Bac Binh aquifer has little intensive land use, with the exception again of the cemetery near Phan Thiet; similar precautions should be taken with well field locations for the Bac Binh aquifer as those proposed for the Phan Thiet aquifer. Currently, there are plans for an economic development of land overlying the Bac Binh aquifer. While the aquifer offers the opportunity for a cheap, accessible water supply source, it is extremely important to locate and manage the development in a manner that does not compromise the water quality of the underlying groundwater. The effects of well field abstraction on the water balance can be estimated by means of a groundwater flow model.

A land use management plan is required to ensure long-term compatibility of land use with the available groundwater resources. Essentially, this management plan should seek to avoid the introduction of any intensive land use that will cause either point or non-point source contamination of underlying groundwater resources. Some increase in the economic output of the land could be achieved through low intensity land uses such as silvoculture using selected tree crops without compromising the water quality of the aquifers.

5.2 Description of the Case Study Area

The Bac Binh district is a mountain district of Binh Thuan province; with an area of 182,533 ha, the district contains 17 villages.

By the end of 2007, water output from the Dai Ninh hydropower reached 53 m^3/s, which was enough to meet the irrigation demands for over 7,000 ha of rice production and 1,000 ha of perennial trees. Agricultural trends focus on dragon fruit, short-term industrial trees, cattle, and freshwater aquaculture. With an advantage of abundant natural resources such as clay, sand, ilmenite, zircon, and titanium ores, associated industries of minerals production and processing of agricultural and aquaculture products are now developing, and two industrial areas have been formed in Bac Binh district. Furthermore, with 30 km of coastline and the famous Mui Ne tourist area surrounded by white sand dunes and beautiful landscapes, tourism is now rapidly developing. Many high standard and large resorts are being built.

The current case study focused on two villages in the district of Bac Binh in Binh Thuan province: Hoa Thang and Hong Phong.

Hoa Thang is divided into 3 communes of Hong Lam, Hong Chinh, and Hong Thang, and covers an area of 19,420 ha with a population of 6,514 residents. The main economic activities of the village are agriculture-forest-aquaculture, industry-construction, and commerce-services. The total value for each economic sector is provided in Table 5.1 below.

Table 5.1. Value of each economic sector in Hoa Thang for 2006-2008 (million VND) (Department of Water Resources Management (a) and (b) unpublished).

Total domestic product	2006	2007	2008
Agriculture-forest-aquaculture	12,500	24,875	32,725
Industry-construction	10,892	22,971	28,469
Commerce-services	1,580	1,804	2,256

Under the agriculture-forest-aquaculture sector, around 1,040 ha is reserved for cultivation; from this, 11 ha is used for rice production and the rest is used for vegetation and industrial trees (peanut and cassava). Animal husbandry involves cattle, pigs, and goats; in 2007, this amounted to 3,200, 3,500 and 700 heads, respectively. The total area used for aquaculture in 2007 was 18.4 ha, used mainly for fish and shrimp production, yielding an average of 4.5 ton/ha. Forest resources are poor, and around 67% of the total forest is protected.

The main industries of the village are agricultural and aquaculture processing, mechanic repairs, welding, and turning. There are now five small industrial units.

The commerce-services sector provides telecommunications and transport services. Currently, there are 475 households with telephones (an average of 3 households/phone unit), seven ploughs, and seven trucks provide the main source of transportation for goods and people.

The health care services available in Hoa Thang include a heath station with 150 beds, two doctors and five physicians. In 2008, the health station received 689 cases of illness. As far as education is concerned, in 2008 there were 1,802 children attending school, of which 260 attended nursery school, 814 attended primary school, 678 attended secondary school, and the remaining 50 attended high school.

Hong Phong is a coastal village of Bac Binh district. It consists of three communes of Hong Thinh, Hong Trung and Hong Thanh, and covers an area of 8,979 ha with a population of 1,256 residents. As with Hoa Thang village, the main economic activities of the village are agriculture-forest-aquaculture, industry-construction, and commerce-services.

Under the agriculture-forest-aquaculture sector, around 1,285 ha is reserved for cultivation. In 2007, there were 1,200 cattle, 60 pigs, and 1,400 goats raised. There is approximately 1,001 ha of protected forest, and hence there is no significant forestry production.

The main industrial activities of the village are garment and mason, while the commerce-services sector relies on the activities of small businesses in the area. There are currently 16 small business units in the village.

The health care services available in Hong Phong include a health station of five beds, mainly used for treating first aid cases. Regarding education, in 2008 there were 341 children attending school, of which 50 were in nursery school, 136 in primary school, 135 in secondary school, and 20 in high school (Department of Water Resources Management (a) and (b) unpublished).

5.2.1 Hydrogeological characteristics

According to Thoa et al. (2010), the geological setting of the area (Figure 5.3) is characterised by a ryo-dacitic bedrock (Photo 5.1) which forms steep isolated hills (up to 300 m a.s.l.). It is overlaid by middle Pleistocene eolian sediment consisting of medium-grain quartz sand of a brown-red color, forming sand dunes up to 200 m; Middle Pleistocene marine sediment composed of ilmenite quartz sand; Middle Pleistocene marine sediment with grey-yellow to red-colored quartz sand containing some silt and clay at different levels; Upper Pleistocene eolian sediment of red and orange medium quartz sand; and, Lower Holocene eolian sediment of white to light yellow fine quartz sand. These sediments and bedrock form white and red sand dunes (Photo 5.2) (up to 200 m a.s.l), which occur extensively in the coastal area to the north of Phan Thiet (Figure 5.3).

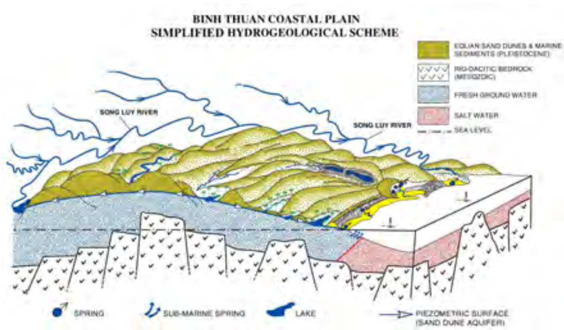


Figure 5.3. Hydrogeological scheme (Thoa et al. 2010).

Photo 5.1. Bed rock in Hong Phong.

Photo 5.2. Red and white sand in the coastal area to the north of Phan Thiet.

The marine sand dunes formation is characterised by the occurrence of an unconfined porous aquifer of variable thickness (40 to 60 m) emerging at ground level in depressed morphological areas (20 to 30 m a.s.l.) and forming wetlands or natural reservoirs, such as in Ta Zon (Photo 5.3), Bau Trang (Photo 5.4), and Bau Noi (Photo 5.5). In the Bau Noi area in particular (approximately 5 km southeast of Hong Phong Village), a pool was formed in November 1999 due to the rising of the piezometric head of the aquifer as a result of the removal of land cover and consequent direct infiltration into the sand aquifer during the last 30 years. This pool is perennial and only slight water level changes are observed during the wet and the dry seasons. This occurrence is very similar to the Bau Trang Lake (Photo 5.4), some 9 km northeast of Bau Noi, where a large natural reservoir occurs, completely supplied by groundwater.

Photo 5.3. Natural reservoir Ta Zon

Photo 5.4. Natural reservoir Bau Trang

The sand dune aquifer is exploited both by direct pumping in places where it emerges (in depressed morphology) or through shallow hand dug wells (5 to 8 m deep). During the dry season, the water requirements of the population are high. In March 2004, most of the shallow wells were dry (Photo 6).

Photo 5.5. Natural reservoir Bau Noi

Photo 5.6. Large diameter shallow well near Hong Phong

5.2.2 Description of the water resources with emphasis on groundwater use

Binh Thuan province is one of the driest areas of Vietnam, with an average annual rainfall of 1,070 mm/yr (see Figure 5.4).

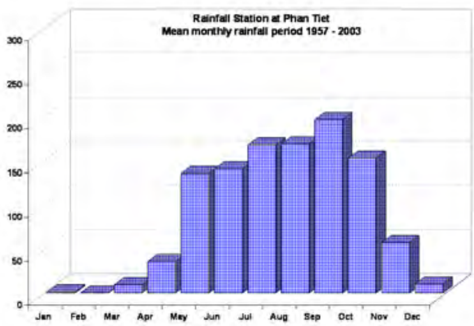


Figure 5.4. Average monthly rainfall in the study area, 1957-2003 (Thoa et al. 2010).

Surface water resources

Because of the steep terrain, surface water runs off quickly; run-off coefficients are therefore between 0.2 and 0.5. The majority of run-off occurs between May and November, with the bulk from July to October. Average annual flow rates vary from over 40 l/s/km² of catchment in the mountainous west to less than 5 l/s/km² on the coastal plain between Phan Thiet and Phan Ri.

Groundwater resources

Binh Thuan has been hydro-geologically mapped by the Geological Survey of Vietnam at a scale of 1: 200,000 to 1:50,000. The hydrogeological mapping reveals two main potential sources of groundwater located immediately to the north and south of Phan Thiet.

The northern source is contained with Quaternary red marine sand aquifer, and is the larger of the two systems extending from Phan Thiet to Phan Ri. In this report it will be referred to as the Bac Binh aquifer. The general thickness of the Bac Binh aquifer varies anywhere from 30 m to 100 m. The red sands overlie water-bearing gravel and sand beds, with the water table located 10 to 20 m below the surface. Much of the surface area has been subject to wartime chemical defoliation and has been slow to re-vegetate. Vegetation, where it occurs, tends to be low scrub. The areal extent of the aquifer is around 900 km^2, and is recharged through direct infiltration of rainfall over the extent of its area. Infiltration rates are expected to be 100 mm/year, or 10% of annual rainfall. This implies a minimum recharge to the aquifer of about 250 000 m^3/day. Well yields amount to 250 m^3/day, and water quality is fresh, being less than 500 mg/l TDS. Iron, nitrate, and nitrite are present and may be at levels requiring treatment before being suitable for domestic use. The aquifer discharges around its perimeter through a series of ephemeral and perennial springs. There is also subsurface discharge to the ocean through a salt/fresh interface located along the coastline.

The southern aquifer system is also contained in a coastal red sand aquifer and extends around 25 km south between Phan Thiet and Tan Thuan. This source will be referred to in this report as the Phan Thiet aquifer. The qualitative characteristics of this aquifer are similar to those of the Bac Binh aquifer, however, it is considerably smaller in area. Its areal extent covers around 250 km^2, and minimum recharge is expected to be 69,000 m^3/day based on 100 mm/year of rainfall recharge.

Aquifer recharge

Management of aquifer recharge (MAR) can be a valuable approach for increasing the volume of water supplies and for maintaining groundwater-dependent ecosystems. MAR can also be used to improve the security and quality of water supplies as well as to protect water resources from saline intrusion. MAR was carried out in sand dune coastal areas of Binh Thuan, Vietnam to fight desertification, as a best practice for ecosystems rehabilitation, as well as a remediation technique for restoring aquifer systems and groundwater storage capacity (Thoa et al. 2006).

The results of MAR in Binh Thuan (2004-2008) confirm that the main aquifer is unconfined with a thickness varying from 33 to 68 m. Groundwater level ranges from ground level to 26 m, with well yield varying from 1.3 to 2.5 l/s. The aquifer is represented by upper-middle Pleistocene and Holocene marine-eolian sediments, consisting of fine-to-medium loose quartz sands. Tritium data at the wells and surface water in Bau Noi, based on the isotope analyses of water samples, suggest that the age of the groundwater is only 20 to 40 years, representing significant localised recharge, even though groundwater is deep over most of the area. An aquifer test was conducted for 162 days of uninterrupted pumping to determine the hydrogeological parameters of the aquifer. It was also used to assess the potential of the aquifer for groundwater supply, and was used to manage aquifer recharge through bank filtration techniques aimed at improving water quality.

The MAR project in Binh Thuan plays an important role in the study of climate change along coastal areas of Vietnam. With climate change, it is expected that droughts will become more extensive in the coastal areas of Vietnam, and this problem has already been observed as drought has occurred more often during the last several decades.

Between 2004 and 2006, the MAR project built capacity and transferred knowledge and experience to scientists in Vietnam, especially young scientists. The results of the MAR pilot project in Binh Thuan were introduced to the leaders of the Binh Thuan Province as well as to the Government of Vietnam, donors, and NGOs in order to support specific future policies and decisions. MAR information was also disseminated to the public through television, broadcasting, print media, and VCDs.

The MAR project in Binh Thuan has also established the monitoring of meteorologial data, underground water levels and water quality since 2005. These data (which is cited from Thoa et al. 2010) will be key for the study on monitoring and evaluating the influence of climate change on coastal aquifers.

5.3 Methodologies

As this project was designed to rely on a review of previous data and local consultations, it did not carry out any hydrogeological field activities of its own. A range of methods was used in order to collect data on the selected indicators. The principal methods used are outlined below.

5.3.1 *Review of national statistics and published studies*

A review of all available statistics from the study area was conducted. This included statistics on: i) administrative units, area, and population; ii) occupation and employment; iii) economic sectors depending on groundwater; iv) pricing and subsidy policies related to groundwater use; and v) existing legal and policy frameworks related to groundwater.

5.3.2 *Informal interviews with groundwater management organisations*

During the survey implementation, a series of extended interviews and visits were made with the Department of Natural Resources and Environment of Binh Thuan Province; the Section of Natural Resources and Environment of Bac Binh district; and the People Committees of Hong Phong and Hoa Thang communes (Photo 5.7). These interviews provided essential information concerning the context of groundwater management issues in the study area.


Photo 5.7. Interviews with the People Committees of Hong Phong and Hoa Thang communes.

5.3.3 *Village survey of households in Hong Thang and Hong Phong communes*

A survey of households in Hong Thang and Hong Phong communes was carried out. The survey format consisted of a structured questionnaire including a combination of short answer and multiple choice questions. A total of 313 households were interviewed from two communes of Hoa Thang and Hong Phong (each commune consists of 3 villages). The questionnaire was written in both Vietnamese and English. Locations of households interviewed are shown in Figure 5.5.

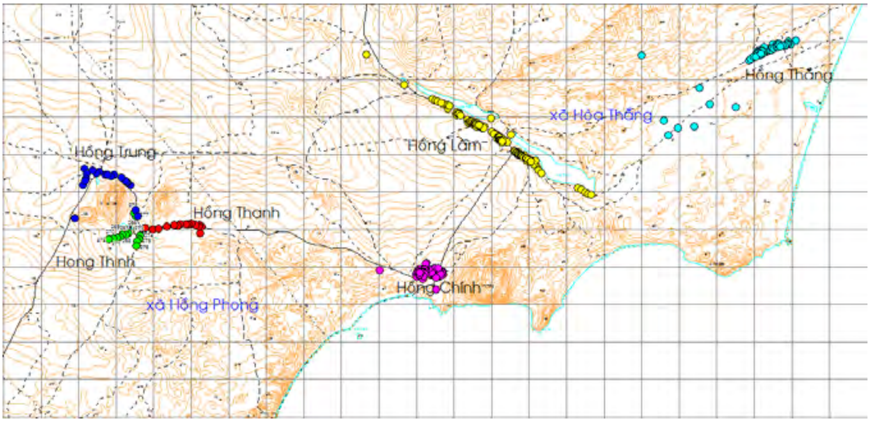


Figure 5.5. Locations of interviewed households in Hong Thang and Hoa Thang communes.

5.3.4 Methodologies used in previous projects

Geophysical investigation

Previous geophysical investigations played an important role in understanding the hydrogeological conditions of the Hong Phong area. Two combinations of geophysical methods are considered optimal techniques for the assessment of potential groundwater resources in the study area: i) electrical resistivity by Vertical Electrical Sounding (VES) and Electrical Potential (EP) with georadar for shallow bedrock (<40 m); and ii) electrical resistivity by VES with seismic prospecting for deep bedrock (Thoa et al. 2010).

A pragmatic approach was used for data interpretation. The starting model of the electrical resistivity distribution was constructed and updated by hand after comparison of its calculated response with the observations. In May 2006, a seismic refraction investigation of a 6,450 m seismic section (T3+T4) located between Bau Trang and Bau Noi, with an approximate southwest-northeast direction, was carried out. The purpose of the seismic refraction investigation was to determine the depth to the basement (bedrock), that is, the thickness of both the sand deposits and the aquifer (Figure 5.6).

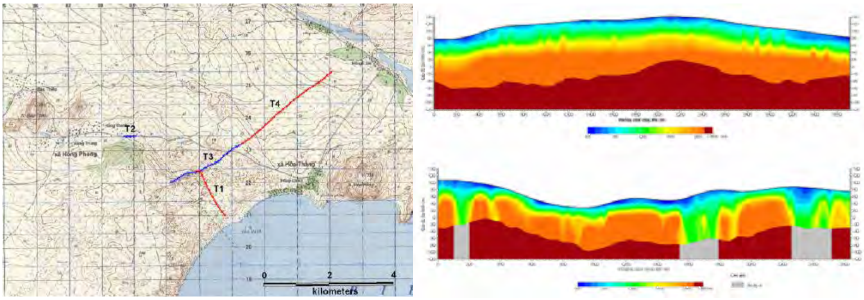


Figure 5.6. Map showing location of seismic refraction sections (left), and seismic refraction sections T3 and T4 at Bac Binh (Binh Thuan) (right) (Thoa et al. 2010).

Drilling

Following the above investigations, the location of exploratory wells in the study area was determined. The main purpose of drilling is to confirm the lithology and hydrogeological structures, to allow aquifer pumping tests to determine aquifer hydraulic characteristics, to take water samples for water quality analysis, and to monitor groundwater levels and determine groundwater flow directions and changes in storage with time. The unconsolidated aquifer, which consists of sand and is considered to be the most potential aquifer in quantity and quality, was investigated in detail and given priority in locating the well screens, in carrying out pumping tests and in taking water samples for water quality analysis. Table 5.2 provides an overview of the wells which were drilled in the case study area.

Table 5.2. Technical characteristics of the wells in Binh Thuan (Thoa et al. 2010).

Well ID	Elevation above sea level (m)	Well depth (m)	Static water level (m)	Aquifer thickness (m)	Drawdown* (m)	Yield (l/s)
	34.18	60.0	4.54	33.20	2.90	2.45
QT-BN	34.43	71.0	4.83	33.17	0.38	2.10
QS3	38.64	79.4	8.78	49.22	9.69	1.87
QSI	32.20	34.0	2.71	N/A	N/A	1.62
QSII	30.38	31.5	0.55	N/A	N/A	2.06
QSIV	N/A	3.0	0.35	N/A	N/A	N/A
QT1-BT	62.10	95.8	25.77	68.23	8.01	1.29
QT2-HT	13.08	65.5	7.75	56.25	6.72	2.04
QT3-HP	109.25	109.0	46.35	46.15	1.52	0.07

*Drawdown after 1,440 minutes of pumping at the rate shown in the column to the right.

Aquifer test

An aquifer test was conducted in the Bau Noi area in order to: i) determine the hydrogeological parameters of the aquifer in order to assess its potentiality; ii) apply managing aquifer recharge methods through bank infiltration techniques at the site to improve water quality and remove the high concentrations of E. coli in groundwater; iii) ensure sufficient time for conducting tests to determine a reliable filtration velocity of groundwater and to establish adequate travel times so that recovered water can be safely used as a drinking water supply.
The aquifer test was conducted for a total duration of pumping of more than 5 months (162 days). The location of the wells is provided in Figure 5.7 below.

Monitoring

Groundwater monitoring is an indispensable component of any MAR project. Information from results of monitoring is essential to ensuring the quantity and quality of recharge water and recovered water. Information from results of monitoring is also used to evaluate the effectiveness of MAR techniques and to estimate the volume of water to be recharged and recovered or to ensure adequate residence time in the aquifer for necessary water quality improvements, such as inactivation of pathogenic viruses, bacteria, and protozoa before it is used for drinking purposes.
Groundwater monitoring was conducted by suspending automatic transducers to record electrical conductivity, temperature, and water level depth (CTD divers) consisting of: i) a Baro Diver to measure air pressure variations of the study area; and ii) four CTD divers to measure the level, temperature, and electrical conductivity of groundwater close to Bau Noi Lake.

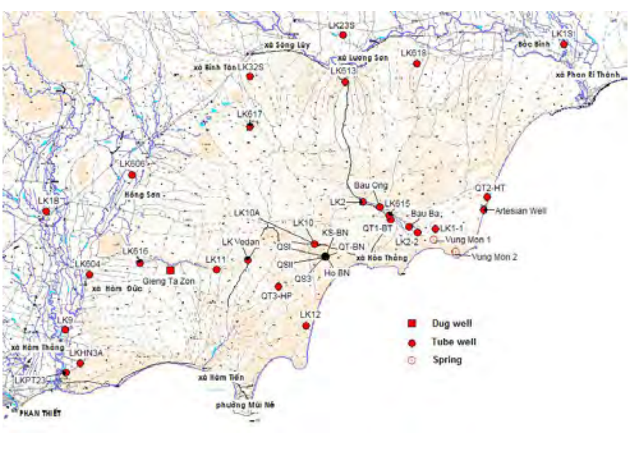


Figure 5.7. Sampling location map (Thoa et al. 2010).

Chemical, bacteriological and isotopic analyses

Water samples at 39 locations for a total of 168 samples (Figure 5.7) were taken in tube wells, dug wells, springs, and lakes.

Samples for bacteriological analyses were taken at 11 locations (Figure 5.7 and Table 5.3) at an interval of one week between May and October 2005, then during two campaigns in 2006. A total of 118 samples were analysed for coliforms, fecal coliforms, Escherichia coli, total aerobic plate count, and Clostridium perfringens.

Table 5.3. Bacteriological sample locations (Thoa et al. 2010).

No.	Locations	X	Y	Type
1	Bau Noi (Ho BN)	1,221,844.82	210,694.24	Lake
2	Bau Ong Lake	1,226,200.52	215,467.13	Lake
3	Bau Ba Lake	1,224,506.14	218,044.18	Lake
4	KS - BN	1,221,871.68	210,642.20	Tube well
5	QT-BN	1,221,873.15	210,651.84	Tube well
6	QS3	1,221,896.43	210,642.89	Tube well
7	QSI	1,221,860.82	210,641.83	Tube well
8	QSII	1,221,847.13	210,641.45	Tube well
9	QSIV	1,221,873.15	210,651.84	Tube well
10	QT1 - BT	1,225,116.42	216,387.61	Tube well
11	QT2 -HT	1,227,085.66	224,891.03	Tube well

For stable isotope analyses, 72 water samples were taken for oxygen-18 and deuterium and analysed in parallel both at the laboratory of the Institute of Atomic Energy, Ha Noi, Vietnam and at the laboratory of Geokarst in Trieste, Italy. 35 water samples were taken for Tritium (3H) and analysed at the laboratory at the Institute of Atomic Energy in Vietnam.

Groundwater flow model

One of the tools used to determine the groundwater potential and safe exploitation of groundwater reserves, with or without recharge enhancement, is a groundwater flow model. After being calibrated, a flow model is used to show the effects of variation in water budget components and is used to forecast the impacts of proposed groundwater abstraction plans as well as the effectiveness of managed aquifer recharge.

According to the flow model using the determined boundaries (Figure 5.8), the amount of rainwater recharge to the aquifer is estimated to be between 68-102 mm/year using the chloride balance equation.

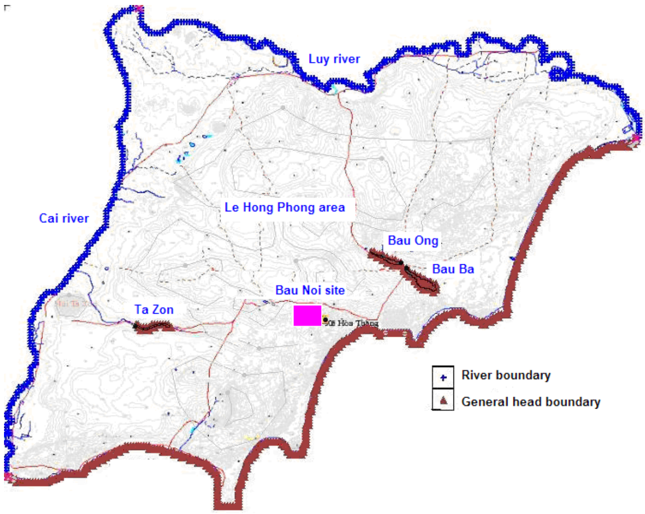


Figure 5.8. Model boundary conditions and Bau Noi site location in the Le Hong Phong area (Vuong 2006a).

The groundwater system in the study area was simulated as a two-layer system. The first layer represents the unconfined intergranular aquifer, having a horizontal hydraulic conductivity (k) of 12.67 m/day; a porosity (n) of 0.36; a specific yield (Sy) of 0.167, to give a vertical hydraulic conductivity 1/10 of that of the horizontal hydraulic conductivity. The second layer represents the weathered zone and bedrock which are considered as an aquitard, that is, having hydraulic conductivity of 10-4 m/day (Vuong 2006a).

5.4 Results

5.4.1 Geophysical Investigation

The results of the VES and EP interpretation gave useful information regarding the depth of the base of the aquifer which has been shown to be between 50-105 m for the "A-B" profile at Bau Noi (Figure 5.9). Groundwater in the aquifers is considered fresh because the values of resistivity calculated by geoelectrical data are at about 20 Ω.m.
Figure 5.6 in the previous section shows a map location of seismic refraction sections and T3+T4 cross sections, constructed on the basis of the seismic velocities (used to determine the consistency of the different layers

with depth). The interpretation of the sections indicate the occurrence of the ryo-dacitic bedrock (aquiclude-impermeable) at depths between 60-140 m below ground level, and the occurrence in the sand of a potential aquifer from ground level to the bedrock.

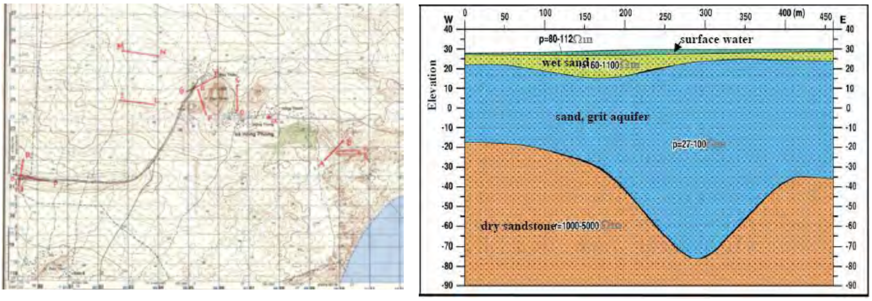


Figure 5.9. Map showing location of geophysical sections and VES profile T1 along Bau Noi (Thoa et al. 2010).

5.4.2 Aquifer characteristics

Results of drilling showed that upper-middle Holocene eolian sediments consisting of yellowish-grey fine to medium sand represent the unconfined aquifer with thickness varying from 33-68 m. Groundwater level ranges from 0-26 m below ground level, and the aquifer has a productivity with a well yield of between 1.3-2.5 l/s (Figure 5.10).

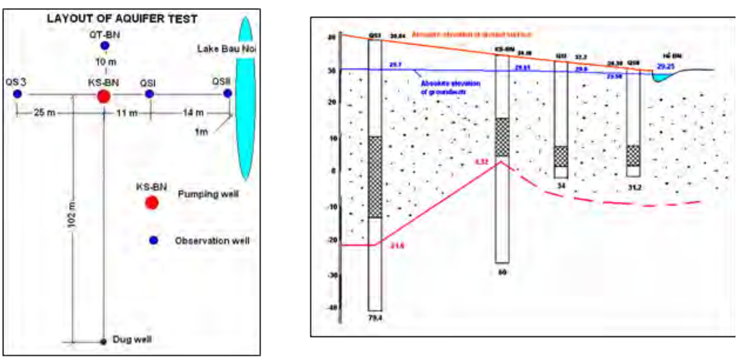


Figure 5.10. Aquifer test layout and cross-section following the line perpendicular to Bau Noi Lake (Nguyen et al. 2010).

The hydro-geological parameters of the aquifer were determined using aquifer test data obtained from methods such as Thiem-Dupuit, Cooper-Jacob (drawdown time and drawdown distance), and Recovery Theis-Jacob using Aquifer Test software (Table 5.4).

Table 5.4. Transmissivity, hydraulic conductivity and specific yield of the unconfined aquifer (Vuong 2006a).

Method	Transmissivity kD, m^2/day	Hydraulic conductivity k, m/day	Specific storage, μ
Thiem-Dupuit	230	-	
Cooper-Jacob (drawdown-time)	538	13.7	0.170
Cooper-Jacob (drawdown-distance)	235	7.8	0.157
Recovery Theis-Jacob	594	16.5	0.175
Average	399	12.67	0.167

The amount of flow passing beneath the Bau Noi Lake is calculated as follows:

Q = BHk (dh/dx), where
Q = amount of flow passing beneath the Bau Noi Lake, m^3/day
B = width of Lake Bau Noi (140m)
H = thickness of the aquifer (=30m)
K = hydraulic conductivity of the aquifer (=12.67m/day)
dh/dx = hydraulic gradient = (29.7 -29.25)/51 =0.009

Figure 5.10 suggests that the flow towards and beneath Bau Noi Lake is approximately 480 m^3/day (5.5 l/s) or 3.4 m^3/day per metre of Bau Noi Lake length. This could be produced by an average recharge rate of 100 mm/year over an area extending back to a groundwater divide approximately 10 km up along the gradient. This is the amount that can be abstracted without causing adverse impacts to the water in Bau Noi Lake. The amount of groundwater flow towards the coastline is estimated to be approximately 3,400 m^3/day/km. This represents a considerable groundwater resource which can be harvested.

5.4.3 Tracer test

A test with isotope Iodine 131 (half life of 8.02 days) was carried out both in static (no pumping) and dynamic (with pumping) conditions. In particular, prior to the beginning of the pumping operation on 21 May 2005, 131I was introduced in the monitoring wells QT-BN and QSI; the average filtration velocity was 1.217 cm/day and 0.593 cm/day, respectively. During pumping (dynamic conditions), the tracer 131I was introduced in the monitoring wells QSII and QS3 and related average filtration velocities were 10.869 cm/day and 7.855 cm/day, respectively.

The Rhodamine WT test was carried out over a duration of 44 days, between 1 June and 14 July 2005, during the pumping operation and consisted of injecting a solution composed of 100 mg of Rhodamine ($29H_{30}O_5N_2Na$) diluted in 20 liters of water into the observation well QT-BN and detecting the arrival time of the dye in the pumped well KS-BN at a distance of 10 m. The mean transit time to the well was 22.43 days, where a concentration peak of the solution was observed with a velocity of 44.6 cm/day (Figure 5.11). The earliest breakthrough was observed at 8 days.

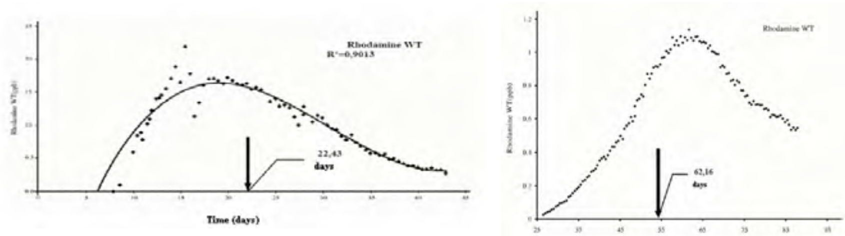


Figure 5.11. Variation of Rhodamine WT concentration in well KS-BN vs. time following release in observed well QT-BN at Bau Noi (L) and in well QSI at Bau Noi (R) (Nguyen et al. 2010).

The second Rhodamine test was carried out between the pumped well and the monitoring well QSI, located 11 m south of the pumped well (groundwater flow direction is toward the south). The results show that the tracer cloud came into the pumping well 26.5 days after injection. Tracer concentrations however, were observed to be lower, between 0-1.1 ppb. The calculated transit time of the tracer cloud is 62.16 days and the mean velocity of water moving between these two wells is 17.70 cm/day (Figure 5.11). The earliest breakthrough was observed at 26 days. The flow for QSI-BN is substantially slower than that from QT-BN and suggests that flow time from Bau Noi to KS-BN will be at least four times longer and is likely to provide adequate residence time for attenuation of low levels of pathogens in Bau Noi.

5.4.4 Groundwater flow model

Results of both steady and unsteady state models show that groundwater flows from the higher elevation area located in the center of the model to surrounding areas. Groundwater flows to Luy and Cai Rivers in the northern and the western regions, while in the south, groundwater drains to the seashore. The Ta Zon, Bau Noi, Bau Ong, and Bau Ba Lakes are considered to be supplied by groundwater in the northernmost, upgradient areas, and to supply the aquifer towards the south (downgradient) (Figure 5.12.)

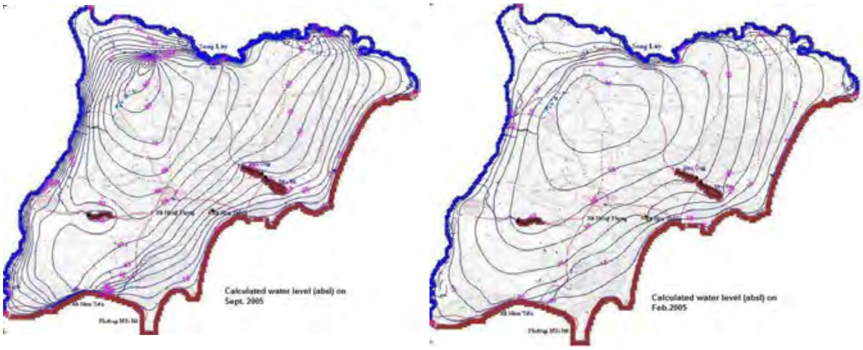


Figure 5.12. Calculated groundwater level in dry season (Feb. 2005) (L) and in rainy season (Sept. 2005) (R) (Vuong 2006a).

The steady state model also shows that the potential groundwater reserves (the total amount of groundwater that may be abstracted) of the area is 230,000 m^3/day, and the safe amount (the amount of groundwater which can be abstracted without causing adverse impacts to the environment) of groundwater abstraction is 138,000 m^3/day; amounts that can be considered as average for many years. In the dry season (December-March), the unsteady state model shows that the potential groundwater reserve is 110,000 m^3/d and the safe reserve is 43,000 m^3/d. These numbers are considered the minimum amounts of potential groundwater and safe reserves. The unsteady state model shows that during the rainy season, the potential groundwater reserves and the safe reserves are 470,000 m^3/d and 201,000 m^3/d, respectively. These numbers are considered the maximum potential groundwater and safe reserves amounts (Vuong 2006a).

5.4.5 Water chemistry and water stable isotopes data

Chemical and isotopic characterisation of surface and groundwater in different periods shows that the sand dunes aquifers, with electrical conductivity ranging from 100 to 1,500 µS/cm, are composed of different water types, characterised by complex mixing processes.

Figure 5.13 shows the Piper plot of water samples from selected sites sampled between 2005 and 2006. The main water type is NaCl, with subordinate $CaHCO_3$, $NaHCO_3$, and $CaCl_2$ water types.

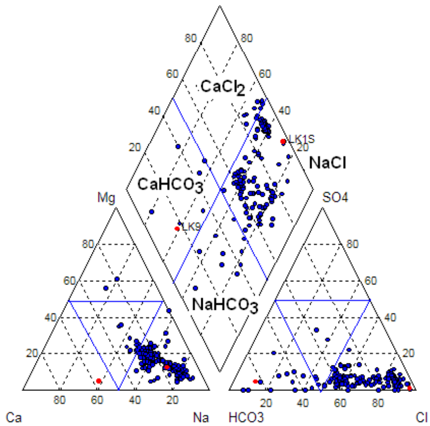


Figure 5.13. Piper plot of water samples (Vuong 2006b).

Melloul and Goldenberg (1998) defined fresh groundwater as having a chloride content between 30 mg/l and 150 mg/l, brackish groundwater between 300 mg/l to 1,000 mg/l, saline water between 10,000 to 20,000 mg/l, and brine water more than 20,000 mg/l. In order to classify the water type of the study area, several round plots were used (Figure 5.14). The water sample at LK9 is of the $CaHCO_3$ type representing fresh groundwater, while sample LK1S is of the NaCl type, representing saline water; samples QT3HP1, VD1, LK11, and VMB2 are a mixed type of the two previous ones. In the Durov plot (Figure 5.14), the line connecting LK9 and LKS1 represents mixing between fresh and saline groundwater.

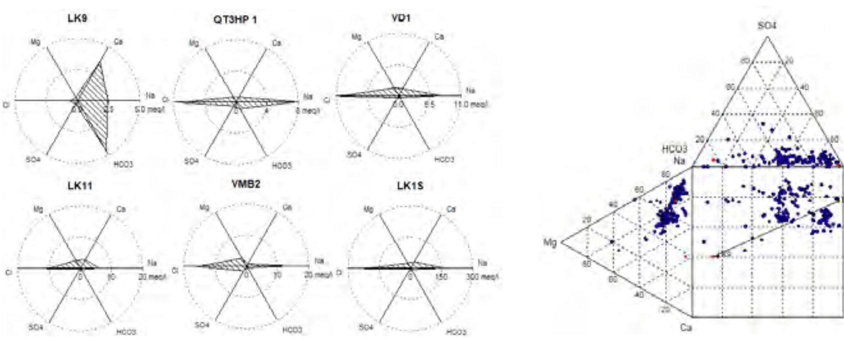


Figure 5.14. Round plots representing different water types (L) and Durov plots of water samples (R) (Vuong 2006b).

Figure 5.15 shows the relationship between K and Cl. Most of the samples are located below the mixing line, representing an increase in K content related to the mixing process of fresh groundwater and sea water. The increased K content may be related to the use of agricultural chemicals.

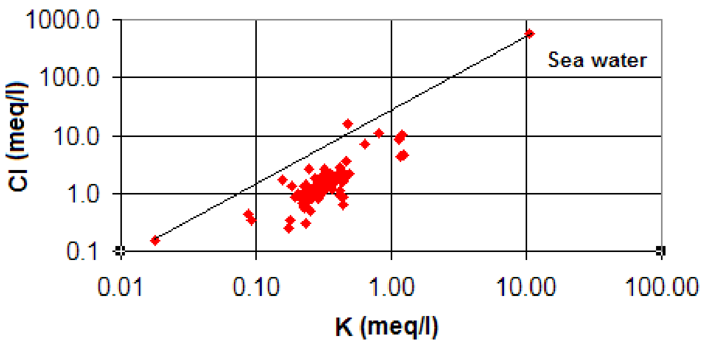


Figure 5.15. Plot of K vs. Cl. The line represents the mixing line of fresh groundwater and sea water (Vuong 2006b).

Groundwater in the study area flows from a high location in the center to the Cai River in the west, to the Luy River in the north, and to the sea in the south and east. An increase or decrease in chloride content depends on the mixing process between fresh groundwater and sea water; when chloride content is considered to be conservative, it will increase gradually from the center of the area to the surrounding boundaries.

The results of the analyses show that chloride concentrations at LK11 and LK Vedan wells, located at the center of the case study area, are high, while those from samples taken near the seashore are low (see Figure 5.16). Assuming that groundwater flows to the seashore, one can explain that chloride concentrations of samples near the seashore can be low, but cannot explain why chloride concentrations at LK11 and LK Vedan are high. Water types from these two samples clearly reflect a mixing process between fresh groundwater and sea water. High chloride concentrations at these two wells may be caused by saline intrusion of sea water below the aquifer in a vertical direction or by marine spray.

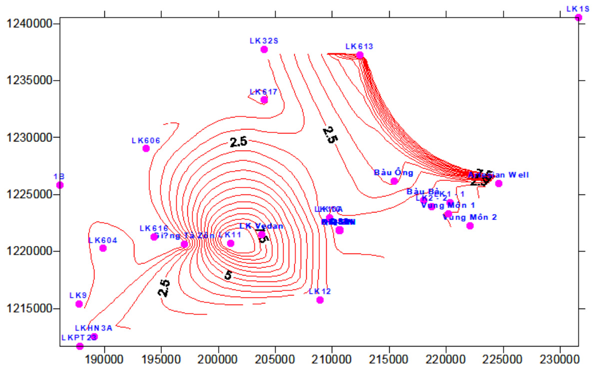


Figure 5.16. Contour map of chloride concentrations (any value >8.5 meq/l can be considered to be brackish) (Vuong 2006b).

As far as pathogens are concerned, a total of 118 analyses showed that the E. coli bacteria in the water decreased with pumping time (Figure 5.17). The exclusion of livestock from Bau Noi Lake combined with bank filtration techniques gave satisfactory results in terms of water quality improvement for this particular pathogen.

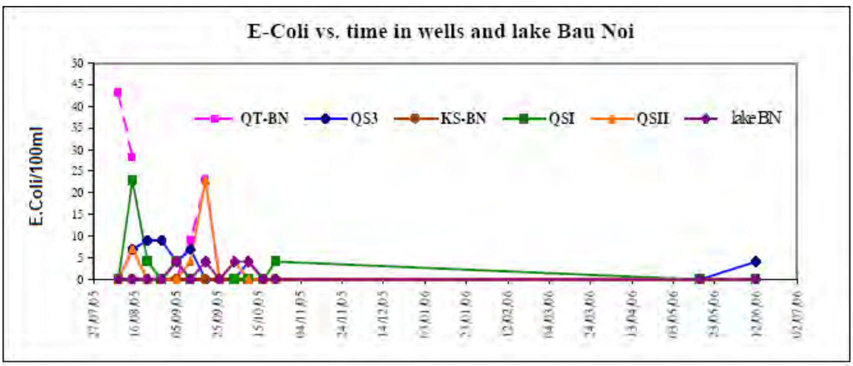


Figure 5.17. E. coli vs. time in wells and Lake Bau Noi (Thoa et al. 2010).

During the monitoring surveys in 2005-2006, samples were collected for stable isotope analyses (oxygen-18 and deuterium). Isotopic values from well and spring water in Binh Thuan area range between -7.3 and -5.7 ‰ for d18O and between -51.0 and -39.1 ‰ for dD, and align along the Global Meteoric Water Line (GMWL in Figure 5.17). The isotopic signature of Bau Noi Lake (Figure 5.18), close to that of local springs and wells, shows a substantial recharge from groundwater with a minor influence from evaporation; values of the other lakes (Bau Ong, Bau Ba, and Ta Zon) seem to emphasise evaporation processes (see the evaporation line in Figure 5.16), affecting the water dynamics from the surface to the bottom (Figure 5.18) with vertical profiles for pH, electrical conductivity, temperature and d18O. Isotopic data indicate that seepage water, discharging along the shoreline, represents a mixing of various proportions between inland fresh groundwater and sea water (see Mixing Line in Figure 5.18).

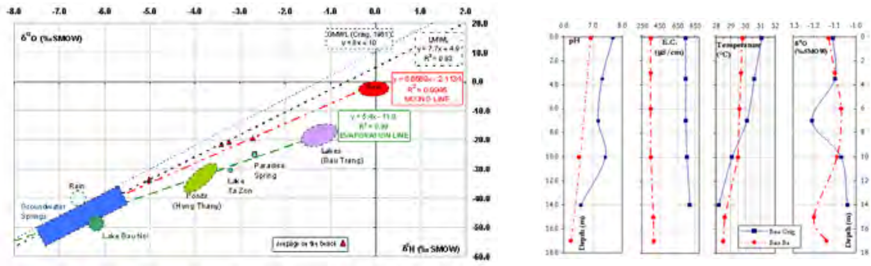


Figure 5.18. Isotopic values of water's samples (L) and water profiles in Bau Trang Lakes (Bau Ban and Bau Ong) (R) (Thoa et al. 2010).

5.5 Economic Sectors Dependent on Groundwater in Binh Thuan Province

The total freshwater supply for the entire Binh Thuan Province in 2010 is 1.0842 billion m^3/year, of which 90.75% is used for agriculture, 4.26% for aquaculture, 2.29% for domestic use, 1.10% for raising, 0.82% for industry, 0.35% for construction and transportation, 0.27% for airport and port, 0.07% for tourism and service, 0.05% for titanium production, and 0.04% for heath . It is estimated that only 5% of the total amount of freshwater comes from groundwater sources (Water Resources development planning of Binh Thuan province in 2011-2020).

5.5.1 Domestic water supply in Binh Thuan province

Urban areas

As mentioned above, 73% of the total water supply for domestic use in urban areas of Binh Thuan comes from surface water sources, while 27% is derived from groundwater sources. There are four water supply stations with the capacity to supply a total of 34,000 m^3/day for 73% of the population in urban areas of the province. These stations take surface water from the Ca Ty, Quao, Dinh, and Luy Rivers and Bau Trang Lake (Table 5.5).

Table 5.5. List of surface water supply stations and their capacity (Department of Water Resources Management 2008).

No.	Station	Commune	District	Water Supply Capacity, m^3/day	Source of water
	Sum			34,000	
1	Phan Thiet	Phong Nam	Phan Thiet	22,000	Ca Ty, Quao rivers
2	Lagi	Lagi	Ham Tien	6,000	Dinh river
3	Bac Binh	Cho Lau	Bac Binh	5,000	Luy river
4	Hoa Thang	Hoa Thang	Bac Binh	1,000	Bau Trang Lake

Rural areas

In Binh Thuan province, there are 54 concentrated water supply stations, 22,956 water wells, 84,284 dug wells and 4,630 water tanks supplying water to rural areas. These facilities, and structures take water from different sources such as groundwater, rainwater, or channel water.

These concentrated water supply stations supply approximately 41,356 m^3/day to rural areas, of which 66.1% is from surface water and 33.9% is from groundwater. The concentrated water supply stations are located at the centres of districts and towns. A list of these stations, their water supply capacities, and water sources are shown in Table 5.6.

Table 5.6. List of concentrated water supply stations of Binh Thuan Province (Binh Thuan Province Master Plan for Rural Water Supply to the year of 2020).

No	Name of water supply station	Put-into-operation year	Capacity, m^3/day		Water source
			Designed capacity, m^3 day	Operated capacity, m^3/day	
1	Vĩnh Hảo - Vĩnh Tân station	2000	500	300	Groundwater
2	Phan Dũng station	2001	200	70	Groundwater
3	Phan Rí Thành - Phan Hòa station	1992	500	800	Groundwater
4	Bình An station	1996	300	500	Groundwater
5	Thôn 3, Phan Sơn station	2009	200	100	Groundwater
6	Phan Điền station	1996	300	300	Groundwater
7	Sông Lũy station	2000	500	700	Groundwater
8	Bình Tân station	2002	500	700	Groundwater
9	Lương Sơn station	2010	670	285	Groundwater
10	Phan Tiến station	2007	160	184	Groundwater

11	Hồng Phong station	2004	200	280	Groundwater
12	Hàm Phú station	2003	250	380	Groundwater
13	SaRa - Hàm Đức station	1994	650	1,009	Groundwater
14	Phú Long station	2002	700	1,060	Groundwater
15	Cây Táo (Hồng Sơn và Thuận Hòa) station	1998	200	230	Groundwater
16	Hồng Liêm station	1996	214	437	Groundwater
17	Mũi Né station	1999	480	578	Groundwater
18	Bàu Tàng - Bàu Ron - Bàu Sen station	2000	510	622	Groundwater
19	Ngã Hai (Tiến Lợi) station	2003	500	541	Groundwater
20	Tân Thuận (1) station	2008	200	240	Groundwater
21	Tân Thành (2) station	2006	1,250	300	Groundwater
22	Ngã Hai (Hàm Kiệm - Hàm Cường) station	2001	800	830	Groundwater
23	Ngã Hai (Hàm Mỹ) station	1999	780	960	Groundwater
24	Thạnh Cần station	2002	250	387	Groundwater
25	Mỹ Thạnh station	2010	150	117	Groundwater
26	Nguyễn Thanh Hùng - Xã Tân Hải station	1996	26	22	Groundwater
27	Tân Hải - Tân Tiến station	2006	400	450	Groundwater
28	Tân Nghĩa station	2011	475	150	Groundwater
29	Tân Hà station	2002	150	241	Groundwater
30	Sơn Mỹ station	2005	280	244	Groundwater
31	Lạc Tánh station	2002	200	278	Groundwater
32	Phú Quý (Ngũ Phụng) station	2007	2200	722	Groundwater
33	Tuy Phong (*)station	2003	14,000	11,000	Surface water
34	Bắc Bình station	1993	5,000	4,500	Surface water
35	Hòa Thắng station	1997	2,500	700	Surface water
36	Phan Thanh station	1995	500	700	Surface water
37	Sơn Lâm station	2009	500	440	Surface water
38	Hồng Thái station	2007	710	720	Surface water
39	Thuận Bắc station	2003	4,360	4,400	Surface water
40	Đông Tiến station	2009	370	120	Surface water
41	Đông Giang station	2006	300	349	Surface water
42	Hàm Thuận Nam station	2004	2,200	1,000	Surface water
43	Ba Bàu - Hàm Thạnh station	2006	400	248	Surface water
44	Tân Tiến (3)	2009	20,000		Surface water
45	Tân Minh - Tân Phúc - Tân Đức station	2005	700	880	Surface water
46	Sông Phan station	1997	400	320	Surface water

47	Thắng Mỹ (Tân Thắng, Thắng Hải) station	2010	960	360	Surface water
48	Măng Tố - Đức Tân - Bắc Ruộng station	2010	1,200	280	Surface water
49	La Ngâu station	2007	250	152	Surface water
50	Tà Pứa - Đức Phú station	2009	70	39	Surface water
51	Suối Kiết station	2010	360	153	Surface water
52	Lạc Tánh (Đức Bình) station	2008	210	184	Surface water
53	Võ Xu - Đức Tài - Nam Chính - Đức Chính	2006	2,400	794	Surface water
54	Long Hải (Phú Quý island) station				
	Total		**72,085**	**41,356**	
	From groundwater		**14,695**	**14,017**	
	From surface water		**57,390**	**27,339**	

5.5.2 Water supply by sector in Binh Thuan Province

Agricultural sector

There are 146 water supply facilities which can irrigate up to 50,000 ha of land in Binh Thuan province (Department of Water Resources Management 2008) (see Figure 5.19). All these water supply facilities use surface water as the main water source. There are two lakes with a capacity of greater than 10 Mm^3 (Song Quao Lake has a capacity of 67 Mm^3 and Ca Giay Lake has a capacity of 30 Mm^3), and six lakes with a capacity of 1 -10 Mm^3.

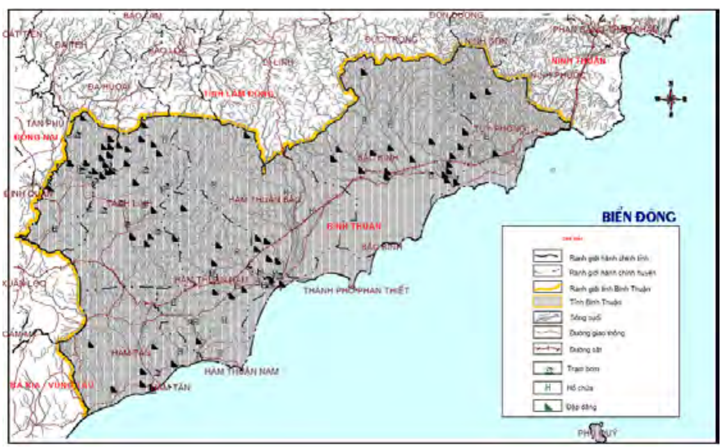


Figure 5.19. Location map of irrigation water supply facilities in Binh Thuan province (Department of Water Resources Management 2008).

Industrial sector

In Binh Thuan Province, there are 5,188 industrial units, of which 93.6% are processing units. Water used in the industrial sector in Binh Thuan (Table 5.7) is mainly sourced from groundwater. The total water used by industries in the province is estimated to be 97.653 m^3/day (Department of Water Resources Management 2008).

Table 5.7. Water used by the industrial sector in Binh Thuan province (Department of Water Resources Management 2008).

	Type of industry	Amount of water used	
		(m^3/day)	(Mm^3/year)
1	Mining	226.17	0.083
a	• Metal mining	13.26	0.005
b	• Rock mining	212.9	0.078
2	Processing industry	97,277.77	35.49
3	Electrical industry	198.77	0.073
	Total	97,652.7	35.643

Aquaculture sector

The total amount of water used for aquaculture in Binh Thuan province (Table 5.8) is about 17 Mm^3/year, of which 11 Mm^3/year is fresh water and 6 Mm^3/year is brackish water.

Table 5.8. Water used for aquaculture purposes in Binh Thuan Province (Department of Water Resources Management 2008).

No.	Items	Fresh water aquaculture	Saline and brackish aquaculture	Total
1	Area for aquaculture (ha)	1,085	1,504	2,589
2	Number of household growing shrimp	0	3,926	3,926
3	Number of household raising fish	1,087	116	1,203
4	Total volume of water used (Mm^3/year)	11	6	17

Tourism and service sectors

Approximately 1.5 million tourists travel annually to Binh Thuan province. The amount of water used by the tourism sector is about 5,048 m^3/day or 11 Mm^3/year. The main source of water for tourism comes from groundwater (Department of Water Resources Management 2008).

Health sector

There are 127 health units in the province with a total of 2,011 beds. Total water used by the health sector (Table 5.9) is estimated to be 181 m^3/day (Department of Water Resources Management 2008).

Table 5.9. Water used by the health sector in Binh Thuan Province (Department of Water Resources Management 2008).

No.	Health unit	Quantity	Number of beds	Amount of water used	
				(m^3/day)	(Mm^3/year)
	Total	127	2,011	180.99	66
1	Hospital	11	1,306	117.5	42.9
2	Surgery	13	190	17.1	6.2
3	Medical station	103	515	46.4	16.9
	Total	97,652.7	35.643		

5.5.3 Water supply by sector in Hoa Thang and Hong Phone communes

The economic sectors depending on groundwater in Hoa Thang and Hong Phong communes are shown in Table 5.10 below.

Table 5.10. Sectors depending on groundwater in Hoa Thang and Hong Phong communes.

Economic sector	Surface water		Groundwater		% of economic sector relying on groundwater
	No. of water supply facilities/ structures	Capacity (m^3/day)	No. of water supply facilities/structures	Capacity (m^3/day)	
HOA THANG COMMUNE					
Domestic	16	554	363	109	16.4%
Agriculture	1	No data	0	0	
Industry	0	0	0	0	
Aquaculture	0	0	0	0	
HONG PHONG COMMUNE					
Domestics	1043	57	1	220	79.4%
Agriculture	0	0	0	0	
Industry	0	0	0	0	
Aquaculture	0	0	0	0	

5.5.4 Pricing and subsidy policies related to groundwater

According to the Decision No 11/2013/QĐ-UBND dated March 15, 2013 of Bnh Thuan People Committee, the price for the consumption of water, regardless of the water source in Binh Thuan is shown in Table 5.11.

Table 5.11. The price for the consumption of water in Binh Thuan province.

No	Utilisation purpose	Consumption price (VND/m^3)
1	For domestic use - The first 10 m^3 • Ethnic minority • Other - Over 10m^3 to 20m^3 - Over 20m^3	3,800 6,000 7,000 10,000
2	For public use	10,000
3	For administrative offices use	12,000
4	For material production purposes	14,000
5	For business and services purposes	18,000

5.5.5 Legal and policy frameworks

The institutional framework for integrated water resources management in Vietnam operates at three decision-making levels: constitutional, organisational and operational. Each are described herein.

The constitutional level consists of International Treaties, the National Constitution, the National Law on Water Resources, the Governmental Decree on the Implementation of this Law, and National Water Management Plans.

The Law on Water Resources (June 21, 2012; Law No: 17/2012/QH13) consists of 10 Chapters with 79 Articles and has been in force since January 01, 2013. Apart from the general provisions (scope of application, legal terms interpretation, State policies, propaganda and education, collection of communities' opinions, and prohibited acts), the LWR 2012 provides regulations on basic surveys of water resources and preparation of strategies and master plans; responsibilities to protect water resources; the rights and obligations to exploit and use water resources; the prevention, control, and mitigation of harmful effects caused by water; water-related financial issues; international relations in respect of water resources management; state management of water resources; inspections and dispute settlement; and implementation provisions.

The Decree 201/2013/NĐ-CP on Detail Guidance for Implementation of the Law on Water Resources guides the implementation of the Law on Water Resources. The Prime Minister decides the establishment of the National Council on water resources, the National Council advises the Government and the Prime Minister on important decisions on water resources. The Prime Minister also decides the establishment of river basin organisations of Hong (red) – Thai Binh river and Mekong river at the proposal of the Minister of the Ministry of Natural Resources and Environment (MONRE). The Minister of the MONRE establishes river basin organisations of inter-provincial river basins at proposal of Head of specialised state management bodies on water resources. River basin organisations are responsible for proposing and recommending to competent state agencies which are in charge of regulation, distribution of water sources, supervision of activities on water resources exploitation, use, protection and prevention, combat and remediation of adverse impacts caused by water in one or several inter-provincial river basins.

The organisational level contains regulations from the Ministries and provincial plans. Under the legal documents which govern water resources management, the MONRE is responsible for state management on water resources, meteorology and hydrology, and integrated and unified management of the sea and islands. Furthermore, exploitation licenses for groundwater are also under the responsibility of the MONRE at the central level, and under the responsibility of the Provincial People's Committee at the local level. Ministries and ministerial level agencies are implementing state management on water resources according to assignments given by the Government. The responsibilities of each ministry are shown in detail in Table 5.12.

Table 5.12. Responsibilities for water resources management in Vietnam

Ministry of Natural Resources and Environment (MONRE)	State management on water resources, meteorology, and hydrology, integrated and unified management of the sea and islands
Ministry of Agriculture and Rural Development (MARD)	State management of agriculture, salt making, fisheries, irrigation, rural development, dyke, flood control.
Ministry of Industry (MOI)	Development of hydropower, building and operating hydropower
Ministry of Science and Technology (MOST)	Prescription and guidance of water standard application
Ministry of Construction (MOC)	Implementation of planning for water supply and drainage in urban areas, industrial zones, and densely populated areas
Ministry of Transport (MOT)	Management and development of waterway transportation, waterway works, and harbours
Ministry of Health (MOH)	Management of drinking and daily life hygiene and safety standards
Ministry of Planning and Investment (MPI)	Coordination and submission of plans for investing funds in water management projects and for disaster caused by water.
Ministry of Finance (MOF)	Guidance of water resource charges, fees, and taxes.

The operational level consists of town regulations, instructions for water user organisations, water supply companies and water services. The ministries are responsible for formulating projects based on general targets for water supply set at the constitutional level. These projects are formulated on the basis of requests for support from the provincial level and rural communities through the line authorities at these levels. For approval of these projects, licenses must be obtained from the Ministry or the Department of Water Resources and Environment. In the case of the Department and the Ministry, there is an obvious doubling in function, as the Ministry is both an implementing agency (operational level) and controlling agency (organisational level).

Description of enforcement practices

Responsibilities for investigation, assessment of water resources

1. The MONRE organises the implementation of investigation, assessment of water resources for trans-national water sources, inter-provincial water sources, and consolidates the results of the investigation, assessment of water resources for inter-provincial river basins and throughout the country.

2. PPCs undertake investigation, and assessment of water resources for intra-provincial water sources and inter-provincial water sources in its territory and submit the results to the MONRE for consolidation.

Responsibilities for water resources inventory:

1) The MONRE takes lead, coordinates with related Ministries, and ministry-level agencies to develop master projects, plans on water resources inventory throughout the country and submit to the Prime Minister for approval; conduct water resources inventory for trans-national water sources, inter-provincial water sources; consolidate, and announce results of the inventory for inter-provincial river basins and for the whole country;

2) PPCs organise the implementation of water resources inventory for intra-provincial water sources; consolidate results of the inventory for intra-provincial river basins, and local water sources, and submit to the MONRE for consolidation;

3) Ministries, ministry-level agencies under their mandates, and powers are responsible for collaborating with the MONRE, and PPCs in implementing water resources inventory.

Responsibility for investigation on current state of water resources exploitation, use and wastewater discharge into water sources:

1) Ministries: MOIT, MARD, MOC, MOT, MCST and related Ministries, and ministry-level agencies under its mandates, powers organise the implementation of investigation, preparation of reports on water use situations in the sector, and area and submit to the MONRE for consolidation;

2) The MONRE conducts the investigation on the current state of water exploitation, wastewater discharge into water sources for inter-provincial, -national water sources; consolidates results of the investigation on water resources exploitation, use, and waste water discharge into water sources in inter-provincial river basins and throughout the nation;

3) PPCs under its mandates, powers are responsible for investigating the current state of water resources exploitation, use, and wastewater discharge into water sources for intra-provincial water sources, local water sources; consolidate results of the investigation on current state of water resources exploitation, use, and wastewater discharge into water sources on intra-provincial river basins, on the locality, and submit to the MONRE for consolidation.

Responsibility for water resources monitoring

1) The MONRE takes lead, coordinates with PPCs in developing a planning of water resources monitoring station network nation wide, and submits to the Prime Minister for approval.

2) Based on the planning of water resources monitoring network, the MONRE develops, manages, and carries out water resources monitoring for the central monitoring station network; Provincial DONREs develop, manage, and carry out water re sources monitoring for the local monitoring network.

Responsibility for developing and maintaining warning and fore casting systems for flood, inundation, drought, salinity intrusion, sea rising, and other adverse impacts caused by water

1) The MONRE has following responsibilities:

a) Develop and maintain the warning and forecasting system on flood, inundation, drought, salinity intrusion, sea rising, and other impacts caused by water throughout the country;

b) Implement warning, forecasting providing and ensuring information, data for preventing, combating against flood, inundation, drought, salinity intrusion, sea rising, and other impacts caused by water in accordance with legislative regulations on water resources, on prevention, combat against inundation, storm, as well as prevention and mitigation of natural disaster.

2) Ministries, ministry-level agencies, and PPCs, given the requirement of prevention, combat against flood, inundation, drought, salinity intrusion, sea rising, and other adverse impacts caused by water, develop a warning and forecasting system for their own operation of ministries, sectors, and localities.

Responsibility for water resources information, database system

1) The MONRE regulates data set, data format; develops, and manages the national water resources information database system, as well as exploitation and sharing of water resources information, data;

2) The MARD, MOIT, MOC, and other related Ministries, and ministry-level agencies in line with their mandates, powers are responsible for

developing, managing, exploiting database systems on water use and integrating into the national water resources information database system;

3) PPCs develop, manage, and exploit the local water resources information, and database system, and integrate into the national water resources information database system.

Responsibility for water resources use reporting

1. Annually, MOIT, MARD, MOC, and related Ministries, ministry-level agencies, and PPCs in line with their mandates, powers are responsible for making reports on their water use and submit to the MONRE before 30 January for consolidation, monitoring.

2. The MONRE regulates on the content, format of the water resources use report.

The authority for licensing, extension, adjustment, suspension of validity, revoke and re-grant of water resources permits

1. The MONRE grants, extends, adjusts, suspends validity, revokes, and re-grants permits in the following cases:

a) Water resources exploitation, use of the national key works approved by the Prime Minister;
b) Underground water exploration, exploitation for the facilities with a flow of 3000m^3/day and above;
c) Surface water exploitation, use for agricultural production, fishery farming with a flow of 2 m^3/second and more;
d) Surface water exploitation, use for power generation with a production capacity from 2,000 kw;
e) Surface water exploitation, use for other purposes with a flow of 50,000 m^3/day and more;
f) Sea water exploitation, use for production, business, service with a flow of 100,000 m^3/day and more;
g) Wastewater discharge with a flow of 30,000 m^3/day and more for fishery farming activities;
h) Wastewater discharge with a flow of 30,000 m^3/day and more for other activities.

2. PPCs grant, extend, adjust, suspend validity, revoke, and re-grant permits for the cases that are not stipulated at Item 1 of this Article.

Responsibility for water resources related finance

1) The MONRE will lead and coordinate with the Ministry of Finance to prepare and submit to the Government the proposed regulation on the fee rate, the calculation method, the collection method and mechanism for managing and using the fee collected from granting water resource exploitation permit.

2) The MONRE will lead and coordinate with the Ministry of Finance to issue guidance on managing and using the budget for water resources baseline investigation, planning, and protection activities.

Responsibility of MONRE in coordinating and supervising activities performed in river basin

1) Play a lead role and coordinate with relevant ministries, ministry-level authorities, relevant governmental agencies, and People's committees of centrally-run Provinces or Cities to prepare the action plan for coordination and supervision works as stipulated in Article 42 of the Decree for inter-provincial river basin, and submit the proposed plan to the Prime Minister for approval.

2) Play a lead role in coordinating relevant authorities in handling and troubleshooting the trans-national and inter-provincial water source pollutions.

3) Appraise and announce the minimum flow in the river or river section for inter-provincial water source, prescribe the minimum flow at the downstream of reservoirs which are under the MONRE's permitting authority.

4) Construct and maintain the monitoring system for exploiting and use of the water resources, and discharging wastewater into the water source in the inter-provincial river basin.

5) Address within the authorised competence or submit to the Prime Minister the proposal on solutions to any issues arising from cooperation with relevant authorities in inter-provincial river basin coordination and supervision works.

Responsibility of Provincial People's Committee in coordinating and supervising activities performed in river basin

1) Develop, approve, and implement the water resource regulation and distribution plan, action plan, or program for rehabilitating rivers, restoring polluted or exhausted water sources within the provincial river basin.

2) Provide instructions in preparation of the reaction plan, remediation of local water source pollution incidents, and coordinate with other localities sharing the same water source in response and remediation of pollution incidents.

3) Appraise and announce the minimum flow in the river or river section for provincial water source; prescribe the minimum flow in the downstream of reservoirs for which granting the water exploitation permit is enabled under the permitting authority.

4) Construct, and maintain the monitoring system for exploiting and utilising the water resource and discharging wastewater into the water source in the provincial river basin.

5) Play a lead role in addressing any arising issues in cooperation with relevant authorities in provincial river basin coordination and supervision works.

6) Cooperate with the MONRE in execution of coordinating and supervising activities performed in river basin

Responsibility of Ministries or Ministry-level agencies

1) Cooperate with the MONRE, and PPCs in coordinating and monitoring such activities as water resource exploitation, use and protection; prevention, combat and remediation of the damage, and adverse effect caused by water in the river basin.

2) Submit the water demand estimation for each water source in the local river basin to the MONRE and the relevant PPCs.

3) Instruct development, adjustment, amendment of implementation plan, programme or project related to water resource exploitation, use and protection; and prevention, control and remediation of damaging effect caused by water in accordance with the water resource regulation and distribution plan; action plan or programme for rehabilitating rivers and

restoring polluted and exhausted water sources in local river basin; and with the announced minimum flow ensured.

4) Instruct development and realisation of the reservoir regulation plan; water exploitation and use plan for river water exploitation works according to the reservoir and inter-reservoir operational rules issued by the competent authority and according to the water resource regulation and distribution plan in the river basin.

5) Cooperate with relevant authorities to address any issue arising during the river basin coordination and supervision process.

5.5.6 Socio-ecological systems

The population structure of Binh Thuan is described here based on the 2007 statistics from Binh Thuan province, while the population structure of Hoa Thang and Hong Phong communes is described based on the results of the interviews with 313 households of the two communes.

Population structure of Binh Thuan province
The province has a total of 96 communes covering an area of 7,810 km² with a total population of 1,175,227 people at an average density of 150 persons/km². Around 60% of the population live in rural areas, with equal numbers of males and females. Table 5.13 indicates the work force in the province.

Table 5.13. Balance of social labour (as of 1 July 2014), Binh Thuan Province (Binh Thuan Bureau of Statistics 2014).

	Total (Persons)
A. Number of persons at working age above 15)	845,451
1. Able to work	831,077
2. Disabled	14,444
B. Distribution of labour force	
1. Number of employed persons in economic activities	681,473
2. Number of persons of working age and able to work who attend school	49,064
3. Number of persons of working age and able to work staying at home as primary caregiver	53,809
4. Number of persons of working age, able to work and economically inactive	22,771
5. Unemployment	23,888

Population structure of Hoa Thang and Hong Phong communes
The household structure of the two communes are quite similar. The average number of family members is four persons with a male to female ratio

of 1:1. Details of household structure of each communes are provided in Table 5.14.

Table 5.14. Household structure of the Hoa Thang and Hong Phong communes (Binh Thuan Bureau of Statistics 2014).

	Number of family members	Male	Female
Hoa thang	3,86	1,93	1,93
Hong Phong	3,90	1,98	1,92

The education level in these two communes is rather low, with only 5% of the population having completed secondary school education or higher. More than 50% of the population has not received basic education or has received no schooling at all.

The main source of household income in Hoa Thang is from agriculture followed by fisheries, with 56% of household income coming from agricultural activities and 12% from fishing activities. In Hong Phong, the main source of household income is agriculture (90%). Table 5.15 provides more detailed breakdowns of sources of household income for the two villages. Interestingly, 72 % of the population claim to be unemployed, based on the information received during the interviews conducted with 313 households.

Table 5.15. Main sources of household income in Hoa thang and Hong Phong provinces (GWAHS-CS survey data).

	Agriculture	Barbershop	Cake product	Carpenter	Driver	Employment	Fishery	Laborer	Mill	Pension	Photographer	Remittance	Salary	Shop	Tailor	Vendor	Workshop
Hoa thang	56.45%	0.35%	0.35%	0.35%	0.31%	0.31%	11.99%	6.72%	0.31%	3.04%	0.35%	1.55%	7.34%	0.31%	0.71%	8.89%	0.66%
Hong Lam	60.19%	0.00%	0.00%	0.00%	0.93%	0.93%	0.93%	11.11%	0.93%	6.48%	0.00%	0.93%	9.26%	0.93%	0.00%	6.48%	0.93%
Hong Thang	76.19%	0.00%	0.00%	0.00%	0.00%	0.00%	12.70%	1.59%	0.00%	1.59%	0.00%	1.59%	0.00%	0.00%	0.00%	6.35%	0.00%
Hong Chinh	32.98%	1.06%	1.06%	1.06%	0.00%	0.00%	22.34%	7.45%	0.00%	1.06%	1.06%	2.13%	12.77%	0.00%	2.13%	13.83%	1.06%
Hong Phong	90.77%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	3.33%	0.00%	0.00%	0.00%	0.00%	4.23%	0.00%	0.00%	1.67%	0.00%
Hong Thinh	92.31%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	7.69%	0.00%	0.00%	0.00%	0.00%
Hong Trung	80.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	10.00%	0.00%	0.00%	0.00%	0.00%	5.00%	0.00%	0.00%	5.00%	0.00%
Hong Thanh	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

5.5.7 Vulnerabilities of the groundwater system

The exploration of vulnerabilities of the groundwater systems will be limited to an area of 927 km², bounded by the Cai River to the west and the Lui River to the north (see Figure 5.7). There are several important issues that must be considered and investigated if groundwater resources are to be developed, including existing water users, salt intrusion, environmental effects, and land use. Each are discussed here.

Existing water users

Groundwater resources are not used to any great extent through abstraction from wells over the main body of the aquifer. However, the natural discharges from these aquifers through a series of springs around the periphery support a significant amount of rural irrigation and crop production. Therefore, any development of groundwater resources must be managed in such a way as to ensure that these spring flows are not reduced to unacceptable levels. Alternatively, supplementary supplies could be developed for these users. These could be provided from the main aquifer with appropriate engineering and management.

The well field layout will be crucial in determining what effect abstraction may have on these spring discharges, and wells should be sited so that their drawdown effects on the springs are minimised. Well field design will therefore require a good understanding of the hydraulic characteristics of the aquifer, and an ability to predict the extent of drawdown for production wells.

Salt water intrusion

Both the Phan Thiet and Bac Binh aquifers discharge to the ocean through a salt water/freshwater interface located within 1 km of the coast. Exploitation of groundwater resources is likely to result in landward intrusion of the interface if this discharge is reduced, with a consequent lowering of the potentiometric head in the vicinity of the interface.

The saline interface has been mapped in a preliminary fashion with electrical resistivity techniques and some well census information. This mapping should be confirmed using wells constructed in order to accurately determine the location and configuration of the interface, and to allow for future monitoring of any movement. Multiport monitoring wells are relatively simple and effective means for achieving this.

Clearly, the well field should be located and managed in a manner that will ensure that salt water intrusion does not present a threat to its long-term operation. Some of modelling of the drawdown effects of alternative well field and pumping scenarios can be utilised to design the optimal layout.

Environmental effects

The primary environmental concern with the aquifers relates to wetlands located within the northern area and to environmental systems associated with the spring discharges. These environmental systems should be evaluated to determine the extent of their dependence on groundwater resources for sustenance and the extent of their value, either as water supply sources or for their social or ecological value. They should also be assessed in terms of the water quantity and quality regimes necessary to ensure they are not damaged to unacceptable levels. The primary tool for evaluating alternative development and operation strategies for any well field is a hydraulic model of the groundwater, as discussed earlier. Techniques to maintain wetland environmental systems can be employed using methods such as artificial recharge.

Land use and water quality protection

Binh Thuan province has 800,000 ha located in the southern part of the study area. Based on information taken in 2008, 26,000 ha is unused land and 95,000 ha is under agriculture, with 78,000 ha being perennial crops, the majority of which is rice production. Most of the land overlying both the Bac Bin Hang Phan Thiet aquifer is sandy, infertile and consequently vacant.

The Bac Binh aquifer has little intensive land use, with the exception of the cemetery near Phan Thiet. Similar precautions should be taken with well field locations proposed for the Phan Thiet aquifer. There are plans for an economic development on the land overlying the Bac Binh aquifer. While the aquifer offers the opportunity for a cheap, accessible water supply source, it is extremely important to locate and manage the development in a manner that does not compromise the water quality of the underlying groundwater. The effects of well field abstraction on water balance should be able to be predicted through a groundwater flow model.

The general compatible nature of land use over groundwater resources will require that a land use management plan be developed to ensure that this compatibility is maintained. Essentially, this management plan should seek to avoid the introduction of any intensive land use that will cause either point or non-point source contamination of underlying groundwater resources. Some increase in the economic output of the land could be achieved through low intensity land uses, such as sylviculture using selected tree species, without compromising the water quality of the aquifers.

5.5.8 Measurement of GWAHS Indicators

The elements of vulnerability, as defined by the GWAHS-CS project, are explored through the generic set of four indicators selected by the project: hazard, exposure, sensitivity, and resilience. This case study explores how the indicators could be applied and interpreted in the context of Hoa

Thang and Hong Phong communes of Bac Binh district, Binh Thuan province. It explores the relationship between the various individual indicators, and discusses the degree to which the selected indicators capture the intended elements of vulnerability. The information provided herein was collected during the interviews conducted with 313 households in the two communes located in the study area.

Hazard

Hazards are threats to a system, comprised of different perturbations and stress. The generic hazard sub-indicators are discussed below (see Chapter 1).

Groundwater quantity

There are two aquifers in Binh Thuan province: Bac Binh aquifer is the larger of the two with a size of 900 km^2, while the Phan Thiet aquifer is 250 km^2. The minimum recharge of the Bac Binh aquifer is estimated to be 250,000 m^3/day through the direct infiltration of rainfall, while the average yield of wells is 250 m^3/day. Unfortunately, there is no information available about the number of wells that are fed by this aquifer, but nevertheless, it can be assumed that, if current conditions remain the same, no shortages of groundwater are to be expected. Currently, the ratio of GW abstraction/ GW recharge is 0.0055.

However, it is expected that livestock breeding, which requires water for irrigating pastures, and processing industries, will increase and gain in importance within the province. Thus, the pressure on groundwater resources is also expected to rise. Currently, there are concrete plans for economic development of the area overlying the Bac Binh aquifer. It can be expected that the planned activities will make use of the groundwater and thus increase pressure on the resources.

Figure 5.20 shows the 2010, 2015, and 2020 projections for the water balance of the river catchment where the case study communes are located. It shows that water availability is projected to stay the same for three years, while the total water utilisation will increase by nearly 22% by the year 2015, and 67% by the year 2020. However, under this scenario, the water balance will remain positive, even during the dry season in 2020. If trends continue, then negative water balances can be expected for the future.

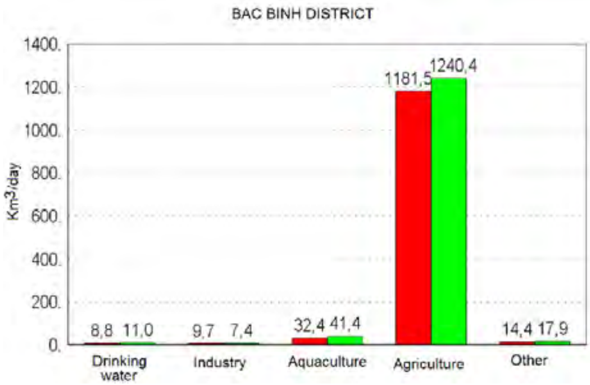


Figure 5.20. Water balance projections for the respective river catchments of rainy and dry seasons for 2010, 2015, and 2020. The first bar indicates water availability, the second indicates projected water utilisation, and the third indicates the balance between the first two columns (Water Resources Development Planning Binh Thuan province in 2011-2020).

As the village of Hong Phong is located quite close to the boundary of an adjacent river catchment, it is reasonable also to look at this catchment, where a different picture emerges. Here, projections show a negative water balance of around 50 m³ for the dry season of both 2010 and 2015.
Figure 5.21 shows projections for water needs for 2010 and 2015 in Bac Binh district (Department of Water Resources Management 2008). It clearly shows that the highest amount of fresh water will be needed for agricultural purposes.

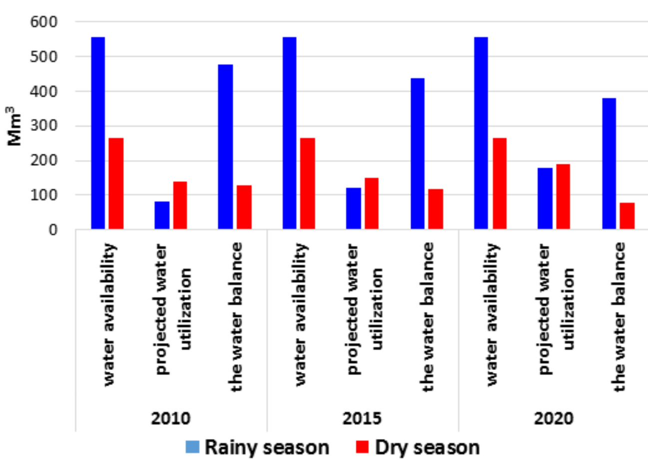


Figure 5.21. Projections for water needs in Bac Binh district. Red bars show projections for 2010, green for 2015 (Department of Water Resources Management 2008).

Groundwater quality

At present, most of the land overlying the two aquifers is infertile and unused. Therefore, groundwater resources are not at a particular risk of contamination from human activities. However, any planned development activities might change this situation. Care should be taken at the northern frontier of Phan Thiet aquifer where a cemetery and a rubbish disposal area provide considerable potential for local groundwater pollution. Tests showed that in general, the quality of the groundwater is good. Levels of total dissolved solids (TDS) are generally below 500 mg/l, most of them being between 100 and 400 mg/l. With regards to TDS, according to WHO (2008), most of the samples are of "excellent" standard (less than 300 mg/l), and the rest are of "good" standard (between 300 and 600 mg/l). When looking at the data of the 75 sampled wells of relevance for the study area, 74 of them were clearly within the levels of the National Technical Regulation on Drinking Water Quality of the Ministry of Health and also of the WHO Drinking Water Guidelines (WHO 2008). Only one tube well (QT3HP) showed high levels with regards to TDS (650 mg/l), chloride (257 mg/l), and nitrate (74 mg/l).

However, when looking at arsenic concentrations, large parts of the study area clearly exceed the threshold recommended by the Vietnamese government Ministry of Health and WHO (0.01 mg/l). Analyses from the closest test wells showed concentrations of around 0.05 to 0.07 mg/l.
Another threat to the aquifers results from their connection to the ocean. At present, the aquifers discharge into the ocean. However, this situation might reverse and saline water might enter the aquifers in the case of stronger exploitation of the groundwater resources, resulting in a lowering of the potentiometric head in the vicinity of the interface.

During the survey, shortages in water supply and pollution of water used for domestic purposes and for production were not recorded.

Exposure

Exposure concerns the degree, duration, and/or extent to which a system is in contact with, or subject to, perturbation. While there are numerous different services provided by ecosystems, this study concentrated on the provision of groundwater and its relevance for communities, agricultural and industrial production, as well as aquaculture.

Dependence of population on groundwater

About 5% of the total freshwater for Binh Thuan province comes from groundwater sources, with only 3% of the freshwater being used for domestic purposes (Department of Water Resources Management 2008). These numbers show that at the provincial level, dependence on groundwater for domestic purposes is very low. Despite the low utilisation in the surveyed villages, groundwater is of importance for domestic supply within the province. In urban areas, 27% of the water supply for domestic use comes from groundwater while in rural areas this share is even greater at 51% (Department of Water Resources Management 2008). For the two surveyed communes, dependence of the population on groundwater for drinking is 25%.

At the village level, the household survey showed that only one out of every six surveyed villages depends largely on private wells for freshwater supply; the other villages use piped water. The piped water is largely sourced from lake water, with an additional amount of about 250 m^3/day of groundwater resulting from the project for the management of aquifer recharge in Binh Thuan. Hong Thang is the only village surveyed where households depend entirely on groundwater for domestic purposes. Furthermore, 48 out of 63 surveyed households mentioned that agriculture was their main income-generating activity and that this activity is also largely dependent on groundwater, with 38 households reporting groundwater as the main water source for their activities. Five households mentioned rainwater as their main source, and the remaining five agricultural households did not provide this information. Additionally, in the village of Hong Lam, 16 out of the 112 surveyed households depend on groundwater for drinking water purposes, and seven households depend upon it for production.

Dependence of major economic sectors on groundwater

The previous section briefly explained the dependence of agricultural activities on groundwater at the local level in Binh Thuan Province. However, most of the agricultural activities in the surveyed area are mainly supplied by surface water which is taken from several lakes within the province. This being said, the dependency of the population on groundwater for agricultural production is 24.5%.

In sectors other than agriculture, data are only available at the provincial scale. In contrast to other activities, industrial activities in Binh Thuan are heavily exposed to groundwater-related hazards, as they largely depend on groundwater. The importance of industrial activities is expected to increase as Binh Thuan province is planned to be one of seven economic development regions within the country. Thus, the overall importance of groundwater in the region will also increase.

Aquaculture and tourism are further important economic sectors in Binh Thuan province. While aquaculture activities do not use groundwater, tourism is mainly depending on this resource. As there are plans to put a stronger focus on tourism as an economic activity within the region, the dependence on groundwater can also be expected to increase.

Ecological vulnerabilities

Apart from any impacts on agricultural systems, changes in groundwater quantity and quality might affect surrounding wetlands, which are fed by springs from the aquifers. Sources of pollution may include animal waste, saline water intrusion, fertiliser use, deforestation, and titanium exploitation.

Well density

Current well density is measured to be 0.02 wells/ha at the commune level; information about any changes in well density is currently not available from national data.

Sensitivity

Table 5.16 provides the set of sub-indicators selected by the GWAHS-CS project for sensitivity and their relevance to the study sites in Binh Thuan.

Table 5.16. GWAHS-CS Project Selected Indicators for Sensitivity

Generic Indicator	Binh Thuan Assessment		
	Highly relevant	Relevant	Irrelevant
Groundwater vulnerability	x		
Population density	x		
Household structure	x		
Education Level		x	
Occupation	x		
Ethnicity			x
Household income	x		
Access to savings/credit		x	
Duration since settled in the area			x
Seasonal or primary house		x	
Health status related to water-borne diseases	x		
Type of provider system		x	

Groundwater vulnerability

This indicator describes the intrinsic vulnerability of the aquifers under consideration. It is a combination of hydrogeological factors, such as net recharge, soil properties, topography, unsaturated zone lithology and thickness, aquifer media, and hydraulic conductivity.

The northern source of groundwater is contained within a Quaternary red marine sand aquifer and has a thickness varying between 30-100 m. The red sand overlies water-bearing gravel and sand beds with the water table being 10-20 m below the surface. The southern aquifer system is also contained in a coastal red sand aquifer.

Population density

Population density is one aspect influencing human pressure on groundwater resources. The population density in Bac Binh district is currently relatively low at 67 persons per km^2. Population density is 23 persons/ km^2in the two communes of Hoa Thang and Hong Phong. Unfortunately, there is no information available about the historical development of population density. As there are also no projections for future development, it is not possible to make an assessment about the dynamics of population growth and how this might impact pressure on groundwater resources.

Household structure and education level

This sub-indicator describes the number of family members, as well as their age and gender. Particular attention is paid to the head of the household through the sub-indicator on education level. The average size of a household within the survey is 4.8, varying between 4.4 and 5.2 for the six different villages surveyed. On average, 2.8 people per household are active in income-generating activities (varies between 2.4 and 3.7). The education level is comparably low, with 44% of the surveyed household heads not having completed basic education. Another 40% reached the primary or preparatory stage, while only 6% of the household heads completed secondary education or higher.

Occupation

As with the sub-indicator on education level, this sub-indicator refers to the head of the household. It is particularly relevant with regards to occupations which depend directly on groundwater resources for generating income, such as agricultural activities. The following charts provide an overview of the occupational structure of the surveyed villages (Figure 5.22), clearly showing the high rate of dependency of all villages on agricultural activities. It is however interesting to note that during the surveys, 72% of the interviewees claimed to be unemployed.

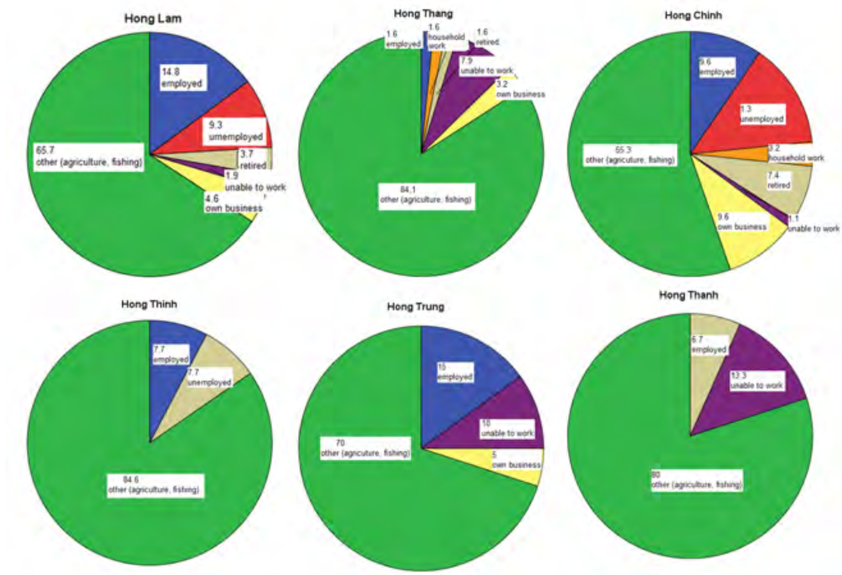


Figure 5.22. Occupations in Hoa Thang, Hong Thang and Hong Chinh villages (top) and occupations at Hong Thinh, Hong Trung and Hong Thanh villages (bottom) (in percentage).

Ethnicity

All surveyed households in the study area belong to the same ethnic group (Kinh). Thus, this indicator was not included in any further analysis.

Household income

This sub-indicator is of great importance for determining the sensitivity of a community, as financial assets are one of the most important aspects influencing livelihoods and economic development of people. There are about 17 sources of income, but the main source of income is from agriculture (73%). Unfortunately, there are no data available concerning the income and changes in income of the surveyed households.

Access to savings/loans

Access to savings and loans is another important factor defining the financial assets of a household. While no respondents indicated any savings, 61% of the total number of households reported having access to loans. The average amount of available loans is 13.8 million VND (approximately US $770, 2010 figures).

Duration since settled in the area

Based on the interviews that were conducted in the case study area, the average duration of settlement in the area was reported to be 24 years. This is a relatively short time of residence in the area and shows that the development and growth of the surveyed villages is recent. One potential implication is that supply of freshwater will have to be constantly upgraded.

Health status related to water-borne diseases

The interviewed households were asked if any household member has been suffering from any water-borne diseases. No household reported any sick household members from contaminated water. This either confirms the good quality of the water, or it is due to the habit of the people in that area of boiling water before use.

Resilience

Table 5.17 provides the sub-indicators for estimating and measuring resilience, as used in this case study.

Generic sub-indicator	Binh Thuan Assessment		
	Highly relevant	Relevant	Irrelevant
Access to alternative sources of water	x		
Additional strategies to deal with groundwater problems	x		
Access to knowledge of groundwater degradation processes		x	
Access to information about groundwater management		x	
Institutional set-up related to groundwater management		x	
Existence and enforcement of legislation and policies	x		
Groundwater-related infrastructure		x	
Out-migration from case study site			x
Existence of and participation in social networks		x	

Table 5.17. GWAHS-CS Project selected indicators for resilience.

Access to alternative sources of water

With regards to alternative sources of water, the focus of the questionnaire was on utilisation of these sources rather than access to alternative water sources. Thus, if a household had access to an alternative source of water but did not have to use it because the main source was working properly, this information was not captured by the survey. Furthermore, the survey only captured alternative sources of water for drinking purposes, while water for productive purposes was not captured. Out of the 313 surveyed households, 92 reported that they had to use alternative water sources for drinking. Remarkably, as the only village that depends on groundwater for domestic purposes, Hong Thang was the only village where no respondents reported any utilisation of alternative water sources.

As for the alternative sources of water selected, 53 households used bottled water, while the remaining households relied on water tanks. In Hong Phong commune, where 79% of all households reported the utilisation of alternative water sources, the duration was always for less than three months. In Hoa Thang, where the share of these households was much smaller, the duration varied between less than one month to more than one year. There is no information available on the reasons for having to use alternative water sources. No household reported polluted water or any diseases, while all households reported that there was always enough water to satisfy demand.

Additional strategies to deal with groundwater problems

In the case of deficiencies in groundwater quantity and quality, the utilisation of alternative freshwater resources appeared as one option, which, however, could be quite costly. It was found that the people living in the case study area always boil their water before use, which may serve as a strategy to deal with certain minor quality-related groundwater problems. It also shows that there is a certain awareness about deficiencies in water quality.

5.6 Synthesis and Discussion

The project has provided a reliable assessment of the potential for managing aquifer recharge, including an overall understanding of the technical issues involved with managing aquifer recharge for the region and for Vietnam.

This project demonstrated that good quality water can be supplied to local villages affected by longstanding water shortages via the well field located in Bau Noi that is capable of supplying 220 m^3/day. The project showed that with the use of bank filtration techniques, pumping from the production well KS-BN provides a higher and more reliable quality of water rather than pumping directly from Bau Noi Lake, without causing Bau Noi to dry out if pumping is restricted to 5.5 l/s. Similar applications might be possible elsewhere in Vietnam, where natural treatment of water from aquifers adjacent to streams and lakes can provide a safer and more reliable source of water rather than surface water itself.

Increased supplies of water are possible by adding more wells with at least the same distance from Bau Noi to well KS-BN (approximately 25 m): results from field tests suggest that 60 m should represent an adequate separation distance between pumping wells.

5.7 Vulnerability Assessment of Water Resources and the Influences of Global Climate Change

This case study is different from the others reported in this publication in that it focused on a region that does not suffer from major water problems as of yet, and groundwater resources are not threatened for now; the other studies included in this publication deal with regions of the world where the pressure on groundwater resources and the dependency of the populations on this resource is high. However, if one is not careful, Binh Thuan could follow similar trajectories under the multiple threats of population increase, industrial development, and impacts from climate change. Increasing demand is being placed on water resources by various economic sectors and communities that are not yet vulnerable (as shown in this case study), but could well end up facing water supply problems in the future. It is therefore important to continue monitoring the vulnerability of the social-ecological systems while in parallel ensuring that the water resources are not put under excessive pressures through future development.

Three main types of hazards affect groundwater resources in Binh Thuan province: saline intrusion along the coast, rapid tourism development, and titanium ore extraction. The plans for mitigating saline intrusion include making a map of areas vulnerable to saline intrusion and limiting development in such areas, as well as making it necessary to have a licence in order to extract groundwater. There is no monitoring of saline intrusion apart from a previous UNESCO project. In terms of managing the hazard of coastal storms, plans are in place to build storm water retention infrastructure in order to control the release of storm water flows.

To adapt to climate change, the central government has issued an activity plan for the whole country and the provincial Department of Agriculture and Office of Rural Development has subsequently issued their own plan in accordance with the central government's plan. This plan involves designating at-risk zones, increasing awareness among farmers (e.g. which types of crops and trees can be grown with little water during what time of year), protecting forests, land use planning, and locating water works and -infrastructure in locations which are suitable for development. An example of action under this plan is an attempt to encourage farmers not to grow rice beyond 2020 and instead, encourage them to grow less water-intensive crops (Department of Water Resources Management (a) and (b) unpublished)

5.8 Policy Implications

Management policies: The case study in Binh Thuan province has identified several areas where improvements to groundwater resource management could be made. First, it is apparent that a comprehensive groundwater management programme is lacking. This is particularly important due to the close interrelation between surface water and groundwater, with surface pollutants easily able to enter the groundwater system. There is currently no cooperation between government and non-government organisations for monitoring groundwater resources. Second, there exists an institutional gap between government and the community concerning potential climate change impacts. Increasing tourism in the area poses challenges for future water use. The Binh Thuan region could offer insights for other regions of Vietnam since it already has experience as one of the drier regions of the country. The government's current practice however is to adopt the precautionary principle towards groundwater use because of threats posed by saline intrusion.

5.9 Capacity Development Programmes and Further Research

Several opportunities were identified for providing water in the study area (Figure 5.23). From the analyses of the hydrogeological conditions, the following opportunities were identified for providing water to the case study area (Thoa et al. 2010):

- pumping water from Bau Trang to Hong Phong directly;
- extracting groundwater at Bau Noi at 487 m^3/day;
- extracting groundwater at Bau Noi at 3,000 m^3/day over a 1 km line of wells, or pumping water from Bau Trang to Bau Noi pond to enhance recharge and recovery;
- pumping the alluvial aquifer adjacent to Bau Trang (bank filtration of water) and then directly to Hong Phong;
- harvesting water from roofs in Hong Phong village for storage in tanks or wells, and improving water harvesting in Bau Thieu;

- pumping water from springs with high flow rate and good water quality; and,
- pumping water from Luy River for recharge at Tazon depression.

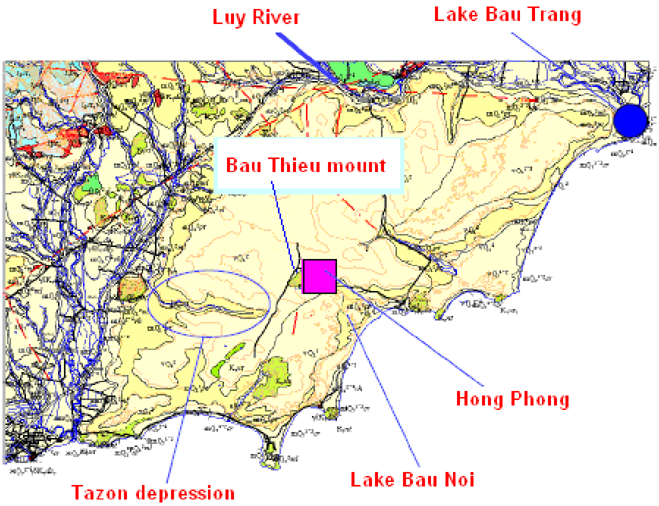


Figure 5.23. Locations of suggested projects for increased water supply in Bac Binh (Thoa et al. 2010).

Several opportunities were also identified for conducting ongoing research activities to improve available knowledge. First, in order to conduct a realistic assessment of groundwater resources, it is advisable to have more groundwater monitoring stations. Presently there are only four sites, though the wells are being monitored at different depths. Second, the type of treatment recommended for high iron, nitrate, and nitrite concentrations needs to be identified so that groundwater is fit for domestic use. Third, the mining of titanium is economically important, but nevertheless, care is needed to avoid potential pollution of groundwater resources; further studies are needed in this area. Finally, the salt water/freshwater interface needs to be studied in more detail using geophysical, hydrochemical, and isotopic methods.

5.10 References

Binh Thuan Bureau of Statistics. 2014. Binh Thuan Province Statistics Book.

Binh Thuan Province Master Plan for Rural Water Supply to the year of 2020. 2013. Center for Rural Clean Water and Sanitation. August 2013

Department of Water Resources Management. 2008. Water Resources Planning of Nam Trung Bo area. Internal report. p 195

Department of Water Resources Management (a). Unpublished. Social-economic development planning of Hoa Thang Village to 2015. Internal report

Department of Water Resources Management (b). Unpublished. Social-economic development planning of Hong Phong Village to 2015. Internal report

Thoa NTK, Arduino G, Giang NV, Van PTK and Vuong BT, 2006. The model for management of aquifer recharge in sand dune area of Bac Binh, Binh Thuan. Vietnam Journal of Earth Sciences 28(4):389-410

Thoa NTK, Van PTK, Giang NV and Vuong BT. 2010. Research on scientific basics and technology for management aquifer recharge in Vietnam. Science and Technology Publisher.

Vuong BT. 2006a. Groundwater flow model at Le Hong Phong area. Vietnam Journal of Earth Sciences 28(4):470-483

Vuong BT. 2006b. Formation of groundwater chemical components in Nam Trung Bo costal area. Vietnam Journal of Earth Sciences 28(1):83-91

WHO. 2008. Guidelines for drinking-water quality. The third edition incorporating 1st and 2nd addenda, Vol.1, Recommendations. World Health Organization, Geneva

Acknowledgements

The following people have provided invaluable assistance to the development of this report:

The residents of the communes of Hong Phong and Hong Thang have advised on the development of the field survey, and hosted numerous research visits with kindness and good humour.

Mr. Pham Van Sinh, Mr. Pham Van Hung, Mrs. Do Thi Thanh Hoa and Mrs. Nguyen Thi Hoi have ensured the smooth running of all of the project activities in the field.

The Departments of Water Resources and Environment of Bac Binh district and Binh Thuan province have supported the project activities at Hong Phong and Hoa Thang communes.

The team of the Project for the Management of Aquifer Recharge in Binh Thuan, Vietnam has allowed the use of its results for this report.

Dr. Marcus Kaplan has provided essential advice on the vulnerability of socio-ecological systems as part of this report.

The GWAHS Project leaders and case study teams from other regions have provided stimulating discussions and support to the development of the case study.

Ms. Olivia Dun and Ms. Evalyne Katoboro at UNU-EHS have ensured the smooth administration of the project, overcoming logistical and communications challenges with good humour and efficiency.

Full Contact Details of People Working on the Project/Report

Dr. Bui Tran Vuong - Division for Water Resources Planning and Investigation for the South of Vietnam; 59 street No2, Binh An ward, district No2, Hochiminh city, Vietnam; buitranvuong@gmail.com.

MSc. Doan Ngoc Toan - Division for Water Resources Planning and Investigation for the South of Vietnam; 59 street No2, Binh An ward, district No2, Hochiminh city, Vietnam; dntoan.ld8@gmail.com

MSc. Pham Van Hung, Division for Water Resources Planning and Investigation for the South of Vietnam; 59 street No2, Binh An ward, district No2, Hochiminh city, Vietnam; hungtnnmn@gmail.com

Eng. Do Thi Thanh Hoa, Division for Water Resources Planning and Investigation for the South of Vietnam; 59 street No2, Binh An ward, district No2, Hochiminh city, Vietnam

Eng. Pham Van Sinh, Division for Water Resources Planning and Investigation for the South of Vietnam; 59 street No2, Binh An ward, district No2, Hochiminh city, Vietnam; phamvansinh16@gmail.com

Eng. Nguyen Thi Hoi, Division for Water Resources Planning and Investigation for the South of Vietnam; 59 street No2, Binh An ward, district No2, Hochiminh city, Vietnam

CHAPTER 6

Bangladesh Case Study: Arsenic Contamination of Groundwater for Domestic Use

Kazuki Tsuji[1] and Masahiro Murakami[2]

[1] Gizyutu Kaihatsu Consultant Co., Ltd., Former Visiting Professor, Kumamoto University, Japan
[2] Professor Emeritus, Kochi University of Technology, Japan

6.1 Main Challenges of the Case Study Area

One of the most significant groundwater problems to threaten human security, in Bangladesh and the surrounding region, is arsenic contamination in shallow alluvial aquifers in the Padma-Meghna-Brahmaputra delta of Bangladesh (Figure 6.1) (Smith et al. 2000, Safiuddin and Karim 2001, Rahman et al. 2001, Parvez et al. 2006). In the combined areas of West Bengal and Bangladesh, around 150 million people are at risk from arsenic-contaminated groundwater (Rahman et al. 2001). It is believed that the arsenic is of natural origin. Using Bangladesh as a case study of this problem, this study will aim to: 1) clarify the cause of arsenic contamination of groundwater in alluvial deposits of the Ganges delta; and, 2) delineate the optimal effective countermeasures including deep boreholes or distributed small-scale types of water purification systems in Bangladesh.

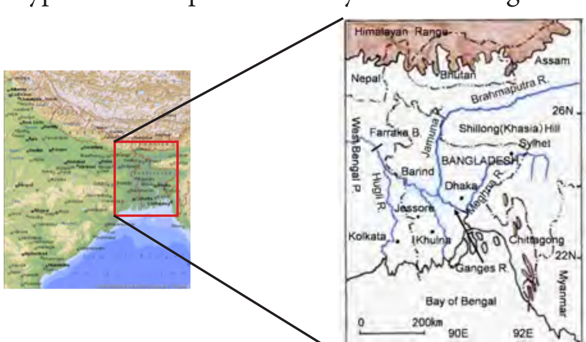


Figure 6.1. Location of the study area (Source: Microsoft Encarta97WorldAtlas).

6.2 Description of the Case Study Area

The lower Ganges plain, located in South Asia, is an extensive delta and is therefore inevitably prone to frequent occurrences of floods. Aquifers containing high groundwater potential are underlying throughout the plain. They are transboundary aquifers extending from West Bengal, India to Bangladesh and comprise multiple groundwater basins, finally discharging into the Bay of Bengal. The lower Ganges plain measures about 300 km in an east-west direction and about 350 km in a north-south direction, occupying a total area of about 110,000 km^2. The southern part of the Ganges plain is not only a widespread wetland endowed with a great variety of ecological systems, but also a site where active arc deltas develop even in the present time (Coleman and Huh 2004). This study focuses on the arsenic contamination problems in the multi-layered aquifers of Bangladesh.

6.2.1 Arsenic groundwater pollution problems in Bangladesh

In Bangladesh, most drinking water used to be collected from open dug wells and ponds which contained little or no arsenic, but did contain contaminated water which transmitted diseases such as diarrhea, dysentery, typhoid, cholera, and hepatitis. Initiatives to provide safe drinking water over the past 35 years have helped to control these diseases, but in some areas, they have had the unexpected side effect of exposing the population to a different health problem, that of arsenic groundwater contamination (BGS 2001). It is a new problem, unfamiliar to the affected population, and it has attracted the attention of concerned academics, professionals, and UN agencies due to the millions of people who may be affected by drinking arsenic-rich water. There is also concern regarding the future adverse health effects which may arise as a result of water already consumed by local populations in poorer regions without access to public health information on the threat of diseases, including arsenic contamination. While poorer people have no access to countermeasures to remove arsenic from the shallow groundwater, wealthier people may have access to a different source of drinking water from the deep aquifer system by drilling deep boreholes to a depth of more than 100-150 m below the ground surface.

From the existing studies to date, as well as this study, the arsenic contamination of groundwater in Bangladesh has been found to be of geological origin. Arsenic was found in the alluvium sediments which were deposited during the post-glacial age, about 19,000 years before physics (BP) (Pirazzoli 1991), when the seawater level lowered to 120 m below the present level, afterwards rose as high as 4 m above the present level, before finally retreating to the present level. During this post-glacial age, the climate was warmer than it is presently, which enhanced the growth of emergent types of aquatic plants, such as reeds, in marsh areas of the delta in Bangladesh. These reeds efficiently adsorbed the arsenic in the flow water of the Ganges River which then accumulated in the body of the plants. The origin of peat layers with high arsenic content at the shallower depths of less than 100 m in the alluvial deposit is dependent on the alternating sedimentation of the decayed reeds and fine particles in the post-glacial age. Similarly, the zone of high arsenic contamination is mostly confined to the several horizons of the peat and silt layers in the alluvial deposits at a depth of less than 100-150 m from the ground surface.

6.2.2 Social and economic activities

Bangladesh has a population of 169 million with a growth rate of 1.6% (2015 est.). Population density is as high as 1,033 people per km², which ranks Bangladesh as the twelfth most densely populated country in the world. More than 20% of its entire population lives in Dhaka, the capital and largest city of the country. In 2014, the per capita income of Bangladesh was estimated to be US $1,190, with a gross domestic product (GDP) of US $209 billion, making it the 44th largest economy in the world. The economy has grown at an annual rate of 6-6.5% over the past few years. While more than half of the GDP comes from the service sector, nearly two-thirds of Bangladeshis are employed in the agricultural sector, with rice ranking as the single most important product (CIA 2014, World Bank 2014).

Economic growth is rather endogenous, with slow growth in foreign direct investment and the country's economy heavily dependent on foreign aid. Although one of the world's poorest and most densely populated countries in the world, Bangladesh has made major strides to meet the food demands of its ever-growing population.

6.2.3 Water resources

The Ganges plain has a tropical monsoon climate characterised by two dominant seasons. The rainy season prevails from May to October, fed by monsoons from the south. Annual precipitation rates in the plain amount to 2,000-3,000 mm in the south to mid region, and 5,500 mm in the extreme northern area of Khasia Hill, where dense tropical jungles grow thick. Towards the northwestern border zone annual rainfall decreases gradually, totaling about 1,500 mm. The Ganges plain has frequently suffered from inundation overflow from major rivers since historical times. In addition, cyclones bring about severe disasters such as floods, debris flows, and erosion of river levees. The dry season occurs during the rest of the year, from November to March.

The Ganges River originates far west of the Indian sub-continent and flows southeastward into the Hindustan plain where it joins the Jamuna River (named the Brahmaputra River downstream) in the central part of Bangladesh. The combined drainage basin of these two major rivers measures about 1.75 million km^2 (FAO/AQUASTAT 2014). Annual discharge of the two rivers has an average volume of 34,540 m^3/second at the time of pre-control of the Farraka barrage in India. There is a bias ratio discharge rate of 13.4 between rainy and dry seasons. International riparian issues between India and Bangladesh have been a long-standing problem between the upstream and downstream communities in the Ganges River system. Under the influence of global climatic changes in monsoon Asia, Bangladesh will experience increasing impacts from both droughts and floods.

Annual surface water produced internally in Bangladesh is estimated to be 83.91 km^3, while the natural renewable water resources including flows from other countries amounts to 1,206 km^3. Groundwater recharge in Bangladesh is estimated to be 21.09 km^3. Per capita internal renewable water resources (IRWR) and natural renewable water resources, including external countries, are estimated to be 652.2 m^3 and 7,621 m^3, respectively (FAO/AQUASTAT 2014).

It has been suggested that there are between 8-12 million shallow tubewells in Bangladesh. It is estimated that up to 85% of the Bangladesh population prefers to drink well water. Piped water supplies are only available to little more than 10% of the total population living in large agglomerations and some district towns in Bangladesh. The contribution of groundwater to total irrigated areas in Bangladesh has increased from 4% in 1971 to 70% in 1999. Current estimates of the contribution of groundwater to overall irrigation water vary from 70% to as high as 90% (Shah and Krishnan 2005).

6.3 Overview of Case Study

The occurrence of groundwater varies over the globe depending on the local geology and climatic environment. Drinking water in rural communities, villages, towns, and cities in the world is heavily dependent on groundwater resources. It is estimated that as many as 2 billion people depend on aquifers for drinking water, and that 40% of the world's food is produced by irrigated agriculture that relies heavily on groundwater, especially in the flood plains of south Asia including India and Bangladesh.

The quality of water depends mainly on its origin within the geological environment. Arsenic may be found in freshwater which has flowed through arsenic-rich rocks. Severe health effects have been observed in populations drinking arsenic-rich water over long periods of time in countries around the world, including Argentina, Australia, Bangladesh, Chile, China, Hungary, India, Mexico, Peru, Thailand, and the U.S.A. In Bangladesh, West Bengal (India), and some other areas, most drinking water used to be collected from open dug wells and ponds which contained little or no arsenic, but were contaminated and transmitted diseases such as diarrhea, dysentery, typhoid, cholera, and hepatitis. Providing safe drinking water over the past 35 years has helped to control these diseases, but in some areas they have had the unexpected side effect of exposing the population to different health problems, such as arsenic contamination (BGS 2001, UNESCO 2006).

Since the 1970s, extensive well drilling programmes have contributed to a significant decrease in the incidence of diarrheal diseases in developing countries. Many dug wells were replaced with shallow boreholes through several steps. Until the discovery of arsenic in groundwater in Bangladesh in 1993, millions of shallow boreholes were intensively drilled by foreign aid organisations, including the United Nations Children's Fund (UNICEF), which conceived that boreholes were free from the threat of infectious diseases. However, the British Geological Survey (BGS 2001) showed that shallow tube wells in 61 of the 64 districts in Bangladesh were contaminated by arsenic (As), with 46% of the samples showing arsenic concentrations above 0.01 mg/L and a further 27% above 0.05 mg/L, exceeding the WHO drinking water standards at that time (previously 0.01mg/L and 0.05mg/L in water scarce and developing countries, respectively; now 0.01mg/L). When considered together with the estimated population in 1999, it was estimated that 28-35 million people were exposed to arsenic concentrations above 0.05 mg/L and a further 46-57 million people were exposed to more than 0.01 mg/L (BGS 2001).

The most common manifestation of arsenic exposure so far in terms of disease is skin lesions. Over the next decade, skin and internal cancers are likely to become the principal human health concern arising from arsenic contamination. According to one estimate, at least 100,000 cases of skin lesions caused by arsenic have occurred in Bangladesh and there may be many more (Smith et al. 2000, Safiuddin and Karim 2001, Rahman et al. 2001).

6.3.1 Groundwater-related problems

Shallow groundwater with high arsenic concentrations from naturally occurring sources is the primary source of drinking water for millions of people in Bangladesh. It has resulted in a major public health crisis threatening the life of people with as many as 35 million people possibly at risk.

A brief history of groundwater use in Bangladesh and related issues are summarised in Table 6.1.

Table 6.1. Brief history of groundwater use in rural areas of Bangladesh and West Bengal.

1960s	Most people used water from dug wells and surface water sources (rivers, ponds, lakes, etc.). These water sources transmitted diseases such as diarrhea, dysentery, typhoid, cholera, and hepatitis.
1970s-1980s	UNICEF initiated a tube well campaign as the solution to the disease epidemics, providing materials for tube wells using UNICEF's own design, and paying costs to install the wells (1 million tube wells and additionally 2.5-3 million or more wells were installed privately).
	During the program's peak, 90% of the wells were installed within walking distance from a village. It was believed they supplied safe water.
1983	First patient was diagnosed with arsenic poisoning in West Bengal Province, India.
late 1980s - early 1990s	Increasing number of people began to show signs of arsenic symptom illnesses.
1993	Bangladesh government firstly admitted arsenic poisoning in patients near the western border.
1995	International conference on arsenic contamination in Kolkata. UN, governments, and NGOs joined the conference.
1998	BGS: Geohydrological, geochemical, and screening of wells contaminated by arsenic surveys (until 2001).
	SOES: Jadavpur University, Kolkata and West Bengal screening of wells contaminated by arsenic survey (until present).
1998-2006	Bangladesh Arsenic Mitigation and Water Supply Project (BAMWSP) in nation-wide screening program of drinking wells.
2004	National Water Management Plan (approved by the Council, Ministry of Water Resources, Bangladesh).
	National Policy for Arsenic Mitigation 2004 and Implementation Plan for Arsenic Mitigation in Bangladesh (Local Government Division, the Ministry of Local Government, Rural Development and Co-operatives, Bangladesh).
2005	The West Bengal Groundwater Resources Act, West Bengal, India.
2013	The Water Act, Bangladesh

Various solutions to the problem have been tested since 1993. The first countermeasure was to drill deep tube wells at depths of more than 100-150 m in the artesian aquifer system. The second optional measure was to distribute and equip a community union with a type of small-scale water purification plant to remove the arsenics from the contaminated groundwater where arsenic concentrations were higher than Bangladesh drinking water quality standard levels. Some international cooperation agencies and NGOs have been carrying out a series of emergency measures projects in Bangladesh since 2000.

6.3.2 General aquifer characteristics

It is important to pay critical attention to the topographic and geohydrological development history of the Ganges plain as it relates to aquifer formation in association with arsenic accumulation and dissolution in transboundary aquifers. The development history of the Ganges plain originated from global scale sea-level changes during the late Quaternary period. During the latest glacial age 18,000 to 19,000 years BP, the sea level lowered to about 120 m below the present sea level (Figure 6.2). This is evidenced by geological remains in ocean floor deposits, underground incised valleys, and terrace deposits in uplifted limestone around the world.

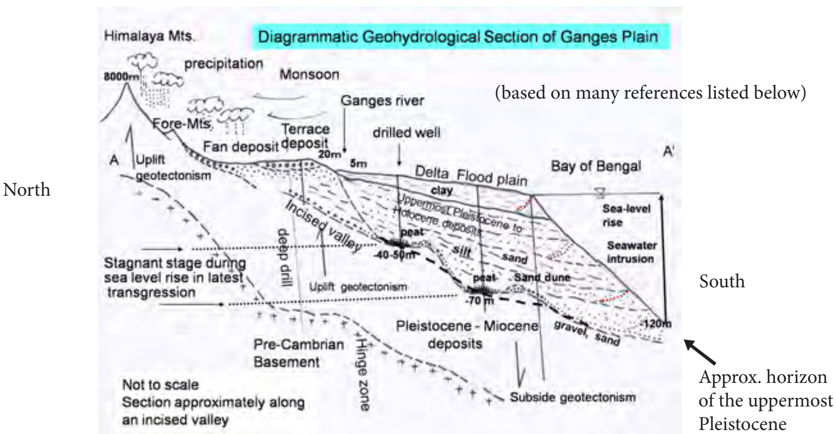


Figure 6.2. Diagrammatic geohydrological section of the Ganges plain in north-south direction (depicted mainly based on Chida 1975, Umitsu 1997, Khan 2000, Goodbred Jr. and Kuehl 2000).

The aquifer system in Bangladesh, which is mostly occupied by the Ganges plain, is simply classified into two categories: shallow and deep, which are not necessarily distinguishable from one another. This is because it is generally understood that the shallow aquifer lies 100 to 150 m below the ground surface, whereas the deep aquifer lies below such depths, which is changeable in different areas. From a geohydrological perspective, the geological boundary between the two aquifers approximately corresponds to sediment layers in the upper Pleistocene epoch.

Moreover, a distinct submarine valley, at a depth of more than 120 m below sea level, is recognisable off-shore to the west of the Bay of Bengal. The submarine valley continues to deepen, probably due to subduction movements. In comparison, to the southeast of the Ganges River estuary, a gentle-sloped broad valley is seen demarcating bathymetric contours at depths greater than 50 m. It is estimated that these two submarine valleys are probably downstream of the two incised valleys underlying the Ganges plain, which were eroded in the latest glacial event as mentioned above and successively buried in the subsequent sea-level rise leading to the present day level (Figures 6.2 and 6.3) (Tsuji 2009). Figure 6.2 shows a geohydrological cross-section approximately in parallel to the incised valley. The buried fossil valley (namely, the Paleo-Jamuna River course) to the west was identified for the first time by the Japan International Cooperation Authority's (JICA) nine deep borings, that were located along the Jamuna River levee in the central part of Bangladesh (Chida 1975). The buried valley successively continued south, where another boring revealed underground geology in Khulna (Umitsu 1997). Additionally, Goodbred and Kuehl (2000) researched geology in depth by boring at Bagerhat far south of Khulna, unveiling the existence of thick deposits comprising fluvial sand (BH-1 in Figure 6.3). Another valley to the east is expected to roughly trace the present Ganges River course, since the submarine valley is seen offshore of the estuary.

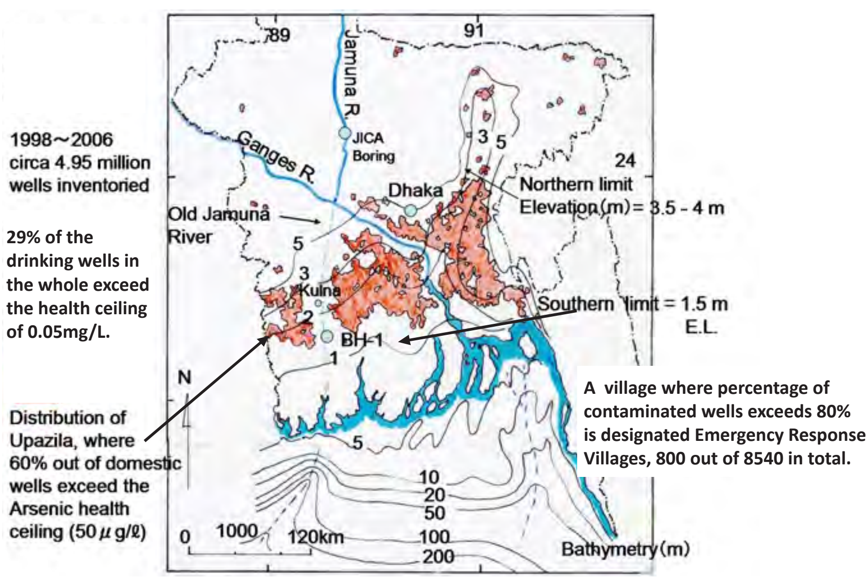


Figure 6.3. Highly arsenic contaminated zones, two low contaminated channels, and topographic elevation contours on the plain and bathymetric contours under the Bay of Bengal (simplified and adapted from BAM-WSP 2006, Parvez et al. 2006, BGS 2001).

It is of great interest to note that the northern limit of the arsenic-contaminated belt of groundwater corresponds to 3.5-4 m contours in ground surface level elevation, which is equivalent to seashore line at transgression maximum in 5,300 calibrated years BP (Goodbred and Kuehl 2000, Shahidul Islam 2001). The southern extremity of the arsenic-contaminated groundwater area is demarcated roughly along the surface level elevation contour of 1.5 m, where tube wells of deeper than 300 m are drilled to avoid saline water intrusion from the southern margin of the delta where shallow wells are impractical because of the presence of saline water (Figure 6.3).

6.3.3 Groundwater monitoring network

A systematic monitoring network observing groundwater levels and water quality has not been established in Bangladesh. The Ministry of Local Government, Rural and Co-operatives (MLGRDC) has, however, integrated a deep aquifer database since 2006 and initiated groundwater evaluation through simulation modelling. Recently the Water Act (2013), based on the National Water Policy (1999), provided extensive frameworks for integrate development, management, extraction, usage, protection, and conservation of water resources in Bangladesh (Ahmed 2013). The monitoring is believed to be in progress. In addition, the Ministry completed screening of arsenic contamination of the drinking wells, both shallow and deep, in 2006 (Figure 6.3). This screening was mainly carried out in the south of the country. On the other hand, in West Bengal Province, India, a groundwater monitoring network has been in operation since 1988, mainly in the capital city of Kolkata. The School of Environment Studies (SOES) at Jadavpur University, Kolkata has played a principal role in researching and screening for arsenic contamination of groundwater in West Bengal (SOES 2007).

6.4 Results of the Assessments

6.4.1 Assessment of renewable groundwater resources

The Ganges plain is located downstream of major rivers such as the Ganges River, the Brahmaputra-Jamuna River, and the Meghna River. Therefore, most of the surface water resources of the plain flows in from upstream countries and areas. The hydrological figures relating to water resources shown in FAO/AQUASTAT (2014) are presented on a country basis. Consequently, since the figures about the Ganges plain are not so easy to calculate individually, the figures for Bangladesh as a whole are indicated here instead. The groundwater component of total renewable water resources (TRWR) in Bangladesh is 21.12 km^3/year, which is equivalent to 1.72% of TRWR which also includes surface water. In contrast to the surface water component of TRWR, renewable groundwater amounts are relatively small compared to surrounding Asian countries because of the geographical and geohydrological location of Bangladesh (FAO/AQUASTAT 2014).

6.4.2 Assessment of groundwater quality of the aquifer

The crucial issues in relation to water quality are arsenic contamination in the Ganges plain and that it has originated from natural aquifers. The Bangladesh Arsenic Mitigation and Water Supply Project (BAMWSP) has complied with the county-wise arsenic contamination ratio map of Bangladesh (Figure 6.3). The SOES has produced a similar district-wise map of West Bengal Province, India. These maps provide a general overview of the extent of contamination in the whole Ganges deltaic plain (SOES 2007).

The number of samples taken by SOES, however, is only 2.9% of those taken by BAMWSP, which has inventoried approximately 4.95 million drinking wells in Bangladesh. BAMWSP revealed that 29% of these wells exceeded the health limit of 0.05mg/L of arsenic. In the same context, SOES inventoried 140,150 drinking wells and revealed that 24% of them in West Bengal Province were contaminated above the critical level of 0.05mg/L of arsenic. The health ceiling standard is the same in both countries (0.05mg/L), which is five times higher than the WHO standard. However, no accurate discussion, area by area, is applicable to a whole part of the two maps since the area index differs in each map. It is of great importance that the two maps can be conceived not only as a distribution index map of contamination percentage of arsenic in groundwater, but also as a hazard map for human health.

The high percentage of contaminated zones exceeding 0.05 mg/L arsenic in drinking wells extends into the southern part of Bangladesh across an east-west belt of approximately 100 km wide, and is thought to extend across the international border to the west (Figure 6.3). Consequently, the contamination distribution pattern continues into the eastern part of West Bengal. In contrast, the belt is discontinuous to the north and to the far west of West Bengal Province. Based on the zonal belt extending to the east-west in the south of Bangladesh, the general trends of arsenic contamination in the Ganges plain are outlined below.

First, the highly contaminated zone, where 60% of the wells exceed the ceiling value (colored in red in Figure 6.3.), is split into two low-contaminated channels in a north-south direction. The channels run independently of each other, tracing a similar course to the buried fossil valleys which were incised in the latest Quaternary period. Second, the aquifer depths containing arsenic are judged based on the relation between arsenic content versus well depth. The British Geological Survey (BGS 2001) clarified that wells with high arsenic content were centered in wells of less than 150 m in depth where the arsenic concentration averaged 0.1 mg/L, to a maximum of 1 mg/L. In particular, wells measuring more than 0.1 mg/L were concentrated in those wells ranging from 20 to 100 m in depth. Wells deeper than 150 m rarely gave high arsenic levels. Generally, there are few drinking wells in Bangladesh penetrating deeper than 150-200 m. It is evident that contamination is concentrated in wells which are shallower than 150 m in depth. Additionally, it is important to note that some technical problems existed regarding sealing of the annular space, which exists between the drilling hole and the casing pipes. Poor refilling of the space with impermeable materials leads to leakage of arsenic from the upper aquifers to the lower aquifers.

The principal countermeasures established by the government in Bangladesh were the installation of sand and gravel filter tanks to lessen arsenic levels to below 0.05mg/L. Moreover, the MLGRDC designated 800 villages out of 8,540 villages as Emergency Response Villages, where 80% of the drinking wells exceed the health criteria of arsenic. In these villages, they proceeded to initiate the installation of treatment facilities to remove arsenic from an appropriate water source in situ. In West Bengal, piped water supplies cover almost all urban areas, but rural areas have not been endowed with such systems and still rely heavily on groundwater.

6.4.3 Economic factors: pricing and subsidy policies

Groundwater supplies 97% of drinking water in Bangladesh. The outcomes of BAMWSP and the establishment of national policies (discussed later in more detail) have enabled the government to proceed more systematically with the construction of safe alternative water supplies. For promoting arsenic alleviation measures, the National Policy for Arsenic Mitigation 2004 and Implementation Plan for Arsenic Mitigation in Bangladesh (MLGRDC 2004) provides an informative and practical official guideline for a specific construction process of safe water devices. The national policy incorporates principal statements such as: “Access to safe water for drinking and cooking shall be ensured through implementation of alternative water supply options in all arsenic affected areas” (MLGRDC 2004; p2). It is followed by the implementation plan for arsenic mitigation, and the annex objectively describes the detailed construction design of wells, sand filters, and disposal of wastes from arsenic, in addition to well management and case management of arsenicosis patients. It also delineates the details of the plans, design, and specification of filter facilities and medical protocols; these are based partly on existing facility examples constructed by ODA and NGOs to date.

At the priority stage where the government selected 800 villages as Emergency Response Villages (see section 6.4.2 above), these villages were prioritised for having safe alternative water source devices installed. In reality, the villages categorised herein totaled 8,540 villages in the whole country, but implementation at the primary stage was limited to only 9.4% of all priority villages due to cost. One alternative water facility for 200-300 residents costs between US $2,400-2,900 for construction of a standard type, which comprises drilling of a shallow well as a new water source, though this also depends on budget capacity and support from NGOs (Table 6.2).

Table 6.2. Example of alternative water facilities constructed by several organisations (Source: Tsushima 2003).

Village	Alternative Sources	Treated method	House-holds	People benefit-ted	Output	Cost (US$)	Associates or NGOs	Yield (1/day)
Sonargaon	Deep well, 244 m	Direct	110	667	10 taps	5,000	NGO Forum Partner	un-known
Daudkanji	Rain harvesting, dug well, 8.5 m	PSF	114	675	26 taps	6,833	NGO Forum Partner	un-known
Marwa	Dug well, 9.1 m	GSF	80	un-known	2 taps	un-known	unknown	1,300 – 1,500
Panjia	Deep well, 220 m	Direct	45	220	un-known	750	Rotary Club	un-known
Putkhali	Oxbow Lake (dead arm of river, Boar	SSF	308 3 vil-lages	1,167	14 taps	23,500 Pipe-line water supply system	JICA AAN 2004	8,000 tank

In practice, an assistance organisation (NGOs, etc.) provides 90% of the total cost for safe water devices, whereas the remaining 10% is borne by local people on site, either as a cash payment or as offered labour service. Out of the construction materials, filter gravel is relatively expensive (approximately US $60/ tank) due to scarce availability. Filter sand is procured from the north as well.

Management and maintenance costs are handed over to local cooperatives (known as unions) in order to promote self-governance. Sand and gravel in a tank need to be washed 2-3 times per year, depending on the source water quality. Sand- and gravel-filtered water abstracted from dug wells and/ or ponds are periodically checked by local government or NGO officers, chiefly for arsenic content.

Drinking water is based on specifications of supplying 5 L/day/capita for drinking, and therefore one filter tank of 1.5-2.0 m^3 in volume can supply 300-400 residents on average (or 150 to 200 residents depending on the water source, if another demand of 5 L/day is added for cooking). It is desirable that one tank is located within 500 m of the living area of the community. The most favourable alternative is an arsenic-safe well deeper than 150-200 m as it mostly can be used directly. Eventually, it is recommended that a deep well be drilled by a man-driven local drilling method (known as the Donkey method) if geohydrological conditions are favourable. Up to recent years, approximately 107,000 alternative water facilities have been installed in the contaminated areas (DHE 2016).

In addition, JICA, through the Japanese NGO and non-profit organisation Asia Arsenic Network (AAN), tried to construct regional pipeline systems distributing water sources from nearby crescent lakes (called boars) to 308 households (1,500 people) (JICA/AAN 2004). It is noted that this type of response is recommended if relevant circumstances, such as community agreement to pay a part of construction cost and willingness to offer maintenance labour, are satisfied. However, water quality deteriorated remarkably when algae grew thick in the lake during the hot season which can occur to any lake or pond under similar environmental conditions. Also, this system requires difficult negotiations with local people to organise a union, not only to collect funds to cover construction costs, but also to manage facilities in the future on their own.

6.4.4 Government intervention

The most critical issues regarding sustainable management of groundwater resources include the organisation of a union (an upper organisation of a few villages) to proceed with alternative safe devices and handing over its maintenance to a union, and establishing overall local governance within unions. In order for the installation of alternative facilities to be successful, local residents must be involved from the initial stage, a union of an appropriate size must be organised which is within walking distance of a selected tank location, local residents must be convinced of private ownership ("pay and get" principle) of alternative facilities, and finally, there must be continued cooperation. Filtered water quality is checked at least once a month by NGOs and local government representatives.

Apart from the construction of the facility, nutritional guidance is provided by a health worker in order to recognise and reduce symptoms of arsenic poisoning. The issues mentioned above need watchful guidance and periodic aftercare from representatives at the local government level, particularly in the initial stage.

6.4.5 Description of existing legal and policy frameworks specific to groundwater in Bangladesh

A list of the policies and guidelines on water resources, recently made public by the Bangladesh government, is provided in Table 6.3. The ultimate objectives of the policy are to show what will happen and what actions must be taken in relation to the risk of arsenic contamination of drinking groundwater. In view of the foresight and know-how prescribed in the government publications, it is easily understandable that Bangladesh has been tackling one of the most dramatic aquifer issues in the world for more than 15 years. The policies and plans are all well-prepared and excellent technically, but the numbers of remedial facilities required to be installed are too abundant to cover all the contaminated areas for the allowable period and within the affordable budget.

Table 6.3. Policies and guidelines relating to groundwater and water resources in Bangladesh.

Year	Policy and Plan
1985	Groundwater Management Ordinance
1992	National Environmental Policy
1994	National Forestry Policy
1996	National Energy Policy
1998	National Fisheries Policy
1998	National Policy for Safe Water Supply & Sanitation
1999	National Agricultural Policy
1999	Industrial Policy
1999	National Water Policy
2004	National Policy for Arsenic Mitigation 2004 and Implementation Plan for Arsenic Mitigation in Bangladesh
2004	National Water Management Plan (approved by the Council)
2005	Sector Development Programme, Water and Sanitation Sector in Bangladesh, Vol.1, Main Report
2005	Pro-Poor Strategy for Water and Sanitation Sector in Bangladesh
2013	Water Act

Of the policies and plans enacted by the government, the National Water Management Plan 2004 deals with the most fundamental policies on water resources and capital costs. The Plan separates these into three phases, which are allocated as follows (see also Table 6.4 for associated costs): i) short-term plan of ongoing and new activities (2000-2005); ii) medium-term indicative plan (2006-2010); and, iii) long-term perspective plan (2011-2025). Implementation is monitored regularly and updated every five years. The main objectives of the plan are: i) the rational management and wise-use of Bangladesh's water resources; ii) to improve the people's quality of life by the equitable, safe and reliable access to water for production, health, and hygiene; and iii) to provide clean water in sufficient and timely quantities for multiple uses, and preserve the aquatic and water-dependent ecosystems.

The Plan is composed of 84 different programmes planned over a 25-year period. The programmes are grouped into eight sub-sectoral clusters including institutional development, an enabling environment, main rivers, towns and rural areas, major cities, disaster management, agriculture and water management, and environment and aquatic resources. They are spatially distributed across eight planning regions of the country. Their primary focus is surface water developed by major rivers (such as the Ganges River), probably due to the toxic groundwater problems and international riparian issues with India. Overcoming the arsenic contamination problems are classified in one of the regional programmes. The programmes relating to water resources (as shown in shaded rows in Table 6.4) occupy nearly 93% of the capital costs; these are now approaching the end of the medium-term phase.

Table 6.4. Programme capital costs (Source: MOWR 2004).

Taka billion	No. of Programmes	Short '00-'05	Medium '06-'10	Medium '06-'10	Residual from '26	Total	%
Institutional Development	10	3.8	6.7	8.0	1.5	19.9	2.2
Enabling Environment	13	0.8	0.9	1.8	-	3.6	0.4
Main Rivers	12	8.4	14.3	155.2	45.3	223.2	24.5
Towns and Rural Areas	8	29.5	88.3	133.7	13.4	264.9	29.0
Major Cities	17	22.1	93.9	185.6	10.3	311.9	34.1
Disaster Management	6	5.0	7.8	13.7	0.7	27.2	4.4
Agriculture & Water Management	8	1.7	7.2	29.5	7.2	45.6	5.0
Environment & Aquatic Resources	10	3.1	5.5	9.7	-	18.2	2.0
Total	84	74.4	224.7	537.1	78.3	914.5	
Equivalent US$ billion		1.5	4.4	10.5	1.5	17.9	

Following the example of a previous effort in the alleviation of arsenic threat, it is strongly recommended that the Haor and Beel (an extensive lake that forms yearly due to the flooded water of the Megna River watershed in the lower Haor basin, in the northeast of the country) are equipped with a dyke to impound water in a reservoir and distribute treated water to the arsenic-contaminated areas via pipeline networks. Also, the reservoir can link the existing dams in the eastern Hill Region with the cascade system. Plans for the international main rivers, such as the Ganges and the Jamuna Rivers, will require an enormous budget and a long period of time before completion. By making use of the domestic natural lake, the project will have an added benefit of alleviating some of the tension in the international river conflict between Bangladesh and India.

The executive summary of the plan underlines the concerns expressed by policy-makers upon discovery of the seriousness of the arsenic problem, stating that "the recent discovery of arsenic contamination of the shallow aquifer has set back past success in bringing safe water supply to the rural population in particular" (MOWR 2004). Therefore, as mentioned above, the National Policy for Arsenic Mitigation 2004 and Implementation Plan for Arsenic Mitigation in Bangladesh had set out important and urgent objective actions to supply safe water. Out of the ten national policies outlined in the Regional Programme of the National Water Management Plan (2004), a few of the most important issues include the following objectives and policy statements:

- Objective: The policy provides a guideline for mitigating the effect of arsenic on people and environment in a holistic and sustainable way.
- Policy Statement: Access to safe water for drinking and cooking shall be ensured through implementation of alternative water supply options in all affected areas. All arsenicosis cases shall be diagnosed and brought under an effective management system. Impact of arsenic on the agricultural environment shall be assessed and addressed.

This Plan will also supplement the National Water Policy and National Policy for Safe Water Supply and Sanitation, both created in 1998, in fulfilling the national goal of poverty alleviation, public health, and food security.

Furthermore, the National Policy for Arsenic Mitigation (2004) clearly states that "Groundwater is a national resource and a suitable Groundwater Act should be enacted to control all activities regarding groundwater, exploration, extraction, and management". In 2013 the Water Act was established to integrate management of water resources in Bangladesh as mentioned before in 6.3.3. Chapter 5 prescribes declaration of water stressed areas and fixing the lowest safe yield, followed by restriction on abstracting groundwater. Accordingly, it is vitally significant that further attention be focused on setting up actual monitoring frameworks to prevent a probable issue of groundwater level decline on both aquifers, which would result in contamination between multi-layered aquifers for irrigation and domestic purposes.

6.4.6 Environmental vulnerability of socio-ecological systems

This section will describe the vulnerabilities that will be faced by the aquifers in the Ganges plain, including those in Bangladesh. It is important to note that the forecasting accuracy of meteorological and hydrological models needs to be as precise as possible in order to support future policies. Many points addressed here are taken from the latest outcomes of the Meteorological Institute of Japan. They forecast that annual precipitation will generally increase in south and south-east Asia (Kitoh et al. 2008). Accordingly, both annual mean river flow and maximum monthly river flow will increase as well. On the other hand, minimum monthly river flow will decrease considerably due to increased differences in seasonal rainfall between the dry and wet seasons.

As groundwater is one component of the hydrological cycle on a global scale, changes of quantities and patterns of rainfall, as well as river waters, summarised above, are expected to bring about changes in groundwater conditions. Furthermore, if groundwater table levels begin to fall, this will have significant implications on socio-ecological systems since groundwater is essential for human life as a water source. The following points can be considered:

1) The influence of global climatic changes on rainfall in the region will affect groundwater recharge of the shallow aquifer system.
2) Groundwaterquality will be vulnerable to saline intrusion caused by sea level rise in lowlands. As the Ganges Plain is mostly located at elevations lower than 5 m above sea level, drawdown of the water table of shallow groundwater easily induces sea water intrusion below the plain. Also, sea waters run back deep inland along the major rivers and deteriorate soils near levees.
3) Vulnerability of groundwater to abstraction of domestic shallow wells will be caused by a decrease of stable basic river water flows during longer dry seasons which are expected to be induced by extremely fluctuating patterns of precipitation. At the same time, unstable precipitation reducing water supplies will result in more withdrawal of irrigation water from deep wells.

4) More abstraction for irrigation water originating from deep wells will induce the decline of water tables in shallow aquifers caused by leakage and squeezing out of groundwater from the shallow and impermeable layer to deep aquifers.
5) In accordance with groundwater leakage, groundwater prone to arsenic contamination will spread vertically and extensively in multi-layered aquifers.

The consequences of 4) and 5) can result in harmful damage of groundwater.

6.4.7 Socio-economic vulnerability linked to groundwater

Many types of socio-economic vulnerabilities have emerged which can be linked to the issues of arsenic-contaminated groundwater, including political, social, and legal vulnerabilities. These will be discussed briefly here.

Groundwater development has suffered political vulnerability due to the transboundary aquifer in the Ganges plain. In West Bengal, arsenic patients were first officially reportedly in 1983 in the south of the province. Arsenic-contaminated groundwater was discovered in northwest Bangladesh in 1993, some ten years after the first patients were reported. An international conference was held in Kolkata, India in 1995, where relevant information was exchanged for the first time between both countries, with the exception of information previously released in scientific publications. If prompt counteractions had been taken earlier to install alternative water sources and doubtful patients had been accurately diagnosed in the contaminated area, it is possible that the extent of the problem could have been reduced. If there had been a better and faster information exchange between both countries, more people might have survived and fled from the arsenic hazard and its health consequences.

Water resources are also vulnerable to rapid population growth and its uneven distribution. The population for urban and rural Bangladesh is expected to increase as shown in Figure 6.4. The trend projected in the figure forecasts relatively high increases in urban areas, which will also accelerate the social vulnerability outlined below. In addition, inhabitable areas and cultivable lands vulnerable to floods and sea level rise will result in a more centralised population, causing an increase in the scarcity of the domestic safe water supply and a decrease in the level of sanitation.

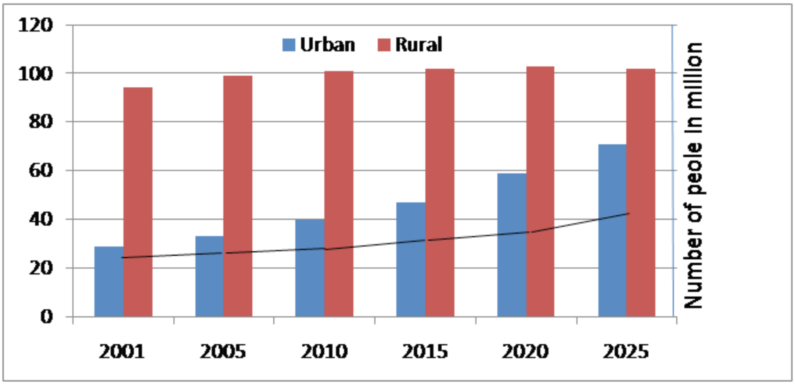


Figure 6.4. Urban and Rural population projection in Bangladesh (Source: MLGRDC 2005).

Groundwater vulnerability of drinking wells and irrigation wells, driven by the abstraction of deep irrigation groundwater, results from interference between both aquifers' well waters. This may have a significant impact on food production and food supply, thus requiring a compromise between food and water security (Ahmed et al. 2003, Rahman and Ravenscroft 2003). Rice is a fundamental crop and industry in Bangladesh and West Bengal; in particular, national growth relies heavily on the expansion of agricultural output. Groundwater is used in large-scale irrigation, which is enhanced by deep wells, especially during the dry season both in Bangladesh and West Bengal. This successful irrigation has contributed to the green revolution in Bangladesh.

Evidently, extensive contamination of groundwater has brought about serious problems. It is generally admitted that rice is endurable against arsenic. Arsenic levels in rice, vegetables, other crops and soils were recently investigated in both contaminated and uncontaminated fields. Recent conclusions indicate that the arsenic content is not considered to be of significant concern for human health. However, it is obvious to point out that arsenic concentrations in plants irrigated with contaminated water are almost double when compared to those irrigated by uncontaminated water on most vegetables.

With respect to litigation, a lawsuit was reported in United Kingdom wherein the appellant, a man living northeast of Dhaka, Bangladesh, had a reasonable prospect of success in an action against the named respondent, the Natural Environment Research Council (NERC, upper level office of BGS) in 2004 (Atkins et al. 2006). The claim was that the appellant suffered from arsenic poisoning because the health authorities in Bangladesh did not take steps to ensure that the appellant's drinking water was not contaminated by arsenic. This claim concerning the drinking water was made based on the NERC geological report. Until 1983, the appellant was drinking water from a pond. From 1983-1992, the British ODA continued a project (known as DTW2) for deep well irrigation in areas surrounding Dhaka. A hydrogeologist was employed by the BGS, and tested 16 well designs in 1988, which were located in a relatively small area northwest of Dhaka. Subsequently, he proposed a program when there was no evidence of arsenic in the drilled wells in 1991. The appellant began to drink the well water instead of the pond water, and later developed symptoms associated with arsenic poisoning, which have worsened over the years.

The case made it through to the House of Lords, which dismissed the appeal in 2006. By a majority, it was decided that the appellant had no reasonable prospect of satisfying a court that in all circumstances the NERC owed him a duty of care (House of Lords 2006). It is understood that this case originated from a lack of information exchange between the organisations concerned and local residents. Furthermore, this implies that similar claims may arise in many places, regardless of the country and overseas aid organisation. It is expected that more lawsuits may take place in the future.

In view of these diverse socio-economic vulnerabilities, alternative water sources are urgently required to be installed for domestic use to help secure human health in the Ganges Plain.

6.5 Capacity Development Programmes and Further Research

6.5.1 Description of enforcement practices

The first phase of the arsenic contamination mitigation projects was integrated and represented by the Bangladesh Arsenic Mitigation and Water Supply Project (BAMWSP) between 1998 and 2006. This project comprised such activities as identification of the contaminated aquifers, screening of drinking wells, raising awareness about arsenic contamination symptoms amongst the local people, identification of patients, and installation of alternative water supply facilities. Such activities were performed in cooperation with 270 upazilas (the administrative unit below the district level; of which there are 472 in Bangladesh) in the southern half of the affected territory. In 2004, towards the end of the first phase, a policy decision was taken to establish a phased approach when the National Arsenic Mitigation Policy and Implementation Plan were approved by the government (MLGRDC 2004).

The second phase has paid considerable attention to the sustainability of the mitigation activities by way of reflection on the outcomes of the activities during the first phase. This is because the number of installed facilities which were non-operational, not in use and left abandoned reached a high ratio during this time. Table 6.5 shows the results of a survey conducted on the conditions of safe water devices (SWD) installed by several arsenic mitigation projects in Jessore, a western marginal region. The wells are divided into shallow and deep wells. This demarcation depends upon site geohydrological succession, where shallow and deep wells are grouped at the depth of approximately 100-120 m below the ground surface.

Table 6.5. Safe water devices (SWD) in 179 villages in Jessore District in 2005 (Source: MLGRDC/JICA 2007).

SWD	Constructed	Operational	Not in use	Not in use ratio (%)
Not in use ratio (%)	108	71	37	34.3
Pond sand filters	24	8	16	66.7
Arsenic iron removal plants	22	18	4	18.2
Deep tube wells	519	471	48	9.2
Total	673	568	105	15.6

The high percentage of wells not in use was thought to be the result of mechanical parts trouble, water quality deterioration caused by poor maintenance, and the occurrence of water shortages during the dry season. It was expected, therefore, that these problems would be solved with proper training for maintenance and operation of the devices by skilled villagers on site.

With this background on the policy in Bangladesh, we introduced a case study in Chowgacha and Sharsha Upazilas, Jessore District, located in the western international border region (Table 6.6). The project, entitled Sustainable Arsenic Mitigation under Integrated Local Government System, was implemented by JICA in collaboration with the local government under the supervision of the Ministry of Local Government, Rural Development and Cooperatives (MLGRDC). The project was primarily implemented during 2006-2008, but later was extended by one year in order to focus on the monitoring and evaluation of the project's impacts.

Table 6.6. Basic statistics in the upazilas of Chowgacha and Sharsha in Jessore District (Source: MLGRDC/JICA 2007).

Upazila	# of villages	Total tube wells	Arsenic safe < 50ppb	Arsenic cont. > 50ppb	% Contamination	Number House holds surveyed	Total pop.	Male patients	Female patients	Total patients
Chowgacha	159	24,204	18,984	5.256	21.72	52,207	253,457	156	119	275
Sharsha	172	32,441	24,879	7.562	23.2	75,830	303,876	184	128	312

It is well worth noting that this project has helped to identify a way to stabilise and root foreign aid in a developing country in an effective way, since the basic viewpoints, way of thinking, and the procedures were mostly based on collaborations with local government and NGOs in Bangladesh. The JICA team was only the support organisation. This was the first instance where JICA assigned a Japanese NGO, the Asia Arsenic Network (AAN), to a social development cooperation project. Above all, it is significant to note that the project pinpointed the establishment of a comprehensive system through education and on-the-job training of villagers and local staff, creating incentives to construct safe water devices by themselves. Based on the Interim and Final Reports of the project, the outcomes are summarised below (MLGRDC/JICA 2007 and 2008).

6.5.2 Sustainable Arsenic Mitigation under Integrated Local Government System

The main objective of the Sustainable Arsenic Mitigation under Integrated Local Government System project in Jessore was to develop and establish a collaborative model among the local government, local NGOs, and on site villagers under the Ministry's and JICA's supervision. It aimed to stimulate the local people's initiative to proceed with the sustainable use of alternative devices. The project published an Interim Report in September, 2007 (MLGRDC/JICA 2007) and a Final Report was issued in 2008 (MLGRDC/JICA 2008). The main components of the project's activities include: i) capacity building for villagers; ii) coordination of arsenic mitigation activities through the establishment of committees; iii) ensuring safe water supplies; iv) water quality monitoring; v) health management for arsenicosis patients; and vi) monitoring and evaluation. Each are described here briefly.

i) Capacity building for villagers: The initial stage began with increasing the general awareness with local people of the health effects resulting from drinking contaminated groundwater, followed by the establishment of user committees. Moreover, a piped water supply system was introduced as a special program to sensitise people to the concept of paying a monthly fee to maintain the facilities. A field motivator/facilitator was assigned to each union or committee so that water supplies could be continuously maintained within the limit of permissible arsenic levels.

ii) Coordination of arsenic mitigation committee: With a policy in 2000, the government established Arsenic Mitigation Committees (AMC) at district, upazila (about 250,000-300,000 persons), union, and ward levels; however, in reality, they were inactive in many areas. The project therefore implemented re-construction of AMC at each administrative level. The AMC in turn established such systems as application-approval of SWD, arsenicosis patient surveillance, and maintenance and monitoring, including arsenic chemical tests. Also, a budget for purchasing medicine was arranged and allocated.

iii) Ensuring safe water supplies: Safe water is effectively obtained based on correct recognition of geohydrological circumstances in the area. Above all, safe water devices should be selected and designed in view of geohydrology, land use conditions, and availability of funds. Criteria for selecting suitable sites for devices were set up on the basis of geology, the water table, and well installation. Evaluations were organised in line with steps such as existing data analysis, mapping, and groundwater quality. Necessary training and surveying of these fields were transferred to local staff to evaluate technical aspects.

iv) Water quality monitoring: Water quality is essential for evaluating drinking water. The work flow process from obtaining a sample of water to a laboratory test was established, and necessary training and exercises were given to local staff.

v) Health management for arsenicosis patients: This component looked at managing the conditions of patients by doctors and health care workers. This involved field surveillance, training of doctors and medical assistants, identifying suspected patients and confirmation of sick patients, patient data management, medicine distribution, and appropriate guidance and support to treat arsenicosis patients (primarily through providing safe water and nutritious food).

vi) Monitoring and evaluation: This final stage was conducted to appraise the project execution based on the existing evaluation through basic statistics of villagers' capacity. AMC activities were regarded as the baseline, followed by recognition of the technical support systems, which DPHE offered for SWDs and the Upazila Health Complex. Monitoring focused on project management, and the care taken to prevent discrimination of socially vulnerable groups on account of arsenicosis symptoms.

As mentioned above, the project primarily focused on the selection of SWD by the villagers themselves and supporting them to apply the installation of the most suitable device on the least contaminated site. Such application flows and formats were systemised for each component, and transferred through the project's execution to the local villagers.

6.6 Conclusions and Recommendations

It is currently reported that there are approximately 10 million shallow tube wells in existence in Bangladesh. This number is expanding every year. In 2006, BAMWSP revealed that roughly 29% of drinking wells exceeded the arsenic health ceiling of 0.05 mg/L, while approximately 8 million tube wells had been installed. The percentage of contaminated wells is expected to change if the analyses of newly installed wells are carried out and added. This figure underlies a basic indicator on which a mitigation strategy is formulated; on the other hand, the figure itself shows the country's vulnerability to arsenic contamination.

Furthermore, the increase of wells, regardless of whether they are shallow or deep, will bring about a decline in water level, finally inducing downward leakage of contaminated groundwater among the multiple layered aquifers. This could create a conflict between those who use shallow drinking wells and those who use deep irrigation wells to extract groundwater for each purpose. Moreover, leakage of groundwater affects surface land subsidence in areas of low and flat elevation. Sea water will intrude inland aquifers close to the sea, and low plains will be more vulnerable to floods.

In anticipation of these predictions, the National Policy for Arsenic Mitigation 2004 (MLGRDC 2004) clearly states that "Groundwater is a national resource and a suitable Groundwater Act should be enacted to control all activities regarding groundwater, exploration, extraction and management" (MLGRDC 2004 p23). Therefore, it is recommended that a groundwater law be enacted to comprehensively control disorderly abstraction of groundwater so that groundwater hazards such as land subsidence, sea water intrusion, and expansion of groundwater prone to toxicity can be prevented. It is well known that excessive abstraction of arsenic groundwater in deep aquifers induces toxic water leakage into deep aquifers from above for many years. The balance between the two aquifers should be maintained at an appropriate level of yield.

Evaluation of optimal abstraction quantities has been initiated by the simulation model studies of a US Geological Survey team (Michael and Voss 2008 and 2009). They made field experiments to inject arsenic–rich water into a deep aquifer zone and monitored the trace of the concentrations of arsenic (Radloff et al. 2011). They found that "the concentrations of arsenic of the pumping water decreased by 70% compared with that injected after 24 hours". And they concluded that "the decline in arsenic concentrations is due to adsorption on sediments". The goal of the simulation model study by use of the experimental data is to precisely reveal "how to manage groundwater system to avoid arsenic exposure by ensuring that well pump only low-arsenic water". Furthermore, we can identify where optimal areas are and which aquifers are better to withdraw low-toxic water from in the near future based on their three management scenarios of pumping patterns. The results will help in materialising national basic management policies of groundwater development in the Bangladesh and West Bengal basins.

It is strongly stressed that the map on arsenic-contaminated groundwater needs to be understood not only from a scientific viewpoint, but also to be perceived as a "hazard map" to human security. This is because it draws attention to the fact that as many as 30-35 million people in the Ganges plain, who do not have any other safe water sources in their day-to-day lives, are currently exposed to a high probability risk of cancer. The BAMWSP reported that approximately 38,000 arsenicosis patients have been identified in Bangladesh. Additionally, since the groundwater in Bangladesh is contained in the transboundary aquifers beneath the extensive, flat and low-elevated Ganges Plain, which crosses both Bangladesh and India, political and/or socio-economic issues may occur. Accordingly, such situations will require better and sustainable exchanges of information and communication so as to prevent compounded international problems.

Groundwater comprises one component of the global hydrological cycle, and hence the groundwater flow system is greatly influenced by negative impacts such as a decrease in rainfall and local sea-level rise. These unfavourable circumstances will bring about a variety of related socio-economic vulnerabilities to the people of Bangladesh. Careful concern for preventing the occurrences of groundwater hazards and vulnerabilities should be paid to monitoring the quantity and quality of groundwater in Bangladesh.

6.7 References

Ahmed KM. 2013. Ground water management in Bangladesh: policy and institutional arrangement in Bangladesh. Retrieved from: http://www.capnet-bd.org/publications/presentation/Kazi_Matin_Uddin_Ahmed_BCAS_GW_Managment_Bangladesh.pdf

Ahmed F, Ashraf Ali M and Adeel Z (eds). 2003. Fate of arsenic in the environment. United Nations University, Tokyo. p 208

Atkins PJ, Hassan MM, Dunn CE. 2006. Toxic torts: arsenic poisoning in Bangladesh and the legal geographies of responsibility. Transaction of the Institute of British Geographers. 31(3)272-285

BAMWSP (Bangladesh Arsenic Mitigation and Water Supply Project). 2006. Retrieved from: http://www.bwspp.org/photo_albam.html#SCreening%20Resulat [no longer available]

BGS (British Geological Survey). 2001. Arsenic contamination of ground water. Retrieved from: http://www.bgs.ac.uk/arsenic/

Chida M. 1975. JICA study report on subsoil investigation works for Jamuna River bridge construction. Project, 2nd Stage Report, S1-S8

CIA. 2014. The work of a nation: Bangladesh. The World Fact Book. Retrieved from: https://www.cia.gov/library/publications/the-world-factbook/geos/bg.html#]

Coleman J and Huh OK. 2004. The world delta database/the Ganges-Brahmaputra Delta. Retrieved from: http://www.lsu.edu/WDD/ASIAN/ganges-Bramaputra/ganga.htm

DHE (Department of Public Health Engineering). 2016. Arsenic contamination and mitigation in Bangladesh. Retrieved from: http://www.dphe.gov.bd/index.php%3Foption%3Dcom_content%26view%3Darticle%26id%3D96%26Itemid%3D104

FAO/AQUASTAT. 2014. Retrieved from: http://www.fao.org/nr/water/aquastat/countries_regions/Profile_segments/BGD-WR_eng.stm

Goodbred Jr SL and Kuehl SA. 2000. The significance of large sediment supply, active tectonism, and estuary on margin sequence development: late quaternary stratigraphy and evolution of the

Ganges-Brahmaputra Delta. Sedimentary Geology 133: 227-248 House of Lords. 2006. Session 2005-06 {2006} UKHL 33. Opinions of the Lords of Appeal for Judgement in the Cause. Sutradhar vs. Natural Environment Research Council. p 20

JICA (Japan International Cooperation Agency)/Asia Arsenic Network (AAN). 2004. Arsenic mitigation project reports, 2004. Pipeline Water System BAOR: The Water Source. p 12

Khan FH. 2000. Geology of Bangladesh. The University Press Limited, Dhaka. p 207

Kitoh A, Hosaka M, Ueguchi K and Nohara D. 2008. Impact of climate change on precipitation and river flow. Symposium on Science and Practice of Basin-scale Water Policy for Population Upsurging Asia.

Michael HA and Voss CI. 2008. Evaluation of the sustainability of deep groundwater as an arsenic-safe resource in the Bengal Basin. Proceedings of the National Academy of Sciences of the United States 5(25): 8531-8536. [Available at www.pnas.org/cgi/doi/10.1073/pnas.0710477105]

Michael HA and Voss CI. 2009. Controls on groundwater flow in the Bengal Basin of India and Bangladesh: regional modeling analysis. Hydrogeology Journal 17(7):1561-1577

MLGRDC (Ministry of Local Government, Rural Development and Cooperatives). 2004. National policy for arsenic mitigation 2004 and implementation plan for arsenic mitigation in Bangladesh. p 92

MLGRDC (Ministry of Local Government, Rural Development and Cooperatives). 2005. Sector development programme, water and sanitation sector in Bangladesh. Vol. 1, Main Report, p 158

MLGRDC (Ministry of Local Government, Rural Development and Cooperatives)/Japan International Cooperation Agency (JICA). 2007. Sustainable arsenic mitigation under integrated local government system in Jessore. Interim Report. p 97

MLGRDC (Ministry of Local Government, Rural Development and Cooperatives)/Japan International Cooperation Agency (JICA). 2008. Sustainable arsenic mitigation under integrated local government system in Jessore. Final Report. p 104

MOWR (Ministry of Water Resources). 2004. National water management plan. Approved by National Water Resources Council. p 46

Parvez F, Chen Y, Argos M, Hussain AZMI, Momotaj H, Dhar R, van Geen A, Graziano JH and Ahsan H. 2006. Prevalence of arsenic exposure from drinking water and awareness of its health risks in a Bangladeshi population: results from a large population-based study. Environmental Health Perspectives 114(3):355-359

Pirazzoli PA. 1991. World atlas of holocene sea-level changes. Elsevier, Amsterdam. p 300

Radloff KA, Zheng Y, Michael HA, Stute M, Bostick BC, Mihajlov I, Bounds M, Huq MR, Choudhury I, Rahman MW, Schlosser P, Ahmed KM and van Geen A. 2011. Arsenic migration to seep groundwater in Bangladesh influenced by adsorption and water demand. Nature Geoscience 4:793-798. [Available at: http://www.nature.com/ngeo/journal/v4/n11/full/ngeo1283.html]

Rahman AA and Ravenscroft P (eds). 2003. Groundwater resources and development in Bangladesh. Background to the Arsenic Crisis, Agricultural Potential and the Environment. The University Press Limited, Dhaka. p 466

Rahman MM, Chowdhury UK, Mukherjee SC, Mondal BK, Paul K, Lodh D, Biswas BK, Chanda CR, Basu GK, Saha KC, Roy S, Das R, Palit SK, Quamruzzaman Q and Chakraborti D. 2001. Chronic arsenic toxicity in Bangladesh and West Bengal, India--A Review and Commentary. Journal of Toxicololgy - Clinical Toxicology 39(7): 683-700

Safiuddin Md. and Karim Md. M. 2001. Groundwater arsenic contamination in Bangladesh: causes, effects and remediation. Proceedings of the 1st IEB international conference and 7th annual paper meet; 2001 November 2-3; Chittagong, Bangladesh: Institution of Engineers, Bangladesh. http://www.eng-consult.com/pub/ArsenicIEB.pdf

Shah T and Krishnan S. 2005. Bangladesh sensitization tour: Groundwater Governance Project Report.

Shahidul Islam M. 2001. Sea level changes in Bangladesh: the last ten thousand years. Asiatic Society of Bangladesh, Dhaka. p 185

Smith AH, Lingas EO, Rahman M. 2000. Contamination of drinking water by arsenic in Bangladesh: a public health emergency. Bulletin of the World Health Organization 78(9): 1093-1103

SOES (School of Environmental Studies). 2007. Groundwater arsenic contamination in West Bengal-India. Reported work done by SOES. Jadavpur University, Kolkata, India Retrieved from: http// www.soesju.org.arsenic/wb.htm

Tsuji K. 2009. Groundwater in Asia. Touka Shobou, Fukuoka, pp 115-136 [in Japanese]

Tsushima S. 2003. Report of alternative water devices in Eastern Bangladesh (manuscript). p 6 [in Japanese]

Umitsu M. 1997. Topography in the Ganges Plain. In: Kaizuka S. (ed). Topography in the world. University of Tokyo Printing, Tokyo. pp. 108-120 [in Japanese]

UNESCO. 2006. Groundwater contamination inventory. IHP-VI, Series on Groundwater

World Bank. 2014. World development indicators 2014. World Bank, Washington, DC

Acknowledgements

We are greatly indebted to AAN (Asia Arsenic Network, Project Leader: Mr. Kazuyuki Kawahara) and Mr. Ryuji Ogata of JICA Expert of MLRDC at that time for their intensive aid in Bangladesh and kind offerings of the reports and materials. Also we are very grateful to Professor Kengo Sunada (Project Leader), Yamanashi University for the assistance to our research, which was one of the CREST (Core Research for Evolutional Science and Technology) from 2003 to 2008. Thanks are due to the JST (Japan Science and Technology Authority) for financial support.

CHAPTER 7

Moving Forward: Securing and Sustaining Groundwater for Livelihoods and Development

Corinne Schuster-Wallace

School of Geography and Earth Sciences & Dept. Civil Engineering, McMaster University, Ontario, Canada

In addition to being an alternative source of drinking water in water scarce regions, groundwater is key for development and livelihood security. However, over-exploitation of groundwater is threatening sustainability, while pollution from industrial and urban wastes and agricultural runoff threaten water quality. Given the importance of groundwater for human livelihoods, health, and food security, groundwater management is closely linked to human wellbeing.

7.1 Key Themes

Analysis of key vulnerability indicators within a coupled socio-ecological system framework across five countries has enabled examination of the dynamic and changing relationships between groundwater resources and the people who rely on them. Several key themes emerge regarding sustainable groundwater management and the development of resilient groundwater systems. These are discussed in the following sections, followed by an exploration of vulnerabilities that exist and potential mitigation strategies.

7.1.1 Theme 1: The importance of ecosystem services

Ecosystem services play an important role in maintaining groundwater quality and quantity. For example, reeds and other wetland plant species filter out contaminants. Forest cover not only prevents soil erosion, but increases water retention, and therefore groundwater recharge by providing slower infiltration pathways that minimise surface runoff. However, groundwater mismanagement and overexploitation can have negative impacts on ecosystem services through reduced base flows in rivers. This is usually the stable portion of river flows, where the water table meets the surface, and is augmented by rainfall and surface runoff, which is inherently more unstable. Falling water tables result in falling water levels as the water table lowers beneath the ground surface. This degrades wetlands and strands vegetation that requires their roots to be submerged in water, such as mangroves. Furthermore, as the water table falls, soil can subside as it dries, impacting infrastructure.

Over geologic time periods, a negative feedback loop between wetlands and groundwater can establish contamination pathways. As identified in Bangladesh (Chapter 6), layers of decomposed reeds that, when living, filtered arsenic out of the water, are releasing those contaminants back into the soil and water upon decay. These organic layers then become sources of groundwater contamination, as opposed to mechanisms for water purification. Indeed, this is an important issue that has to be resolved when utilising natural wetlands, or constructing artificial ones, for wastewater treatment. Contamination, particularly with heavy metals, precludes use of the biomass for food or fertiliser, as the contaminants can (re-)enter the food chain. In many cases, these have to be burned, contributing carbon and pollutants to the atmosphere.

Many soil and rock matrices further provide slow filtration of water, improving microbiological water quality as pathogens either get trapped (chemically or physically) in the soil matrix, or die off during aquifer residency. In some instances this is used to provide a final treatment phase for wastewater; partially treated wastewater is sprayed over aquifer recharge zones so that natural filtration processes provide final treatment. In this manner, not only is the water subject to additional treatment (or polishing), but it artificially recharges groundwater aquifers and protects against overexploitation. It should be noted that this is only possible for microbiological contaminants. Heavy metals and persistent organic pollutants, once introduced into an aquifer, can be very expensive and virtually impossible to remove or remediate. This purification of groundwater is very important in locations where people depend on springs for drinking water, e.g. Binh Thuan Province, Vietnam (Chapter 5).

In many sub-Saharan African countries, these shallow groundwater resources are tapped as springs by digging down and placing a concrete dam with pipes to capture the groundwater flow for collection (Figure 7.1). Given how shallow these aquifers must be for them to be captured in this way, they are vulnerable to surface contamination through contaminated surface water infiltration, particularly if animals defecate in the vicinity (groundwater under direct influence of surface water, or GWUDI). If contaminated water is used for irrigation, crops can become contaminated. Thus, people are exposed not only directly through drinking water, but indirectly through the food that they consume (Dickin et al. 2016).

Figure 7.1. Springs tapped for water supply in East Africa (Schuster-Wallace).

7.1.2 Theme 2: Anthropogenic impacts on groundwater quality

As introduced in the previous section, groundwater flow can remove microbiological contaminants in some soil and rock types. However, human activities threaten aquifer groundwater quality through more than just microbiological quality. Simply digging or drilling wells to access an aquifer introduces contaminant pathways, bypassing natural filtration processes. Risk of contamination is exacerbated with every additional well placed into the aquifer, as well as by the types of human activities being undertaken in the vicinity. Risk of contamination increases significantly when wells are abandoned, especially if they are not decommissioned and capped properly. These wells provide rapid transport corridors for contaminated water to access aquifers, no matter how deep and naturally protected the aquifer.

Chemicals resulting from agricultural and industrial activities tend to be persistent in the environment and therefore, in aquifers themselves. Once introduced, they will form a plume of contamination within an aquifer. Urban development introduces other contaminants, such as pharmaceuticals, salts, solvents, and paints. For example, Beni Salama, Wadi El Natrun, Egypt (Chapter 2) manufactures chemicals from salts found in the region.

The increase in impermeable surfaces in urban environments exacerbates this through runoff and concentration in low lying areas. Economic development is an unavoidable necessity, particularly in low and middle income countries. However, stable economic growth in regions with a high dependency on groundwater, especially for agriculture, will be compromised through poor aquifer management. As illustrated in these case studies, many semi-arid and arid environments intersect with a dominant agricultural sector and high dependency on groundwater.

Other human activities that compromise groundwater quality include overpumping in coastal regions. Drawdown in these locations causes saltwater incursion into the aquifer and eventually through the wells. Sea level rise, as a consequence of climate change, exacerbates saltwater intrusion in coastal areas. Poor management and over-irrigation in marginal agricultural lands can have the same effect, with a salt layer developing on the soil surface. This saline water is not potable, forcing anyone who relies on it as a drinking water source to seek alternatives. Many crops are salt intolerant, requiring a switch to salt tolerant species and/or brackish water aquaculture to maintain livelihoods. Knock-on effects include changes in local diet to accommodate alternative crops being grown.

In Tra Vinh Province of the Mekong Delta in Vietnam (Chapter 4), there is high dependence on groundwater for drinking water, agriculture, and industrial development. In addition to livestock production, farmers have shifted to combined rice-shrimp farming and trebled cropping per year. Resulting pollution and salinity intrusion are combining to increase the potential to develop acid-sulphate soils in the region. Similar pressures are being experienced in Binh Thuan Province of Vietnam. There has been an economic shift from agriculture to tourism, as well as diversification of agriculture from rice to cattle and goats. Not only do these shifts require intensification and increased irrigation (for pasture), pressures are compounded by the relocation of industries from urban to rural locations. In Beni Salama, Wadi El Natrun, Egypt, the water itself is an industry, as it is bottled and sold. However, approximately 30% of aquifer recharge is paleowater; it cannot be replaced.

7.1.3 Theme 3: Tourism

While seen as an economic growth opportunity in many countries with natural resources (wildlife, beaches, etc.), rapid expansion of the tourism sector can have unintended consequences on groundwater quality and quantity. Coastal aquifers in particular are vulnerable to over pumping and therefore saltwater incursion, especially to provide the water volumes most tourists expect to have at their disposal. Golf courses require significant amounts of water and pesticides that have been proven to be detrimental to local groundwater quality (Metcalfe et al. 2011).

7.1.4 Theme 4: Risk balancing and competition

Emerging from the fact that groundwater resources around the world are under threat, if not currently overexploited, yet depended upon by so many for life and livelihoods, sustainable management requires balancing of risks and resource competition. In Bangladesh, for example, the long term (chronic) risk of arsenicosis from consumption of arsenic-contaminated groundwater has to be weighed against the short term (acute) risk of diarrhoea from pathogen-laden surface water, particularly in the rainy season (Chapter 6). Both of these risks have to be weighed against the certainty of death from lack of water to drink. In Tra Vinh Province (Chapter 4), groundwater is increasingly used as a source of drinking water during the dry season, as surface waters are too contaminated. During the wet season, people turn to rainwater for drinking water; i.e. rainwater harvesting.

Agricultural fertilisers and pesticides are another source of chronic health risk, especially in porous soils. Yet food is essential for nutrition and agriculture is a key economic sector in many regions. Moreover, compromises may be required between groundwater volumes for local water versus food security. Societal needs for drinking water include healthcare and school facilities; public locations serving populations more vulnerable to contaminated water supplies (the sick and the young). Industrial development is another source of contamination risk for groundwater aquifers, yet essential for local and national growth and sustainable social development.

When livelihoods are difficult to carve out under the best conditions in these stressed, dryland regions, competition for resources will result as people try to maximise their production, and therefore returns on investment. Two thirds of Bangladeshis are employed in the agricultural sector, with the dominant crop being rice. The main source of irrigation water is groundwater, setting up significant demand for finite volumes of water. In the Mekong delta, competition is exacerbated by different cultural groups growing different crops with different water requirements. Competition, and conflict, in this region increases during the dry season.

7.1.5 Theme 5: Monitoring

Many times in this book, groundwater has been referred to as an "invisible" or "hidden" resource. "Out of sight, out of mind" is a saying that aptly describes the plight of groundwater, particularly in regions of water stress or poverty. This sets up an untenable situation from a sustainable management perspective. Without knowledge of both the current state and trends, and for both quantity and quality, it is impossible to make informed decisions that balance risk and health, livelihoods and environment, and economic growth and social development.

Agenda 2030 calls for a "big data" revolution that must encompass not only monitoring networks, but data sharing, analysis and evaluation capacity, and modelling and forecasting tools. Use of remote sensing and miniaturisation of instruments can enhance our groundwater knowledge, but often comes with a significant price tag attached that is prohibitive to low and middle income countries, and rural communities in particular. Groundwater follows underground topography which does not always correspond to surface topography and watersheds, making inference difficult.

A final challenge in quantifying groundwater is being able to move beyond simple quality, quantity, and economic metrics. Specifically, methods need to be developed and tested that assess and assign both social and ecological values to groundwater resources. These assessments are context-specific, but allow an understanding of how different risks, costs, and competing uses impact not only upon the economy and local livelihoods, but on human wellbeing and the environment. Only in this manner is it possible to undertake true cost-benefit analyses.

7.1.6 Theme 6: Lack of capacity

Capacity is a limiting factor for change. While it is automatic for many to begin thinking of technical capacity to manufacture, install, operate, and maintain infrastructure, many other capacities are required for sustainable and resilient use of our groundwater resources. These include management and policy capacity, measuring, monitoring, analysis, and evaluation capacity, planning and assessment capacity (especially from social sciences perspectives), legal capacity, and enforcement capacity. As a result, efforts can end up being ad hoc responses to crisis situations, rather than proactive and planned.

In many of the case studies presented here, community awareness of problems is seen as an important criterion for positive change. In Egypt, access to knowledge of groundwater degradation processes is seen as the most relevant factor for enhancing community resilience. Capacity through knowledge is empowering; providing community members with understanding of problems, their role, and how they can support change.
However, there is a gap between knowing what is wrong and acting to change the situation. For this reason, community capacity and supporting structures for communication and engagement across stakeholders is as important as any infrastructure investments made to enhance resilience.

In some cases, policy and economic instruments can be employed to change behaviours. Local enforcement of (national) regulations can be an effective stick to ensure compliance, particularly with water quality standards. User pay policies and varying tariff structures for water can incentivise water conservation practices, although in some high income cities, this has been so effective that revenues from fees are now insufficient to cover operating costs.

7.2 Vulnerabilities

Cutting across the themes discussed above are several vulnerabilities that can exacerbate or compound poor management strategies.

7.2.1 Poverty

Poverty creates multiple barriers to human security. The top priority for people living below the poverty line is securing basic necessities for survival. They do not have the luxury of concerning themselves with the environment or potential long term impacts of their current actions. Typically, impoverished individuals are illiterate, as poverty is a barrier to accessing education. In turn, this may prevent them from accessing information, such as public health information which is designed to protect them from exposure to preventable risks. A case in point is arsenic in Bangladesh.

Poverty also prevents people from being able to implement solutions or countermeasures once they are aware of the potential threat(s). For example, if your water source is contaminated with arsenic, options exist to treat that water or develop an alternative water source such as a deeper well. These are not options for those living in poverty and so the prevalence of diseases in this group increases. Thus, while natural geological formation is the root cause of the arsenic issue, health impacts are compounded by the local economic (high dependency on groundwater irrigated agriculture) and social (poor source water quality for drinking water) contexts.

This group is also most vulnerable to groundwater protection measures. For example, one way to reduce groundwater stress is to reduce the area under irrigated cultivation in a region. For those living in poverty, the smaller the landholding farmed, the lower the profit margins. For those living just above the subsistence threshold, this type of intervention could throw them into the poverty cycle, even though the goal of sustainable groundwater management is laudable. Not only is their immediate livelihood threatened, but with it, their ability to access additional investment funds or micro-loans. Additional burdens on these vulnerable people are linked to increased social problems such as drug addiction, smuggling, and robbery in Iran (Chapter 3).

7.2.2 Attitudes, Practices, Perceptions

Any policy or technical solution to enhance sustainability of groundwater resources will fail if local social and cultural contexts are not taken into consideration. Local practices and perceptions can be significant barriers or important facilitators to implementing sustainable solutions. For example, when exploring opportunities for income diversification or alternative livelihoods, traditional cultural practices can provide an alternative that is already accepted and well-established in the community. In Egypt, glass making using locally-sourced natron deposits is a heritage occupation (Chapter 2).

Perceptions and practices are important to understand, especially when implementing new policies, especially economic instruments. In the Mekong Delta, heavy subsidies promote inefficient use and a "pervasive mindset that underground water is limitless". If attempting to use pricing to encourage greater efficiencies in this context, public awareness and education campaigns are essential in order to demonstrate the impacts of current levels of water use withdrawals. Moreover, a staged implementation approach with pro-poor options would reduce the immediate burden, particularly on the most vulnerable populations. Other financing options, such as public-private partnerships (PPPs), can be linked to very strong negative perceptions. While some PPPs have been poorly managed and taken advantage of both the recipient government and communities, when managed properly and equitably, PPPs can be a valuable source of infrastructure financing.

Environmental degradation and health impacts associated with poor groundwater resources and management strategies can have significant impacts on attitudes, practices, and perceptions. This book highlights three examples. The first is the transition from nomadic to sedentary pastoralism in Shibkouh County, Fars province, I.R. Iran (Chapter 3) as a direct response to land degradation. As these nomadic pastoralists build more permanent communities, water becomes an important requirement, satisfied through the drilling of illegal wells. The second is a direct consequence of arsenicosis in Bangladesh (Chapter 6). As the disease progresses, those suffering from visual skin lesions face ostracisation and stigmatisation, often unable to find work or marry. Finally, unintended consequences of management strategies place people at higher risk of illness. In Egypt, cutting off water supplies meant that people had to store their water in containers, introducing an additional opportunity for water-related diseases (Chapter 2).

7.2.3 Global Environmental Change

Global climatic, land use, and population changes compound each other to exacerbate groundwater quantity and quality, and therefore sustainability. Our changing climate is affecting the timing, intensity, and duration of precipitation events over both space and time. This has direct implications for groundwater recharge rates. While it is obvious that no rain means no infiltration of water to aquifers, too high a rainfall intensity also reduces the water infiltrating to aquifers. In this scenario, if the rainfall intensity is greater than the infiltration capacity, most of the rainfall will run off as surface flow into the nearest water body. Steep slopes reduce infiltration rates and this is exacerbated by deforestation because vegetation slows down runoff, giving water a chance to infiltrate the soil. Lowering of the water table through depletion or over extraction of groundwater aquifers can result in subsidence and unstable river base flows, including drying up of springs. These conditions are exacerbated in the dry season when this base flow is important for in-stream ecology and augmentation of water supply to meet demand, contributing to drought conditions and desertification. They are further exacerbated by population movement and urbanisation. Increased population densities increase stress on groundwater resources through increased demand and competition. Urbanisation increases the extent of impermeable surfaces (roads, buildings, etc.), reducing infiltration rates and thereby reducing groundwater recharge. Alone or in combination, these increase vulnerability of groundwater aquifers significantly.

7.2.4 Policy to Practice

Implementing policy in practice is not always straightforward and can have unintended consequences, particularly for the most vulnerable. For example, the national policy for arsenic mitigation and implementation plan for arsenic mitigation in Bangladesh has been described herein as an "informative and practical official guideline" (chapter 6), but financial constraints have meant that less than 10% of priority villages have had alternative drinking water interventions put in place.

Other challenges include management issues as identified in Bangladesh. A union, or local co-operative, was formed to collect community contributions and to ensure sustainable operation and management of the systems. However, these unions required significant stakeholder negotiations just to establish. Success criteria include the engagement of community members from the beginning, identifying an appropriate size for the union, ensuring that community members understand and embrace private water supplies, and maintaining regular local government support.

The case study in Bangladesh further recognised the almost universal systemic failure to sustain interventions (Chapter 6). This typically results from eager investment in upfront infrastructure with little thought given to how operation, management, and maintenance will be funded. Bangladesh is a case in point, with almost 35% of dug wells no longer in use, and more than 60% of pond sand filters, and almost 20% of arsenic iron removal plants no longer functional; even deep tubewells have an almost 10% failure rate.

Legal and political vulnerabilities further undermine practice. Legal vulnerabilities include meeting the human right for drinking water, duty of care, and lack of legal frameworks. Duty of care is most obvious in the Bangladesh case study, with opportunities for litigation over failure to protect against negative health outcomes; i.e. arsenic poisoning. A lack of sufficient or implemented legal frameworks creates vulnerabilities across all case studies; lack of, or poorly developed, groundwater laws, land use management plans, and integration across policies threaten not only groundwater supplies, but those people who depend upon them for life and livelihoods. Negative consequences can include hoarding groundwater for personal use and conflict over perceived rights. The ultimate consequence is a complete moratorium on groundwater extractions as discussed in the Iran case study (Chapter 3).

Political vulnerabilities impact both policy and practice. These political vulnerabilities are exacerbated by a lack of data and knowledge for evidence-informed decision-making. Even if appropriate and adequate information is available, lack of co-ordination, co-operation, collaboration, and information exchange across sectors, stakeholders, and communities thwarts true integrated management of groundwater resources within the broader context of water management. This is exacerbated by poor governance structures, capacity, institutions, and resources, and particularly across political boundaries.

7.2.5 Community Resilience

As established in this publication, the more resilient a community, the more likely that sustainable management of groundwater resources can be achieved. Household size, age, and education levels (particularly of the head of household) have been identified as indicators of sensitivity/vulnerability. In Egypt, low education levels indicate that an individual is unlikely to hold more than one job in order to improve their economic status. On the other hand, the highly educated are likely to commute out of the community for work, no longer strongly connected back to the community.

In the Mekong Delta, lower educated or older individuals are less likely to invest in new technologies.

7.3 Recommendations for Groundwater Management

Overall, these case studies demonstrate that a comprehensive vulnerability assessment tool can aid in understanding the context-specific complexities and feed-back loops that impact local social, environmental, and economic conditions. In addition to the environmental crises brought about by poor groundwater management and overexploitation (e.g. reduced species diversification, soil salination), social and economic crises have been demonstrated, including forced out-migration and increased poverty because of the complex interlinkages in the socio-ecological system. As such, the following recommendations emerge that, taken together, support sustainable management of groundwater resources in an holistic manner, ensuring continuation of environment, economic sectors, livelihoods, cultures, and societies.

- Global, regional, and national mechanisms must be established to support technology transfer, particularly to female and subsistence farmers. National mechanisms must be established to stabilise and facilitate financial flows for foreign aid and other financial mechanisms in low and middle income countries, particularly conflict states.
- Economic instruments must be implemented for full cost accounting and demand management. Strategies employed in the case studies include economic water use efficiency (maximum revenue per water volume). However, it is important to understand all implications and manage potential risk increases accordingly.
- Develop and implement national groundwater strategies/plans.
- Embed regional plans within national strategies utilising direct lines of sight; i.e. integrate across scales and if devolving, ensure that sufficient resources and capacity are devolved alongside the mandate and authority.
- Within countries, engagement with local government and non-government organisations is essential to ensure not only environmental resilience, but social and economic resilience as well.

- Implement managed aquifer recharge (MAR) including the financial, human, and institutional capacity required for successful implementation.
- National governments must establish mechanisms for integration between social and economic development policies (including agriculture) and water resources management policies (i.e. IWRM plus approach).
- The management of causes and consequences associated with groundwater use cannot fall entirely in the purview of water resources management; i.e. public health and social system responses are also required.
- Artificial recharge and appropriate infrastructure must be implemented to capture flash flood regimes, building upon a multiple benefits/multi-purpose approach which includes improving groundwater quantity and quality, maintaining agriculture-based livelihoods, and enhancing resilience against drought and floods.
- Wastewater is not an end point, but a resource in and of itself that can be used (under proper conditions and management) to off set groundwater demand for irrigation, substitute for chemical fertilisers, and/or be used for aquifer recharge.
- Agricultural shifts must be made to context specific, less water intensive crops and better crop cultivation patterns, recognising the need to manage implications of this shift, including local dietary changes to new crops being produced.
- Where environmental degradation has already occurred, brackish water agriculture and aquaculture, or solar desalination can provide viable solutions.
- Water efficiency strategies and technologies must be incentivised, employed, and supported through policy. Examples include demand specific irrigation (crop development and weather), drip irrigation, and absorbent materials in soil matrix to reduce irrigation frequency.
- Policies, strategies, and technologies must be supported by diverse credit options for farmers, including pro-poor and gender strategies.
- Shifts to alternative livelihoods should be promoted and incentivised where appropriate; while still potentially impacting upon groundwater resources, ecotourism, and artisanal industries (organic cosmetics, plant based materials, apiculture, carpet weaving, greenhouse culture) support income diversification and therefore greater livelihood resilience.
- As part of any groundwater management strategy, local-co-operation and empowerment as well as integration of

indigenous knowledge are essential, requiring resources (financial, human, and time) to be allocated as part of the overall budget.

- Public outreach and information dissemination must be undertaken through culturally appropriate media. Key outreach challenges include making groundwater "visible", demonstrating the vulnerability of groundwater to various drivers, training locals on the roles that they can play in sustainable management, educating youth, and incentivising professional youth opportunities in order to build water resources management capacity.
- Build capacity for and utilise remote sensing data, geographic information systems (GIS), and modelling for supplementary information, analysis, forecasting, and scenario-building.
- Create mechanisms for iterative learning and data and knowledge-sharing between policy, practice, and research; bridging evidence informed policies and decision-making.
- Undertake standardised vulnerability assessments of critical/sensitive groundwater aquifers. While the approach presented herein is a solid baseline, demonstrating the need for an integrated and holistic approach to vulnerability, future iterations could include an environmental sensitivity measure, participatory rural appraisal, and collapse of some of the socio-economic indicators in order to reduce the data burden in low resource settings.

7.4 References

Dickin SK, Schuster-Wallace CJ, Qadir M and Pizzacalla K. 2016. A review of health risks and pathways for exposure to wastewater use in agriculture. Environmental Health Perspectives DOI: 10.1289/ehp.1509995

Metcalfe CD, Beddows PA, Gold Bouchot G, Metcalfe TL, Li H and Van Lavieren H. 2011. Contaminants in the coastal karst aquifer system along the Caribbean coast of the Yucatan Peninsula, Mexico. Environmental Pollution 159:991-997

UNITED NATIONS
UNIVERSITY
UNU-INWEH
Institute for Water,
Environment and Health

UNITED NATIONS
UNIVERSITY
UNU-EHS
Institute for Environment
and Human Security

United Nations
Educational, Scientific and
Cultural Organization

International
Hydrological
Programme

ISBN: 978-92-808-6082-5

United Nations University
Institute for Water, Environment and Health
175 Longwood Road South, Suite 204
Hamilton, Ontario, Canada. L8P 0A1