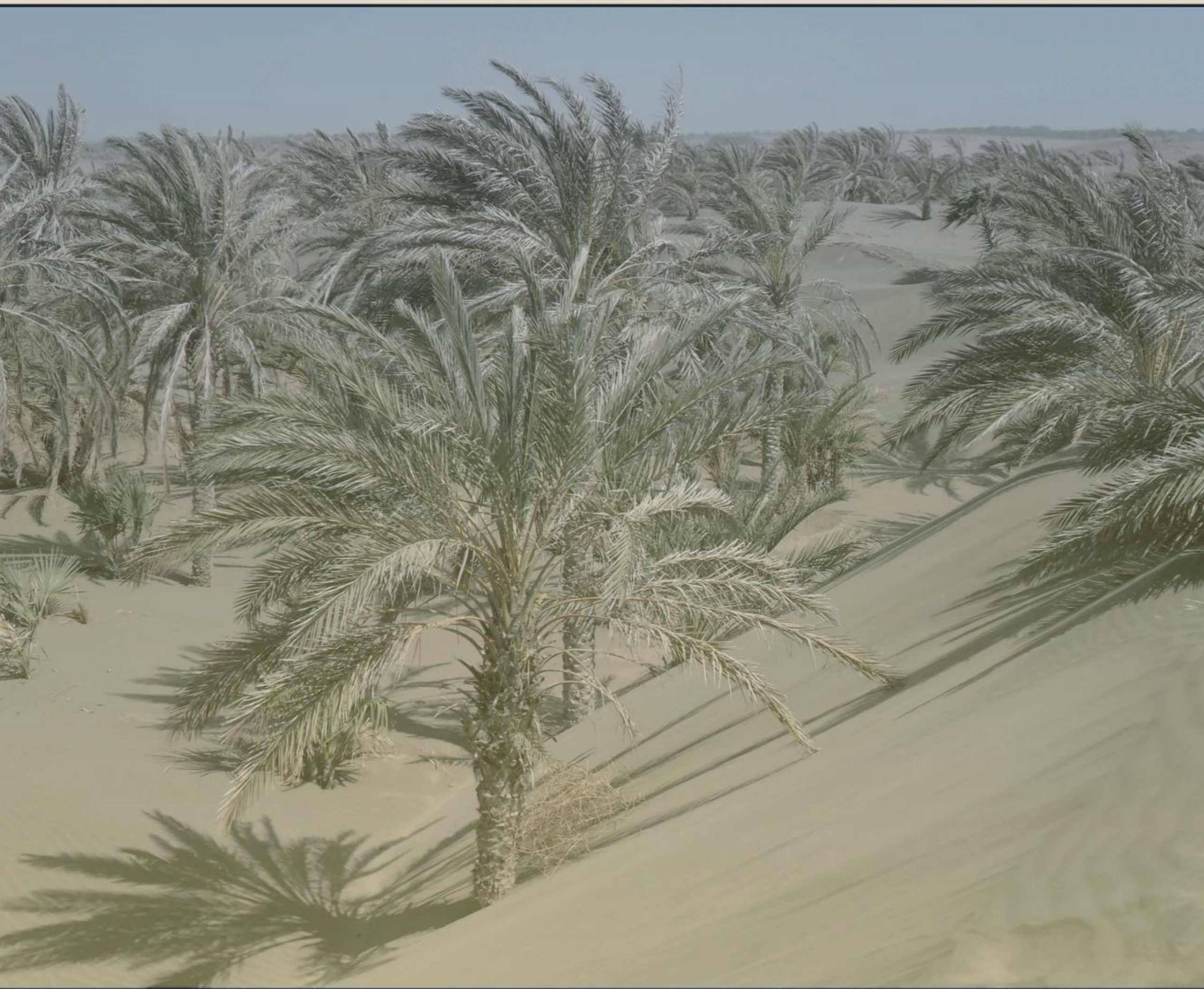
A COMBINED APPROACH TO ASSESS GROUNDWATER RESOURCES DEPLETION IN DATA-SCARCE AREAS; A CASE STUDY IN WADI ZABID, YEMEN



WAHIB SAIF MOHSEN AL-QUBATEE

Propositions

1- Depleting a precious groundwater resource in years is impossible to recoup in a few decades.
(this thesis)

2- As groundwater depletion due to over-exploitation is an inconvenient truth, rainfall shortage is blamed.
(this thesis)

3- Policies to improve farmers' income cannot be successful without a long-term strategic socio-economic study.

4- Desalination of sea water is an inevitable solution for arid coastal regions.

5- Any hours worked beyond 40 hours per week do not improve scientific output significantly.

6- Optimism is key in achieving goals under difficult circumstances and delays.

Propositions belonging to the thesis, entitled:
"A combined approach to assess groundwater resources depletion in data-scarce areas; a case study in Wadi Zabid, Yemen"

Wahib Al-Qubatee
Wageningen, 14 June 2021

A combined approach to assess groundwater resources depletion in data-scarce areas; a case study in Wadi Zabid, Yemen

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A combined approach to assess groundwater resources depletion in data-scarce areas; a case study in Wadi Zabid, Yemen

Wahib Saif Mohsen Al-Qubatee

Thesis

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Abstract

Steady groundwater depletion resulting from overexploitation of groundwater is a problem in many arid and semi-arid regions. Hydro-economic models are often used to study groundwater depletion, to evaluate water reallocation strategies and to develop scenarios for a more sustainable future. However, in data-scarce areas, there are insufficient time-series and spatial data available for such complex hydro-economic models. This PhD study develops and tests the usefulness and suitability of an alternative less complex and less data-intensive combined approach (incl. participatory rural appraisal, integrated data analysis, crop budget model and water balance model) to assess the different aspects of groundwater depletion that are tested in the study area in Wadi Zabid, Yemen. Overall, it concluded that the combined approach is useful to investigate the extent, drivers, the socio-economic impact of groundwater depletion, and to develop scenarios for groundwater storage recovery at the regional level, but it is not suitable at sub-regional level.

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Chapter 1

Introduction

1.1 General background

Groundwater makes up 97% of the world's available freshwater, excluding ice caps and glaciers. The remaining 3% is found in surface water (lakes, rivers and wetlands) and soil moisture (European Commission, 2008). Groundwater is a vital source of water for drinking, agriculture and industry, in addition to being crucial for the ecosystem and environment (Baba et al., 2006; Hadi et al., 2019; De Graaf et al., 2019; Darwesh et al., 2020). During the twentieth century, groundwater abstraction increased dramatically around the world. In the last fifty years, groundwater abstraction at least tripled, with growth expected to continue at a rate of 1.5% per year (Van der Gun, 2012). According to Todd and Mays (2005), groundwater exploitation begins with the drilling of a limited number of wells, after which well numbers and abstraction rates increase over time. Without rational water resources management based on repeated quantitative and qualitative assessments and control over well drilling and water withdrawal rates, groundwater withdrawals may exceed natural recharge capacity, eventually resulting in depletion of groundwater reserves. In the often densely populated coastal regions, another danger of excessive groundwater abstraction is the risk of seawater intrusion. As yet, there is no economically feasible solution to deterioration of groundwater due to high salt concentrations.

World economic growth and infrastructure expansion, accompanied by population growth, have exacerbated threats on the world's already stressed water resources and supply (Darwesh et al., 2020). Arid and semi-arid regions are particularly reliant on groundwater as a major and reliable source for all uses – domestic, agricultural and industrial. This is due to rainfall scarcity and the frequent absence of permanent surface waters, such as rivers. Agriculture accounts for some 90% of groundwater consumption (Döll, 2009; Siebert et al., 2010; Döll et al., 2012). Farming is thus an especially significant driver of groundwater depletion, compared to domestic and industrial usages.

In many countries, groundwater regulation and management is insufficient. Policies with a bearing on groundwater, such as incentives for and constraints to groundwater exploitation, imposing water allocation limits, licensing for and drilling of wells, issuance of water rights and abstraction controls, and monitoring of polluting activities, have many times proven inadequate in the face of worsening groundwater depletion (Nanni et al., 2006). Moreover, inadequate institutional and political arrangements have played a role in depletion (Nanni et al., 2006; Leal Filho and Sümer, 2015; Foster and Custodio, 2019). For safe and sustainable exploitation of groundwater resources, it is essential to establish and implement management regimes which ensure that human-induced outflows (e.g., withdrawals) do not exceed inflow rates (recharge) (Alley et al., 1999). In many cases, anthropogenic outflows must be reduced in order to restore a healthy, sustainable ecosystem and environment; in other words, to maintain a minimum ecological flow (e.g., De Graaf et al., 2019).

Rational groundwater management seeks to meet socio-economic, ecological and environmental water demand at the lowest possible cost without negatively affecting resource sustainability. Striking this balance requires understanding of the water resources system as a whole (surface and groundwater), which can be acquired by applying a spectrum of approaches (technical, economic, social, ecologic, environmental and political), leading to the preparation of management plans enumerating actions to be taken by the responsible institutions (Todd and Mays, 2005). When groundwater resources are at risk of depletion due to excessive exploitation for intensive agriculture or other purposes, a dramatic change in resources management and thus in use is essential to conserve the resource and ensure that it remains available for the future (Foster and Custodio, 2019). However, instituting what is often an about-turn in management is extremely complex, especially in regions that suffer from both water scarcity and data scarcity (Gunkel and Lange, 2017).

The government of Yemen has long encouraged agricultural expansion in order to raise farmers' income as well as to meet local demand for agricultural outputs. Hellegers et al. (2008) and Ward (2009) stated a number of decisions and policies implemented by the government of Yemen to stimulate agricultural expansion, such as a fruit import ban (from 1984 to 1995), a fuel subsidy, public and private investment in well drilling, facilitating imports of equipment related to wells (e.g., rigs and pumps) and development of irrigation infrastructure such as dams and canals. As a result, agriculture land and production increased in the country. Yet, this came at the expense of groundwater resources.

In the study area of Wadi Zabid in the Tihama coastal plain, the government has implemented projects to improve irrigation systems since the 1970s, with the aim of increasing food production. Wadi Zabid is not an exceptional case. In this regard, though it is one of the country's over-exploited wadis, it is representative of developments throughout Tihama Plain, and to some extent in other dry regions of the world. According to Saleh (2012), Yemen's policies did succeed in improving food production, from both crops and livestock. Farmers' incomes rose as well, especially in the upstream and midstream parts of Tihama Plain, including Wadi Zabid. These upstream and midstream areas are irrigated by spate water. However, this higher the agricultural production was accompanied by changes in cropping patterns, particularly a shift away from low economic value crops with relatively low water requirements, such as cereals (sorghum, maize and millet), fodders and some cash crops (cotton, sesame and tobacco), to high economic value crops that require much more water, such as fruits (banana and mango). These changes, which have been particularly observed in the upper part of the wadis, have come at the expense of agriculture in the downstream and coastal areas (Saleh, 2012). Moreover, the catchment of Wadi Zabid, like other wadis, experiences extremely high evapotranspiration, due to the overexploitation of water resources caused by the expansion of agriculture lands (Water Watch and Hydro-Yemen, 2012).

1.2 Problem statement

Excessive exploitation of groundwater has led to a continuous decline of groundwater levels, which is a problem increasingly seen in many parts of the world, such as the Middle East, South and Central Asia, North Africa, North China, Australia and North America (Konikow and Kendy, 2005).

In order to develop scenarios and strategies for sustainable groundwater use, in-depth study is required, examining the extent of current depletion, drivers of depletion (both natural and human-induced, including the role of decision-making related to water, agriculture and water allocation), and links between groundwater depletion and socio-economic status/livelihoods. Socio-hydrological models (see, e.g., Harou et al., 2009; Blair and Buytaert, 2016; Expósito et al., 2020) and hydro-economic models (see, e.g., George et al., 2011a, 2011b; Kumar et al., 2020) are often used to conduct such studies. These do yield insight into potentially sustainable groundwater use scenarios and strategies. However, such studies, which quantify the extent, causes and impacts of groundwater depletion, are not easy to carry out, particularly in regions where there is data scarcity and uncertainty surrounding the limited data that is available. This applies especially to developing countries (Konikow and Kendy, 2005).

The study area of Wadi Zabid in Yemen is one of these regions in which data scarcity prevents researchers from applying complex socio-hydrological or hydro-economic models to assess the state of groundwater resources. A lack of metrological stations, particularly in the downstream and coastal areas of the wadi, has led to a lack of spatially diverse, long time-series meteorological data (e.g., measuring rainfall and actual evapotranspiration across space and time). In addition, there is a lack of recent data on the distribution of spate water (i.e., surface water inflows from the east) over space and time, and a lack of sufficiently detailed land cover and land use maps spanning a long time period. Reliable crop data is also lacking, including water requirements and production inputs and outputs by crop. Finally, there is an insufficiency of subsurface data, including a lack of hydrogeological information about the framework (aquifers, aquitards), and a lack of reliable, detailed (monthly, seasonal or yearly) time-series data on well yields, abstraction rates and groundwater levels.

1.3 Research gaps, objectives and research questions

Data scarcity is a reality in many arid and semi-arid regions, and remains a major obstacle to the use of sophisticated numerical modelling techniques for the study of groundwater depletion. This thesis, therefore, develops and tests the usefulness and effectiveness of an alternative less complex and less data-intensive combined approach for assessing groundwater resources, particularly the extent of groundwater depletion, the drivers of depletion and the socio-economic impact of depletion, and also develops scenarios for groundwater storage recovery. Specifically, four research questions are explored.

The first research question concerns the value of participatory approaches as a strategy to overcome data scarcity issues. Participatory approaches combine the tacit knowledge of stakeholders with the experience of investigators to overcome lack of data on, for example, the hydrogeological regime and the often complex societal ecosystems (Ritzema et al., 2011). This thesis, specifically, examines the usefulness and effectiveness of participatory rural appraisal (PRA), with its various tools, to better understand changes in well water levels over the past half century and the impacts of changes therein on livelihoods. It also explores the use of PRA for obtaining stakeholders' perceptions of the causes of and appropriate solutions to groundwater depletion, especially in an Islamic context where religious values encourage people to consult one another. Thus, the first research question is as follows:

Q1 What is the usefulness of participatory rural appraisal (PRA) for gaining a better understanding of the effects of groundwater depletion on livelihoods and obtaining stakeholders' points of view on the causes of and potential solutions to groundwater depletion?

Sustainable groundwater management requires an understanding of the impact of both natural and climatic conditions and human interventions, such as previous policy decisions (Thomas and Famiglietti, 2015). Therefore, this thesis presents and tests an integrated approach for identifying the primary drivers of groundwater depletion in a data-scarce region. The approach developed encompasses both natural and human-induced drivers of groundwater depletion, with a particular focus on the role of political decisions with a bearing on water management and agriculture, as these are understood as particularly influential on human activities which affect the use of water resources. The presented approach utilizes the limited data that was available locally, for example, on changes in rainfall amounts and surface runoff inflows to the region, alongside well drilling and groundwater abstraction rates. These are combined with data collected and generated within this study, for example, on changes in land cover over time derived from remotely sensed images and a field survey of well water levels. The second research question is therefore:

Q2 What is the added value of an integrated data analysis approach to reveal the natural and human-induced drivers of groundwater depletion?

The implications of a continuing decline in groundwater levels are not limited to the sustainability of this valuable resource for future generations and the maintenance of its quality and availability for drinking and food production. A drop in groundwater levels has enormous economic implications for today's users as well. Among these are the additional energy required to pump groundwater from greater depths, the cost of deepening wells and the price of pumps and generators with greater capacity, as well as the costs of their periodic maintenance. Increased depth of groundwater brings an increased unit cost of pumping, which reduces economic returns to land and water for the various agricultural outputs. Water allocation decisions are particularly important in such contexts (Hellegers and Leflaive, 2015).

To gain an understanding of how groundwater depletion-related changes may effect on-farm water allocation decisions, this thesis presents and tests a simple model based on crop budget, to calculate the economic returns to land and water of particular crops and the sensitivity of such returns to a potential decline in groundwater level. This simple model is tested in the midstream, downstream and coastal areas of Wadi Zabid, as these areas differed in groundwater depths and spate water availability. Thus, the third research question reads:

> *Q3 Is a simple crop budget model sufficient for assessing the impact of an increased cost of groundwater pumping on returns to land and water for particular crops and to indicate recommended alternative water allocations?*

A problem faced in many data-scarce regions is obtaining enough reliable information on the hydrogeological framework, including the 3-D (three dimensional) distribution of aquitards and aquifers (which are rarely homogenous) and rock types and thicknesses, depths, porosities, hydraulic conductivities, transmissivities and hydraulic resistances. To make use of sophisticated groundwater models (e.g., MODFLOW) which feed hydro-economic or socio-economic models, researchers require long and continuous records on rainfall, surface water flows, groundwater levels, groundwater abstraction rates, changes in land cover and water consumption (actual evapotranspiration). This points to the importance of developing approaches that are simpler in nature and less data-intensive. Ideally, these approaches would enable quantification of groundwater depletion rates and exploration of future scenarios that could lead to more sustainable water resource use (storage recovery) – or at least indicate how ongoing depletion could be minimized. Such approaches are appropriate as long as the research question can be answered adequately (Anderson et al., 2015).

This thesis presents and tests the effectiveness and suitability of a simple water budget model to quantify depletion and recovery rates of groundwater levels in the study area of Wadi Zabid and to develop scenarios for current and future sustainable use. Therefore, the fourth research question is:

Q4 What is the usefulness of a simple water budget model to quantify groundwater depletion/recovery rates and to explore scenarios for sustainable future use?

1.4 Methodology

This research presents and tests the effectiveness and usefulness of an alternative, less data-intensive and less complex combined approach in assessing various aspects of groundwater depletion in a data-scarce arid and semi-arid region (Table 1.1). The overall objective was to overcome the intensive data requirements imposed by sophisticated modelling techniques, which call for detailed and long time-series data. This section describes the approach used, in relation to the research questions posed above.

In conjunction with research question 1, the usefulness of PRA was explored. Specifically, PRA tools were applied to learn about changes in groundwater status, such as well types and depths, water levels and water quality, and how these have impacted local livelihoods. As noted, PRA enables researchers to benefit from the tacit knowledge of stakeholders, supplemented by the expertise of multidisciplinary investigators. PRA brings to the fore stakeholders' diverse viewpoints on the causes of problems and on potential solutions (priorities/scenarios). The current research utilized a combination of PRA tools (see, e.g., Mascarenhas et al., 1991; Cavestro, 2003; Bhandari, 2003; Van der Schans and Lemperiere, 2006), including semi-structured interviews (individual and group discussions), resources sketch mapping, daily calendars, timelines, transect walks and direct observation, and problem and solution trees. Each tool gives information on a particular aspect of the question at hand. However, according to Patton (1999), taken together, different tools can complement and confirm one another, serving both to minimize bias and to indicate points of consensus and contradiction. This results in greater accuracy, reliability and validity of findings.

This research used method, data source and investigator triangulation. Method triangulation is the application of at least three tools to confirm the reliability and validity of findings. Data source triangulation is the inclusion of respondents representing different stakeholder groups (i.e., farmers, key informants and migrants) within a study region. Investigator triangulation is the inclusion of investigators from different local institutions, with different related areas of expertise.

Moreover, secondary sources were used where possible to confirm information provided, such as on groundwater levels and groundwater quality. However, applying this approach, gaps in knowledge did emerge, which provided starting points for further investigation. For instance, stakeholders' points of view on the causes of and solutions to groundwater depletion, was examined more rigorously elsewhere in the research, using an integrated approach, including the natural (technical) and human (social) aspects.

Thus, to reveal the natural and human-induced drivers of groundwater depletion (research question 2), an integrated data analysis approach was developed and tested in study area of Wadi Zabid. In particular, the rainfall-runoff relation (see, e.g., Critchley et al., 1991; Van der Gun and Ahmed, 1995; Blume et al., 2007) over the 1970-2009 period was studied to reveal the natural and human-induced drivers of groundwater depletion. Changes in human activities (indicated by land cover change) were mapped using remotely sensed (satellite) images over about the same period. This data analysis was accompanied by an analysis of well inventory data (changes in the number of drilled wells, groundwater levels and abstraction rates over time). The role of policy measures related to water and agriculture was also taken into account, particularly, policies to stimulate or discourage human activities, such as agriculture. This was presented in the form of a historical timeline to clarify the links involved.

The third research question concerns the suitability of a simple model, developed based on crop budgets at the farm gate (see, e.g., Davidson et al., 2009), to evaluate the socio-economic impact of groundwater depletion and potential water reallocations. Specifically, crops' economic returns to land and water were calculated alongside the sensitivity of these returns to worsening groundwater depletion (represented by an increased cost of pumping one unit of groundwater). The model was tested for the midstream, downstream and coastal areas of Wadi Zabid, as these regions differed in groundwater pumping depths and spate water availability. In addition to a literature review, data was collected in mid-2016 using questionnaire-guided interviews and discussions with farmers. Furthermore, a field survey was carried out to investigate the well data.

Table 1.1 Research questions and methods used or developed and tested in this research, alongside the pertinent chapters in this thesis

Ch.	Research questions	Less complex combined approach
2	Q1 What is the usefulness of participatory rural appraisal (PRA) for gaining a better understanding of the effects of groundwater depletion on livelihoods and obtaining stakeholders' points of view on the causes of and potential solutions to groundwater depletion?	A combination of PRA techniques was used: - Semi-structured interviews (individuals and group discussions) - Resources sketch mapping - Daily calendars - Timelines - Transect walks and direct observations - Problem and solution trees
3	Q2 What is the added value of an integrated data analysis approach to reveal the natural and human-induced drivers of groundwater depletion?	An integrated data analysis approach: - Rainfall-runoff analysis - Remotely sensed (satellite) image - Well inventories - Historical timeline (policy measures and human activities)
4	Q3 Is a simple crop budget model sufficient for assessing the impact of an increased cost of groundwater pumping on returns to land and water for particular crops and to recommend water allocations between these crops?	A simple crop budget model was developed.
5	Q4 What is the usefulness of a simple water budget model to quantify groundwater depletion/recovery rates and to explore scenarios for sustainable future use?	A simple water budget model was developed.

Research question 4 responds to another knowledge gap identified in the economic and participatory data analysis; that is, the expected pace of groundwater depletion under ongoing water use and potential scenarios for the future. In view of the data scarcity encountered in the study region, a simple water budget model was developed (see, e.g., Todd and Mays, 2005) and tested. The purpose was to ascertain the model's usefulness for quantifying groundwater depletion/recovery rates and developing and exploring scenarios for sustainable future use. The method was found to have potential as an alternative to more sophisticated numerical groundwater models requiring a comprehensive set of time-series data and detailed descriptions of the hydrogeological framework, including hydraulic properties. The water budget model was fed with historical data regarding rainfall, surface water flows and wells collected from government records (TDA, 2010; NWRA, 2008) and the literature (e.g., DHV, 1988). Field measurements were also carried out, including measurements of well water levels, total depths and pumping depths for about 247 wells.

1.5 Description of the study area

The study area, comprising the midstream, downstream and coastal area of Wadi Zabid, is located between 1,552,000-1,577,457 UTM-N and 293,124- 341096 UTM-E (Figure 1.1). It is part of the Tihama coastal plain in western Yemen. The total catchment spans an estimated 4,450 km^2 (Van der Gun and Ahmed, 1995; Qaid, 2007), which includes the study area (920 km^2) and the remaining upstream area. The study area in Wadi Zabid was chosen because it is experiencing serious groundwater resource depletion. This had led, among other things, to a substantial drop in groundwater levels and serious salinity issues in the coastal region, affecting the livelihoods of all those living in the lower regions of the wadi.

The study area has an arid climate with a dry season (mid-October to end March) and a wet season (April to mid-October). Annual rainfall is characterized by high spatial variability, ranging from 100 mm/yr in the west near the coast to 350 mm/yr in the midstream area and 550 mm/yr in the eastern upstream area. Annual surface water inflows to the study region (over the eastern boundary) exhibited high temporal variability, being on average 46 Mm^3 in the dry season and 213 Mm^3 in the wet season, according to inflow observations at the Kolah streamflow gauging station (1990-2009) (TDA, 2010). The air temperature varies throughout the year between 18° and 40°C. The annual average air temperature is 29.6°C (NWRA, 2009), and the average potential evaporation reaches about 3,000 mm/yr (TDA, 2010).

The study area is located on one of the productive aquifer systems in Yemen. According to Van der Gun and Ahmed (1995), the aquifer is characterized by Quaternary deposits, which are permeable and contain fresh groundwater. Beneath the aquifer, Tertiary sediments are found, which are poorly permeable and contain saline groundwater. The eastern part of the study area represents the recharge zone, while the western part (coastal area) of the study area represents discharge zones, in the form of subsurface outflows to the Red Sea as well as evaporation (see Figure 1.1).

Administratively, the study area part of Wadi Zabid includes three directorates: Zabid, Al-Tuhita and Al-Jarrahi. The population in 2004 was about 312,408, and was estimated to have risen to about 472,500 in 2018, based on a growth rate of 3% per year (Central Statistical Organization, 2005). Residents of the study area depend mainly on crop agriculture and ranching, in addition to fishing, for their income.

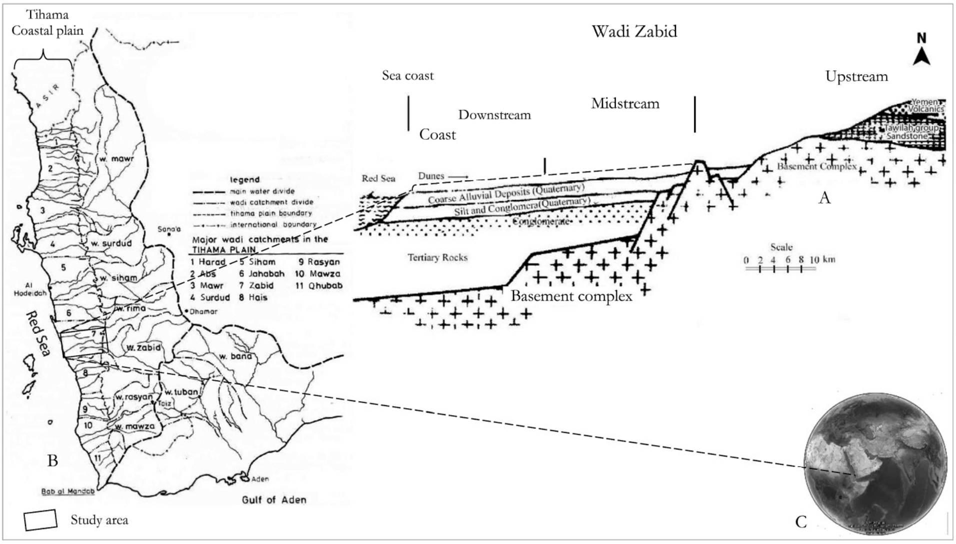

Figure 1.1 Location and cross section through the study area of Wadi Zabid, Tihama Coastal Plain, Yemen. For the purpose of this research, the study area is divided into a midstream, downstream and coastal area (Map source: A- (DHV, 1988), B- (DHV, 1988 after TESCO, 1971) and C- Google Earth: https://earth.google.com/web).

1.6 Thesis structure

This thesis comprises six chapters. The current, introductory chapter presents the general background, problem statement, research objectives and questions, alongside the methods used in this thesis. Chapters 2 to 5 are the core of the thesis, in the form of four journal articles, submitted or published, presenting the analyses pertaining to the four research questions posed earlier.

Chapter 2 presents the implementation of PRA to assess groundwater resources in the Al-Mujaylis area and at other locations in Wadi Zabid and the adjacent Wadi Rima of Tihama coastal plain. The aim here was to understand communities' needs and perceptions regarding groundwater depletion and its impact on local livelihoods. A participatory, bottom-up approach was applied to bring to the fore the tacit knowledge of the community alongside the scientific knowledge of the researchers (investigators), to overcome lack of data and produce reliable insights about how groundwater depletion has impacted local lives and livelihoods. PRA in this case resulted in a better understanding of stakeholders' views on the causes of groundwater depletion and appropriate solutions.

Chapter 3 takes up a knowledge gap identified in Chapter 2, regarding the drivers of groundwater depletion in the study region. It develops and tests an integrated approach to assess the natural and human-induced drivers of groundwater depletion in the data-scarce region of Wadi Zabid. Human-induced factors were identified by linking changes in human activities with governmental policy measures related to water and agriculture. In the wadi, human activities, stimulated by policy measures, were found to be the main driver of groundwater depletion. Yet, the findings from the analysis raise issues regarding the economic value of scarce water resources; particularly, to what higher-value uses with lower water requirements could scarce water be reallocated? This is the subject of Chapter 4.

Chapter 4 zooms in on the economic value of irrigation water in Wadi Zabid. It describes the suitability of a simple model based on crop budgets to calculate the economic returns of a crop to land and water and the sensitivity of these returns to changes in the cost of pumping (due to groundwater depletion) and the availability of spate water (a function of farm location and spate water distribution rights). Returns to land and water were indeed highly sensitive to changes in groundwater depths over time and the free availability of spate water for irrigation. This raises questions on how agriculture can be sustainably practiced in this very dry region, which were explored in Chapter 5.

Chapter 5 studies the effectiveness and usefulness of a simple water budget model to quantify current groundwater depletion rates and to predict future depletion in study area of Wadi Zabid where there is not enough data for sophisticated numerical groundwater models. In the study region, groundwater withdrawals have far exceeded replenishment rates for 50 years. The modelling results underline the unsustainability of the present groundwater use, mainly due to agricultural expansion. The model also proved useful in developing and exploring strategies and scenarios for mitigating or potentially reversing groundwater depletion.

Finally, Chapter 6 summarizes and discusses the main findings of the research and presents implications for future studies and for policy.

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CHAPTER 2

Participatory rural appraisal to assess groundwater resources in Al-Mujaylis, Tihama Coastal Plain, Yemen

Abstract

A participatory rural appraisal (PRA) conducted in the Al-Mujaylis area, Tihama Coastal Plain, Yemen provided a contribution, as a bottom-up approach, to the assessment of the needs of communities and their views on how to avoid groundwater degradation. It was found that PRA tools could be applied usefully in an area with data scarcity and a culturally different context. It is concluded that adopting a research approach between top down and bottom up is most valuable and effective.

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2.1 Introduction

Tihama plain, located along Yemen's Red Sea coast and also known as Yemen's breadbasket, represents a fertile agricultural area of great importance for the food security of Yemen. In the 1970s, a large proportion of Yemen's population (nearly 90%) relied on agriculture and animal husbandry as a source of income. The dominant crop cultivated along the coast was date palm, and more inland date palm, cotton, cereal (sorghum, millet, maize and sesame), fodder, citrus, vegetable crops (onion, tomato and okra), mango and banana were cultivated (Irrigation Improvement Project, 2002). Because of the low prices of imported products compared with domestically produced products, the economic profitability was low (Cohen & Lewis, 1979). As a result, emigration to Saudi Arabia attracted a large segment of the labour force and led to a decline in agricultural production compared with the population growth. By 2010, the percentage of the population who relied economically on agriculture as a source of income was reduced to 54% (Ministry of Agriculture and Irrigation, 2012). Agriculture in the midstream areas mainly depends on the conjunctive use of spate and groundwater for irrigation, while in the downstream areas it depends only on groundwater in addition to scarce rainfall (Al-Qubatee, Ibrahim, From Dalseng, Al-Weshali, & van Steenbergen, 2013).

To improve agricultural production, the Food and Agricultural Organization (FAO) of the United Nations recommended improving irrigation systems in the Tihama region (Tipton & Kalmbach, 1974). The government initiated irrigation improvement projects through the construction of reservoirs and water-harvesting structures. It also supported the agricultural sector by banning fruit imports to enhance the profitability of locally produced fruits, subsidizing diesel fuel, and easing the import of drilling and pumping equipment (Ward, 2009). A study in the area of Wadi Zabid (wadi in Arabic means a valley) concluded that the best way forward was to build 10 diversion weirs (five were actually built) along the wadi to divert spate water into the existing canals and to build structures in the irrigation system to facilitate the control and distribution of water (Tipton & Kalmbach, 1974). This type of spate irrigation requires the strong control and participation of the users in the water distribution, thus a participatory approach is required. Other Middle Eastern governments also tried to overcome high water demand by building similar diversion structures in combination with desalination plants and deepening groundwater wells, but these water supply solutions are costly and often do not reduce the increasing water demands (Zeitoun, Allan, Al Aulaqi, Jabarin, & Laamrani, 2012).

As a result of these investment programmes, agricultural production has increased considerably, e.g., the banana cultivation areas in the midstream of Wadi Zabid increased from 20 ha in 1980 to 3500 ha in 2000 (Van Steenbergen et al., 2010). This, however, happened at the expense of the sustainable use of groundwater resources as the number of drilling wells in Wadi Zabid and Wadi Rima increased by more than five times between 1987 and 2008, from about 2421 to 12,339 wells (National Water Resources Authority (NWRA), 2008). The groundwater degradation is a result of the change in the balance between abstraction and recharge. Negative impacts of the construction of upstream dams on the downstream areas include reduced surface flow/runoff, dried-up wells and water being lost from the dams' reservoirs through evaporation (Al-Qubatee, 2009). In addition, in some areas where people invested in small dam construction, they consider it to be their own property, which resulted in giving themselves priority water rights and restricting others from becoming shareholders (Vermillion & Al-Shaybani, 2004). Groundwater degradation is also a result of the combined effects of (1) the intensification of agriculture activities (El Ayni, Cherif, Jrad, & Trabelsi-Ayadi, 2012); (2) the decrease of the recharge because of the decrease in precipitation and the reduction in river flows caused by the construction of dams in the upstream parts of the catchment (El Ayni, Manoli, et al., 2012); and (3) economic incentives such as the diesel subsidies, which encourage groundwater abstraction instead of groundwater conservation (Burke, Moench, & Sauveplane, 1999; Hellegers, Perry, & Al-Aulaqi, 2011). The declining access to groundwater affects not only food production but also the socio-economic situation of the population, e.g., an degeneration of the health conditions caused by reduced access to drinking water and a reduction in the cultivation and use of medicinal plants (Sharma, 2009). Along the Red Sea coast, the drop in groundwater levels has also resulted in seawater intrusion (NWRA, 2009).

Participatory rural appraisal (PRA) is a term used to describe a growing range of approaches and methods that can be used to encourage stakeholders to participate in analysing and assessing measurements in land planning and to bring their own knowledge to the dialogue (Chambers, 1994). This approach was developed in the early 1990s to initiate a paradigm shift from the top-down to a bottom-up approach, and from blueprint planning to an interactive learning process. It is a shift from extractive survey questionnaires to experience sharing with local people (Cavestro, 2003; Sijbesma & Postma, 2008). In the participatory approach it is important to combine the implicit knowledge of the community with the distinct scientific knowledge of the researchers and decision-makers in order to overcome lack of data on the hydrogeological and the often complex societal ecosystems (Ritzema, Quang Anh, & Thi Kim, 2011), to increase understanding of the complexity of problems, to reach solutions that are acceptable for stakeholders and that can be implemented (Burke et al., 1999; Zanetell & Knuth, 2002), and to achieve effective water governance (Barreira, 2003). Moreover, participatory methods have been used successfully to provide sufficient data for participatory groundwater modelling in areas with lack of continuous data recording, and at the same time lead to an agreement between the stakeholders on the water resources management plan (action plan) to sustain both the livelihood and the ecosystem (Ritzema, Froebrich, Raju, Sreenivas, & Kselik, 2010).

The government started to apply an integrated water resources management (IWRM) approach to managing basins that were facing a critical depletion of their groundwater resources. Taher, Ward, Fadl, Saleh, and Sultan (2013) assessed the first phase of such a project in the Sana'a Basin. They concluded that by implementing IWRM in alleviating water degradation, its advantages were being flexible, adaptable, and responsive to local conditions and needs. However, they suggested that for follow-up phases, more emphasis should be placed on the development of a decentralized participatory approach and to improve water legislation. In Tihama plain, numerous groundwater resources studies have been conducted (e.g., Tesco-Viziterv- Vituki, 1971b; Al-Eryani, 1979; DHV, 1988; Al-Kebsi, 2000; Abu-Lohom, 2002; Nasher, Al-Sayyaghi, & Al-Matary, 2013). These, however, focused mainly on technical aspects such as hydrology, hydrogeology, hydrogeochemistry, geophysics, geochemistry and modelling and lack an IWRM approach. Numerous authors have indicated that complex water-management problems require a fully integrated research approach (social, economic, institutional, political and technical) with a focus on engaging the different and sometimes contradictory interests of all stakeholders (Burke et al., 1999; Hussein, 2016; Margerum, 2007; Pahl-Wostl, 2007; Raadgever, Mostert, & Van de Giesen, 2012; Von Korff, Daniell, Moellenkamp, Bots, & Bijlsma, 2012). Participatory approaches are gaining importance to make information available to researchers, environmental managers and decision-makers (Zvoleff & An, 2014), not only to discuss interventions but also through collective simulation and modelling (Bots, Bijlsma, Von Korff, Van der Fluit, & Wolters, 2011; Dionnet et al., 2013). Although participatory research in the field of natural resources and environmental management is increasing, some aspects are not receiving adequate attention (Trimble & Lázaro, 2014). Especially, the extent to which stakeholders are interested in, and capable of, being involved effectively in governance varies widely, and is often not addressed satisfactorily (Smiley, De Loë, & Kreutzwiser, 2010). In this study, we argue that adopting a research approach between top down and bottom up is more valuable and effective, especially in the areas of high illiteracy. The objective of this paper is to evaluate the use of such a mixed approach to PRA in areas with data scarcity and in a cultural context where Islamic religious values encourage people to apply Shura (Islamic term for consultation) among themselves, with the experts and specialists, and to be more cooperative and altruistic. The usefulness of PRA as a bottom-up approach in assessing the degradation of groundwater resources in the Al-Mujaylis area is evaluated with the aim to obtain a better understanding of the effects on the livelihoods of the local population and of the local stakeholder's views on the problems and their views on appropriate solutions.

2.2 Study area

Yemen has an ancient civilization and historical heritage known as 'Arabia Felix' (Jungfer, 1987). The water harvesting and diverting techniques are the most famous examples (Brunner & Haefner, 1986; Harrower, 2010), i.e., the great and famous dam of Ma'rib with its antique irrigation system that has been in operation for more than two millennia (Brunner & Haefner, 1986). Nowadays, the continuous increase in the construction of harvesting and diversion structures in the upstream/midstream areas without adequate water resources management is resulting in negative externalities such as groundwater resources degradation in downstream areas. The degradation of groundwater resources has both environmental and socio-economic impacts in the affected areas. At the end of 2012, field research was conducted in the downstream (Al-Mujaylis village and surrounding areas) and midstream areas of Wadi Zabid and Wadi Rima (Figure 2.1) to study the cause–effect relationship between land-use changes and groundwater degradation and the socio-economic impacts. Wadi Zabid and Wadi Rima, with catchment areas of 4450 km^2 (Qaid, 2007) and 2900 km^2 (Land Resources Division, 1977) respectively, originate from the Yemen Highlands (Western slopes). The mean annual precipitation varies from 100 mm at the coast to 350 mm in the foothills and to more than 550 mm in the Eastern mountains, with temperatures ranging between 18 and 40°C (NWRA, 2009). The mean annual runoff (water flow) in Wadi Zabid is 136.73 million m^3 (from 1970 to 1987) and in Wadi Rima is 85.68 million m^3 (from 1976 to 1987) (DHV, as cited in NWRA, 2008). Only after exceptional heavy rainstorms does the runoff reach the sea (Tesco-Viziterv-Vituki, 1971a).

The population in the middle and downstream part of Wadi Zabid (Zabid and Al- Tuhita directorates) and Wadi Rima (Bit Al-Fakih directorate) was 464,545 in 2004 (Central Statistical Organization, 2005). The population mainly depends on agricultural activities and ranching for its income. The total cultivated area in the three directorates is about 66,223 ha (Tihama Development Authority (TDA), 2007).

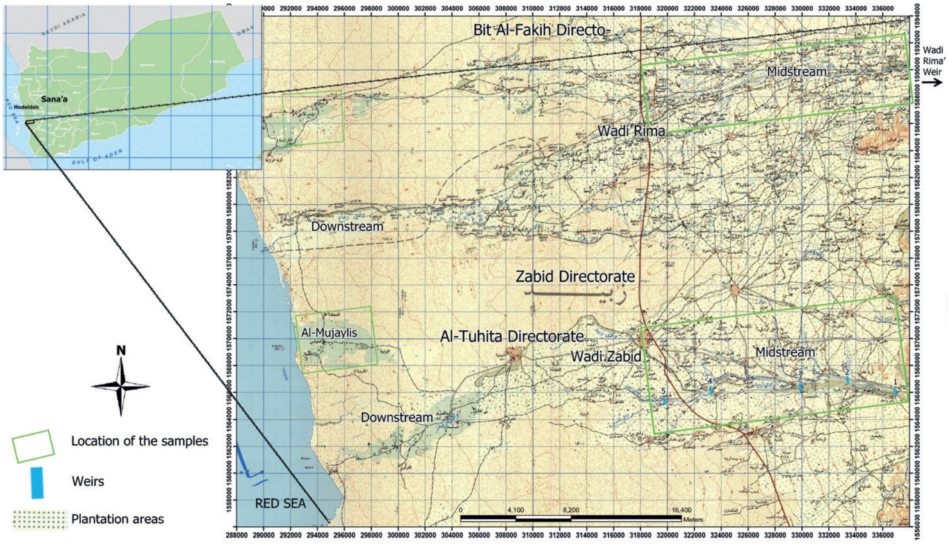

Figure 2.1 Location of the sample communities, Al-Mujaylis and Wadi Zibid and Wadi Rima, Tihama Coastal Plain, Yemen, Zabid sheet no. D38-39 1:100,000 (Survey Authority, 1986).

2.3 Materials and methods

A combination of PRA techniques was used, as described in detail by Mascarenhas et al. (1991), Cavestro (2003), Bhandari (2003) and Van der Schans and Lemperiere (2006). In order to ensure accuracy, to avoid bias, to find points of consensus/contradiction, to facilitate mutual learning, to integrate knowledge and to reach the reliability and validity desired, we used the following approach:

- A combination of six PRA tools was selected, namely semi-structured interviews (individual and group discussion), resources sketch mapping, daily calendars, time lines, transect walks and direct observations, and the preparation of problem and solution trees (Table 2.1). Each tool was used to address a specific topic (Table 2.2), and verification of the data was achieved by methods triangulation of at least three tools to cross-check the results of the different tools. In addition, the triangulation of the data sources was achieved by involving different respondents (farmers, key informants and emigrants), from different areas (downstream and midstream) and including secondary sources of information (previous studies, available data records, maps, Google Earth etc.). Moreover, the investigator triangulation was achieved by involving an interdisciplinary team from different local institutions (the observations of different investigators in the same study area). Local materials, chalk, coal, stone and trees sticks were used to achieve the PRA activities in addition to flip charts, marker pens, maps, global position system (GPS) and cameras.

- The sampling method was 'stratified random sampling' in combination with 'purposive sampling'. Stakeholders from the areas downstream and midstream of Wadi Zabid and Wadi Rima were included. The sampling included different local communities and decision-makers such as farmers and most key informants (parliamentary representatives, managers, engineers, head of the Water User Association (WUA), head of the Irrigation Council, sheikhs, imams and teachers). The group discussions with the different stakeholder groups (farmers and key informants) included groups from the areas downstream and midstream of Wadi Zabid and Wadi Rima (Table 2.1).
- Cross-checking was performed between the results of different PRA tools to study the points of consensus and/or contradiction.
- The results obtained with the PRA tools were compared with available secondary sources of information.
- The study was conducted by an interdisciplinary team of four members from the Water and Environment Center (WEC), the Geological Survey and Mineral Resources Board (GSMBR), the National Water Resources Authority (NWRA) and the Tihama Development Authority (TDA) respectively. One team member was a female researcher who interviewed the women and conducted discussion groups with them. This facilitated the communication process according to local customs and culture (a conservative community with a high percentage of illiteracy).

Table 2.1 Participatory rural appraisal (PRA) tools and number of times tools were applied in the study.

Area	Semi-structure interview		Other PRA tools
	Individual interviews	Group discussions	
Al-Mujaylis	25 (four with key informant and 10 with people who migrated from the area)	Four (one group with women)	- One resources map - One daily calendar - One time line - Two transect walks and direct observations - Two problem and solution trees with ranking
Wadi Zabid	22 (six with key informants)	Three (one with women)	- One daily calendar - One time line - Two problem and solution trees with ranking
Wadi Rima	22 (five with key informants)	one group	One resources map One time line One transect walk and direct observation Three problem and solution trees with ranking

Sources: Al-Qubatee et al. (2013, 2015).

For data analysis, respondents defined and ranked the problems and solutions by themselves in the field. We used memos, flip charts (scanned with a digital camera) and/or audio and video to record all PRA tools applied in the field. Data coding was done manually for the semi-structured interviews and the results of discussion groups according to the objectives of the study (semi-structure questionnaires) and for any other emerging themes. Validity and reliability were achieved through the abovementioned steps.

The interrelationship between the PRA components, inputs for problem analysis, determination of priorities for development and community empowerment, and the outputs are depicted in Figure 2.2. It shows how the implicit knowledge of the community, the interdisciplinary researchers’ experience and the available secondary sources of the information were integrated (1) to identify the problems; (2) to identify appropriate solutions; (3) to find priorities/scenarios for development; and (4) to identify other needs of the community.

Table 2.2 Participatory rural appraisal (PRA) tools applied in the study area.

PRA tools		Description of the tools	NTTA[a]
- Semi structured interview	**- Individual** **- Group discussion** **- Key informant** **- Emigrant**	To know the situation in the area, the problems and the suggested solutions. Open questions were used that allowed the interviewer and respondents to raise new issues and topics during the discussion (Butler, Monroe, & McCaffrey, 2015). Stakeholders were interviewed individually to avoid the influence of or on others, especially in areas where there is mistrust as a result of unsolved conflicts over water resources. Group discussion was used to reach consensus and variety. Key informant opinion is important from the technical, institutional, legislation and political prospective. Some who migrated were interviewed as they are victims of the environmental degradation in the area	44 8 15 10
Resource sketch map		To know the socio-economic status and activities of people. We explained to respondents the purpose of this tool. From ideally the highest location in the area, respondents used local materials (chalk and coal) to draw the sketch map. The resources sketch map included land use, land-use change, and the features and infrastructures in the area	2
Daily calendar		To know farm and household activities in the area, the economic situation and working hours in the fields. Farmers were asked for their opinions on working hours, their main income sources, a household's activities and constraints	2
Time line		To know the situation in the area over the last 50 years. Respondents were asked (especially elderly people) to define major historical events that occurred in the past. Then they can make links between certain water and environmental issues and those events (easy to remember). This tool indicated the changes over time in the land use and agriculture productivity, groundwater situation, desertification, sand dune movement, and migration in the study area. Flip charts were used for this activity	3
Transect walk and direct observation		To know the current situation and to validate the information that was extracted by the other PRA tools. Simple measurements were carried out	3
Problem and solution tree		To know the causes and suggested solutions of the problems in the area from the part stakeholders' point of view. Groups of people sat together to define the water resources problems in their areas using a tree diagram. It was used as a problem analysis technique. Respondents were asked to rank the causes and suggested solutions of the problems according to their point of view and their preferences. A flip chart matrix was used	7

Notes: [a]NTTA, number of times tools are applied.
Al-Mujaylis: 25 semi-structured interviews, four group discussions, two transect walks, one resources sketch map, one time line, one daily calendar, and two problem and solution trees with ranking in addition to direct observation.
Wadi Zabid: 22 semi-structured interviews, three group discussions, one time line, one daily calendar, and two problem and solution trees with ranking in addition to direct observation.
Wadi Rima: 22 semi-structured interviews, one group discussion, one transect walk, one resources sketch map, one time line, and three problem and solution trees with ranking in addition to direct observation.
Sources: Adapted from Al-Qubatee et al. (2013, 2015).

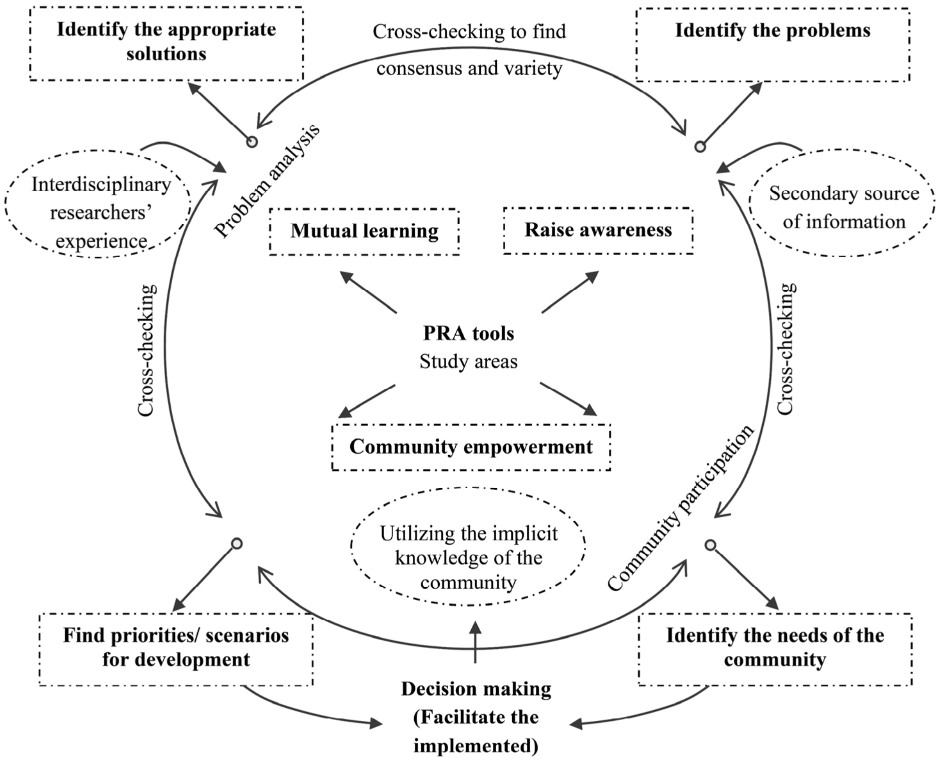

Figure 2.2 Interaction cycle among the different participatory rural appraisal (PRA) components (inputs) used for problem analysis, determination of priorities for development and community empowerment (outcomes).

2.4 Results

2.4.1 Groundwater status

From the semi-structured interviews in Al-Mujaylis (Table 2.1), it was found that in this area groundwater is the major source for drinking, domestic, agriculture and livestock water use. People rely heavily on agriculture for their income in addition to fishing and remittances from their migrant relatives. The dominant agricultural crop is palm tree with some fodder for livestock. From semi-structured interviews, especially from the elderly men and women, we learned that the groundwater level in Al-Mujaylis was at a depth of less than 0.5 m below the soil surface 50–60 years ago. In 2013, the groundwater level had dropped to more than 12 m below the soil surface. From the interviews we also learned that there have been changes in well type and depth, drilling and water pumping techniques.

Respondents expressed their assessment of water quality based on the taste of the water and, in some cases, how it compared with the taste of bottled mineral water. They indicated that the water quality in most wells in Al-Mujaylis is still fresh while other areas have higher water salinity that results in dying of the date palms in Al-Fazah village downstream of Wadi Zabid. This was confirmed by information from secondary sources: electric conductivity (the indicator of total dissolved solids) in most wells in Al-Mujaylis is between 0.7 and 1.6 dS/m, whereas water salinity in Wadi Zabid is between 0.8 and 17.8 dS/m and in Wadi Rima is between 0.6 and 10.9 dS/m (NWRA, 2009).

With one-group discussions (more than 10 respondents) in Al-Mujaylis, time-line tools were used to characterize the changes in groundwater status, agriculture activities and production, desertification and emigration changes since 1962 (Table 2.3). During the interviews, respondents were asked to connect the previous status with distinct past events, and during the discussion attempts were made to connect changes in the status of groundwater, agricultural activities and production, desertification and emigration changes with distinct events. For example, there was agreement between participants that after 1985 the groundwater level started to fall, the total agriculture area started to decline, the desertification areas started to increase and people's emigration from the area increased. The participants also agreed that after 2000, rainfall became more scarce and this was associated with the continuous drop in groundwater levels, the reduction of agricultural areas, a decrease in yields and an increase in desertification, a result being that about 60% of the population in Al-Mujaylis village move away from the area (Table 2.3). In an interview, the head of the TDA indicated that the dams built in the mountain areas of Wadi Zabid decreased the water flow to downstream areas. That was confirmed in other interviews with the head of the Environmental Department of the TDA, Zabid Branch, and the head of the Irrigation Council in Wadi Zabid. The current situation in the area was assessed by transect walks (involving researchers and farmers) and direct observations.

The cross-checking between the outcomes of the PRA activities and the data collected from external sources of information confirmed the results related to the changes in groundwater levels, wells types and depths. Triangulation was used not only to validate findings but also for deepening and expanding researchers' understanding (Yeasmin & Rahman, 2012). However, there is a critique of using this method (Blaikie, 1991). Each method has positive and negatives aspects, but we found that this method helped to get more accuracy and validity.

Table 2.3 Time line in the Al-Mujaylis area.

Year	Spat water	Groundwater status			Agriculture activities			Desertification	Emigration
		Total Depth	Water level	Water quality	Area	Crop type	Yield (%)		
1962	Floods come from heavy rainfall in the area	0.5 m no drilling till 1975	Near the surface (<0.5 m)	Fresh	All agriculture lands	Palm	100%	None	None
1979	Same as above	As above	0.5 m	Fresh	All agriculture lands	Palm	100%	None	Few (10 people)
1985	Same as above	6- 8 m	5 m	Fresh	Start of agriculture lands shrinking	Palm	100%	Start to cover palms	
1990	Same as above	12 m	7- 8 m	Fresh	As above	Palm	25%	As above	30%
2000	Rainfall shortage	16- 17 m	5- 9 m	Fresh	Continuous decrease in agriculture lands	Palm	25%	Continuous cover palms	60%
2011	Same as above	30- 50 m	12	Fresh	Most decreased in agriculture lands	Palm	10%	It remains at 15% of palms	

Sources: Al-Qubatee et al. (2013, 2015).

2.4.2 Impact of groundwater degradation on livelihoods

Negative externalities have emerged in the study area, e.g., desertification has increased and date palms are dying. A resource sketch map, which was drawn by local people in Al-Mujaylis, gives information about the socio-economic situation and people's activities in the area (Figure 2.3). The resource sketch map includes livelihood status, types of houses and infrastructure in the area. This tool allowed us to obtain a better understanding about the overall area because it was drawn when standing on the roof of a high building (a school). By combining direct observations with a Google Earth map, a high level of precision and validity was achieved. The photographs in Figure 2.3 show palm farms invaded by sand dunes, the heavy spread of Prosopis juliflora trees. Prosopis juliflora is an evergreen tree native from South America; it is fast growing, nitrogen fixing, and tolerant to arid conditions and saline soils (El-Keblawy & Al-Rawai, 2005). It survives where other tree species have failed and in many cases has become a major nuisance. In 2000, it was rated one of the world's top 100 worst invasive alien species (Lowe, Browne, Boudjelas, & De Poorter, 2000). Date palm trees are dying as a result of rainfall shortages, groundwater decline and spread of P. juliflora. The results of the PRA activities show that after 2000 sand dunes have covered about 60% of the agricultural lands (Table 2.3).

The increased depth of the groundwater is impairing the economic situation of the people as well. In the past, agriculture did not need extensive irrigation technology because the groundwater was shallow (< 1 m below the soil surface). Today's cost of drilling a borehole to a depth of 40–50 m with pumping equipment is high and can reach US$8400. Most people in the area cannot afford to do this; only those few who can obtain financial support from emigrated relatives or other sources can afford borehole wells.

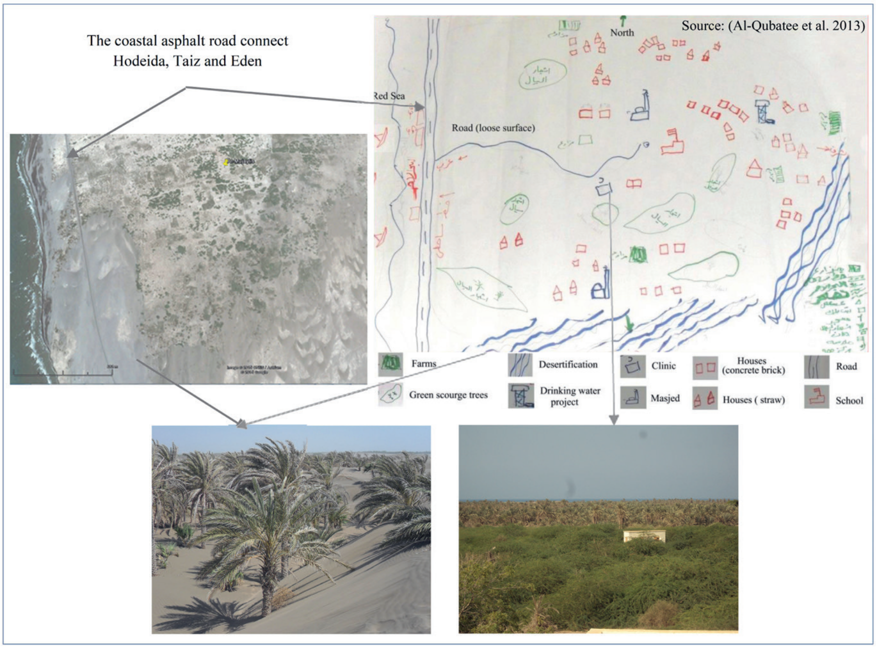

Figure 2.3 Resources sketch map of Al-Mujaylis with connection to Google Earth and direct observation (photographs) for precision and validity: (left) palm trees in Al-Zakham hamlet completely covered and in the process of being covered by sand dunes and (right) the heavy spread of Prosopis juliflora surrounding the palm trees and clinic centre. Photographic sources: Al-Qubatee et al. (2013, 2015).

The production cost of palm tree agriculture has increased due to the harsh natural conditions, and the yield of the palm trees has gone down from 30 kg per palm tree per year in the years before 1990 to only 5 kg per palm tree in 2011. Lack of rain, falling water tables, drought, sand dune movements and the spread of P. juliflora have impacted heavily on agricultural activities. Thus, palm tree agriculture is no longer the profitable business that it was previously.

According to local people, the overall decline in agricultural and livestock activities has led to increased poverty and migration from the area. This is reflected in daily farm activities: farmers spent just three hours per day in the field, and in the numbers of migration and current poverty levels. Al-Mujaylis, which consists of 10 hamlets, has a total population of 2642 (1328 male, 1314 female) according to the last census in 2004 (Central Statistical Organization, 2005). According to a key informant (a teacher), about 85% of the people are living in extreme economic poverty and the other 15% in moderate economic poverty (personal communication with Mr Ibrahim, 2013). Migration has increased after 2000, reaching 50–60% in 2015 (Table 2.3).

2.4.3 Stakeholder views on the causes and solutions of water resources problems

Eight different discussions groups, with 5 to 10 respondents in each group (including farmers and key informants), were formed to identify their problems and to propose solutions (Table 2.1). For example, the groups of people in the downstream areas close to the Red Sea (four different groups) identified and ranked the causes of the water resource problems in the area, proposed solutions for these problems and ranked them according to their priority and preferences (Table 2.4).

Table 2.4 Priorities of the water resources problems and the suggested solutions, downstream of the wadis.

Ranking	Al-Mujaylis	Al-Tefaf	Al-Gah (1)	Al-Gah (2)[a]
Causes of the water resources problems				
1	Rainfall shortage	Poverty	Rainfall shortage	Rainfall shortage
2	Random drilling wells (groundwater depletion)	Rainfall shortage	Spate of irrigation practices	Over abstraction, groundwater depletion
3	Prosopis Juliflora trees	P. Juliflora trees	Over abstraction and groundwater depletion	Increased the agriculture areas
4	Spate irrigation	Construction of diversion structures	Farming crops consume a lot of water, such as banana	Constructed dams in the mountain catchment areas
5	Construction of weirs and dams	Crop pattern change upstream	Constructed dams in the mountain catchment areas	Crop pattern change, mango and banana instead of cereals
6		Groundwater depletion because of high abstraction upstream	Spread of P. Juliflora trees	Absence of high efficiency irrigation techniques
7		Random drilling of wells without the legal distance		
Suggested solutions				
1	Support farmers by modern irrigation etc.	Support farmers (marketing etc.)	Zakat giving	Implement high efficiency irrigation
2	Cope with P. juliflora trees, desertification (reactivate the International Fund for Agricultural Development [IFAD] project)	Cope with P. Juliflora trees and desertification	Implement high efficiency irrigation	Build dams and weirs in suitable places
3	Stop random well drilling and implement distance between wells.	Build the dams at the end of the wadis before water discharge into the sea	Regulate well drilling	Cultivate cereal crops
4	Water harvesting (at the end of the wadis before water discharge into the sea)	Solve the problem of diversion weirs to serve all people	Farm crops that can withstand drought	Use of natural fertilizers
5		Regulate well drilling	Select a suitable location for dams and weirs	

Note: [a]For this group no ranking was done in the field for the causes of the problem.
Sources: Al-Qubatee et al. (2013, 2015).

People in the midstream of Wadi Zabid and Wadi Rima have their own interests and conflicts about the distribution of spate water. For example, people in midstream of Wadi Zabid depend on traditional water rights called in Arabic ‘arf’ (common law) that were introduced by Sheikh Al-Jabarti more than 600 years ago based on the general rule *‘Al-a’la fi-l-a’la’* (priority for the upstream riparian residents). These rules give priority to spate water rights to three groups of users in the midstream of Wadi Zabid within the 20 km downstream of the weirs. The water that exceeds their needs flows further downstream and (only in exceptional cases) reaches the Red Sea, 50 km from the foothills. The outcome of the problem and solution tree exercise for the midstream stakeholders shows the most important causes of the problems and the priority for the suggested solutions in midstream Wadi Zabid and Rima

(Table 2.5). Although there is neither cooperation nor conflict between downstream and midstream residents of the wadis, there were clear similarities in their views about the problems and possible solutions. The leading causes of the problems mentioned in both areas are: (1) rainfall shortage; (2) the effect of the construction of dams and diversion structures; (3) changes in cropping pattern and the low efficiency of irrigation techniques; and (4) random drilling of wells and over-abstraction of groundwater. The common solutions suggested are (1) to support farmers to introduce high-efficiency irrigation techniques and assistance to market their crops; (2) the selection of suitable locations for future dams and diversion structures and better management of the water in the existing harvesting structures; (3) the regulation of well drilling and implementation of the water laws; and (4) the cultivation of crops that can withstand drought and have lower water requirements, e.g., cereals.

Key informants were asked about their role in the solutions for all the above mentioned problems. The response of one parliamentary representative in the region was that each institution should take its responsibility to improve the situation. Suggestions included ideas such as to improve cooperation between government and related institutions and to improve legislation related to water resources to overcome the weak points in the laws (both formal and tradition laws). These results confirmed our expectation that each PRA tool applied was well suited to the various objectives of this study (Tables 2.2 and 2.6).

Table 2.5 Priorities of the problems in the midstream of Wadi Zabid and Wadi Rima.

Ranking	Al-Gerbah area, within the first group of Wadi Zabid	Al-Gerbah area, within the first group of Wadi Zabid (2)	Al-Mawi canal, within the second group of Wadi Zabid	Al-Jarubah area, Wadi Rima
Causes of the water resources problems				
1	Rainfall shortage	Rainfall shortage	Rainfall and spate water shortage	Convert the spate water of Wadi Rima to the southern area
2	Groundwater depletion because of banana farming and an increase in agriculture areas	Random drilling of wells, the water law is not implemented	Banana farming, which consumes a lot of water	No fair spate water distribution
3	Constructed dams in the mountain catchment areas of Wadi Zabid.	Spate irrigation	Constructed weirs and dams in the mountain catchment areas of Wadi Zabid	Rainfall shortage
4	Water law not implemented fairly	Banana farming which consumes a lot of water	Random drilling of wells	Crop pattern change, banana farming instead of cereals
5			Absence of high efficiency irrigation techniques	
Suggested solutions				
1	Stop building harvesting dams in the mountain catchment areas of Wadi Zabid	Implement water law and stop the random drilling of wells	Stop or decrease banana farming	Justice in spate water distribution and implement the law
2	Implement the regulation for drilling of wells	Construct water-harvesting structures	Support farmers by high efficiency irrigation techniques	Support farmers with diesel, marketing and technical
3	Implement new spate water distribution systems as the system in the southern part of Yemen (Lahj & Abyan[a])	Support farmers by high-efficiency irrigation techniques	Regulate the drilling of wells	Educate farmers on how to conserve water
4	Replace banana crop with other crops like cereals	Decrease banana farming by farming another crops like cereals	Regulate the construction of dams and manage the water of constructed dams	Reduce crops that consume a lot of water, such as banana
5			Raise the awareness of farmers about the importance of water	

[a] Spate water rights in those areas: farmers upstream use the spate for irrigation only once, thereafter letting the water pass to the next farm, and so on until the water reaches the last beneficiary who depends on the amount of the spate. The second spate would then begin from the farmer after the last one to receive the previous spate, and so on.
Sources: Al-Qubatee et al. (2013, 2015).

Table 2.6 Usefulness of participatory rural appraisal (PRA) tools to achieve the objectives of the study, arranged from the most to the least useful.

PRA tools and other sources of information	Objectives			
	To assess the degradation of groundwater resources		To obtain stakeholders' views on the problems and their solutions	To overcome lack of data[a]
	Groundwater status	Livelihoods		
Semi-structured interview	+ + + + +	+ + + + +	+ + +	+ + + +
Transect walk and direct observation	+ + + + +	+ + + +	+ + +	+ + + +
Groups discussion	+ + + +	+ + +	+ + + +	+ + + +
Time line	+ + + + +	+ + + +	+	+ + + + +
Problem and solution trees	+ + +	+ +	+ + + + +	+ + +
Key informant interview	+ + + +	+ + +	+ + +	+ + +
Resource sketch map	+	+ + + +	+ + +	+ + +
Daily calendar	-	+ + +	-	+

Notes: Many plus signs (+) mean the strong contribution of the method to the achievement of the objectives; a negative sign (–) means no contribution at all).

[a]Groundwater status, spate water, traditional rights of spate water distribution, irrigation system, land use, livelihoods status etc.

2.5 Discussion

There is strong support for more change from the current management practices towards a more adaptive and flexible approach to get more attention paid to tackle water management from an integrated approach, including human, physical, biological and biogeochemical components (Pahl-Wostl, 2007). The trend in the latest literature is towards considering water as interrelated to other sectors, within the broader context, through a problemshed rather than a watershed approach (Hussein & Grandi, 2017). Many arguments exist regarding the involvement of stakeholders in information production, which is regarded as strategic in shaping policies. In fact, the critical hydropolitics literature argues that discourses are constructed and deployed by powerful groups in a society or by powerful riparian countries in order to drive towards certain (favourable) solutions – while closing less favourable policy solutions (Zeitoun & Warner, 2006). The construction of discourses is linked to public opinion on how they absorb and reproduce through daily practices these discourses, and on how they may challenge and contest dominant discourses. Korfmacher (2001) stated that there is an ongoing debate on the subject of public involvement in the processes of knowledge production and decision making. He mentions several issues that justify the involvement of society, such as the democratic, substantive and pragmatic aspects of the process. The argument he made is that citizen involvement in watershed modelling will support decision-making and the implementation of those decisions. This perspective also supports the idea of educating people with the expectation that better understanding will lead to significant support of policy output. Baldwin and Ross (2012), based on a case study of the water-stressed Lockyer Catchment in Australia, stated that applying an action research methodology and consensus-building techniques in the early stage of the regulation process reduces the number of conflicts, leads to mutual learning and builds trust between parties (government and local communities).

However, there are also arguments against stakeholder involvement. Bureaucratic theory takes the view that some aspects of the decision-making process need technical expertise and are, therefore, best left to agencies with expertise. Korfmacher (2001) argues against public participation in watershed modelling, because they may lack expertise. He argues that there can be the risk of biased input, de-legitimization and/ or over-legitimization, misrepresentation of consensus and insufficient influence. Moreover, Moote, McClaran, and Chickering (1997) stated that providing a forum for social discussion (participatory democracy approaches) on its own does not ensure successful collaboration, consensus and/or that decisions will be acceptable to all stakeholders, especially where different interests emerge.

Raadgever et al. (2012) argues that effective collaborative research will only work where the stakeholders are highly motivated (an accurate stakeholder analysis is required) and have equal input in and influence on the research process. This takes time and calls for an intensive collaborative research process.

In our study, we found that PRA tools are an effective method to benefit from the implicit knowledge of the community in which to fill gaps in our knowledge and data records. The PRA technique facilitated the generation of information over the groundwater status (in the past and at the moment), livelihoods of the local community, problems/constraints and views on appropriate solutions that this study aims to address (Table 2.6). This approach helped us to formulate appropriate solutions and to obtain a better understanding of people's preferences. The application of a combination of PRA tools helps us to reach a better understanding of the current groundwater situation and its effects on the livelihoods of people in the area.

The reliability of the generated information was assessed via triangulation and crosschecking between the outputs of the PRA process with external sources of information. The groundwater table contour map prepared by Tesco-Viziterv-Vituki (as cited in Tipton & Kalambach, 1980) confirms our findings that in areas close to the sea the groundwater table was at a depth of 10 m +MSL (mean sea level), less than 1 m below the soil surface (Tipton & Kalambach, 1980, based on Tesco-Viziterv-Vituki, 1971b). Based on our results, the involvement of stakeholders in problem assessment and the identification of proposed solutions is both important and desirable. This approach gave us insight into the community's perspectives on the issues under discussion, which is virtually impossible to do with just a quantitative approach. The communities suggested solutions that they felt were possible for effective implementation. However, we suggest that adopting a research approach between top down and bottom up is more valuable and effective, especially in the areas with high illiteracy. Lack of knowledge of the community on some issues can lead to unrealistic suggestions that may create conflicts and/or create other problems in future. In this respect, we had to assess whether the suggestions were realistic or unrealistic from a specialist point of view, including the various social, technical and economic aspects.

The disadvantages of applying the PRA method include the greater effort required to analyse the qualitative data generated by six different tools and because of the different emerging themes and, therefore, the difficulty of applying statistical methods for generalization compared with the analysis of quantitative data (structured and closed ended questionnaire). Also, the difficulty in getting representation from the whole community required much time and resources. We overcome this by applying as many of the different PRA tools along the wadi as possible (Table 2.1) and to concentrate more on the results that were ranked by the stakeholders in the field. Another disadvantage of this method is the risk that the discussions are dominated by certain group(s) of people (especially where illiteracy is high). We overcame this by use of individual and group interviews. Individual interviews avoided influence from and on others, while group discussion led to increased mutual understanding and conjunctive learning between researchers and stakeholders.

2.6 Conclusions and recommendations

This paper suggests that PRA is a useful method for assessing the degradation of groundwater and its effects on the livelihoods of the inhabitants of the Al-Mujaylis area, overcoming gaps in the available data and getting a better understanding of the local stakeholders' views on the problems, their causes and appropriate solutions. The method gave a clear picture about groundwater degradation with regard to the groundwater drawdown and the effect this had on the livelihood of the community (a higher cost of farming, increased poverty and migration from the area). The challenge was to select the most appropriate and useful combination of tools to address a specific topic. The strongest tools are the semi-structured interviews, the transect walk in combination with direct observations and groups discussion, time lines, and problem and solution trees (Tables 2.2 and 2.6). The result of group discussion and the use of problem and solution trees reflect the stakeholders' views on the problems, the causes of the problems and appropriate solutions. By applying PRA techniques, stakeholders were able to analyse the causes of the problems and to propose appropriate solutions for mitigating or resolving the water problems in the area. The results of all the groups' input were compared with found areas of consensus (common solutions between the groups living downstream and midstream of the wadi).

The application of the PRA method contributed to obtaining an appropriate amount of data regarding the status of groundwater, land use, livelihood situations and the economic situation of the community. The method fits with our context as less attention has been paid to the social aspects of water studies. However, applying a complete bottom-up approach is not useful, especially in areas of high illiteracy. For example, respondents suggested that the government should subsidize the installation of high-efficiency irrigation techniques. From an experts point of view, however, it can be argued that high-efficiency irrigation techniques in closed water basins will not result in a high water saving because part of the water used in irrigation will return (non-consumptive water) to the aquifer over the short and/or long terms

(Frederiksen & Allen, 2011; Gleick, Christian-Smith, & Cooley, 2011). Respondents also suggested that the government should continue the diesel subsidy. From an expert's point of view, however, economic incentives such as irrigation techniques and/or a diesel subsidy can be better oriented to water-saving activities (Hellegers, Perry, Al-Aulaqi, Al-Eryani, & Al-Hebshi, 2008). This is especially true for areas threatened by environmental catastrophes, such as groundwater depletion, seawater intrusion and desertification, as in our case study area. On the other hand, applying a pure top-down approach is not fully successful and faces some limitations. For example, the government implemented a project to cope with the desertification, but that project was not completely successful because people in the area preferred a water drinking project. Therefore, they were later allowed to convert some of those wells for drinking water. Furthermore, between 2004 and 2006, the government increased the height of two weirs in the midstream area by 1 m because sediments had accumulated upstream of it. Stakeholders downstream were unsatisfied with this, but on the other hand stakeholders on both sides of the weirs suffer from sediment accumulation in front of the weir. Participatory study and consensus-building was required along with the technical study.

From our study we conclude that adapting a research approach that is balanced between a totally top-down and a bottom-up approach and between delegitimization and over-legitimization will be more integrated and useful. The community views and suggestions have to be taken into account and studied by the concerned government institutions in a multidisciplinary approach, including technical, social and economic factors. Only then can appropriate decisions be made about solutions to be implemented. The next step in our study will be participatory groundwater modelling to determine the most appropriate solutions suggested by stakeholders. The implicit knowledge of the local communities helped us to fill the gaps in our data recorded that will be used as inputs in this groundwater modelling. In addition, attention needs to be given to examining the wider impacts of the suggested solutions; the production value of the water; and to find the most commonly preferred solutions by stakeholders. These further developments will help in the policy and decision-making process and facilitate effective implementations.

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CHAPTER 3

Natural and Human-Induced Drivers of Groundwater Depletion in Wadi Zabid, Tihama Coastal Plain, Yemen

Abstract

Groundwater depletion is a problem in many places in the world. We developed an approach to investigate the drivers of groundwater depletion in data-scarce regions. The approach combines natural and human-induced drivers, with the latter focusing on the link between human activities and government policies. We tested the approach in Wadi Zabid, Yemen. Forty years of rainfall-runoff data were analysed, alongside changes in land cover, groundwater abstraction and related policies. No decrease in rainfall was observed, but runoff did decrease slightly. Significant expansion of agricultural lands led to increased demand for irrigation water, which was provided by drilling wells and building water harvesting/diversion structures. In Wadi Zabid, human activities, stimulated by policy measures, were the main drivers of groundwater depletion (water table here fell by 1 m/yr on average over 1972-2016). We conclude that combining natural and human-induced factors is indeed a valuable approach for investigating groundwater depletion drivers.

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3.1 Introduction

Human activities, in combination with natural phenomena, significantly impact the availability and quality of groundwater resources. However, drivers of groundwater depletion have often been studied from either a natural or a human-induced perspective. Few studies have focused on both types of drivers and included links between human activities and government policy measures. The result has been partial explanations of the causes of depletion. Indeed, both land use/land cover and climate change have major impacts on catchment hydrology and largely determine the rate of replenishment and depletion of groundwater systems (Calder 1993; Li et al. 2009; Taylor et al. 2013; Gain and Wada 2014). According to Grum et al. (2017), agriculture and the building of water harvesting and diversion structures are main drivers of changes in land cover[1] and associated hydrological processes. The rainfall scarcity and the reductions in runoff have diminished groundwater recharge in many places, with the effect often most severe downstream. Also, in arid and semi-arid zones, most aquifers show significant depletion because water withdrawal rates are greater than natural rates of recharge (Famiglietti 2014). For the coastal aquifers, the problem is more complicated where seawater intrusion has become a worldwide environmental problem due to groundwater overexploitation (Cai, Taute, and Schneider 2015; Colombani, Mastrocicco, and Giambastiani 2015; Javadi et al. 2015).

The human drives play a fundamental role in stimulating or limiting water-consuming (Graham et al. 2020). A region's water consumption can be particularly affected by agricultural production, associated for example with population and economic growth, changes in crop patterns and irrigation practices. The other human drives that influence agriculture and thus water consumption are governmental decisions and policies. Through these, governments choose to incentivize certain paths of economic growth and development, for example, stimulating agriculture with the construction of dams, weirs and canals to enable

[1] Land cover, which can be determined by satellite imagery, refers to the vegetation (natural or planted) and/or artificial structures which cover the earth's surface. It also includes water, bare rock, sand and others. Land use reflects human activities on the land, and land cover maps provide an indicator of land uses and vis versa is correct.

expanded use of irrigation. Other policies that influence agriculture are subsidies or taxation on agriculture inputs, bans on agriculture imports or exports, loan availability and agriculture marketing also influence the extent to which agricultural activities expand or contract. On the contrary, decisions strengthening infrastructure regarding construction and development of wastewater treatment plants and desalination plants can reduce the increasing depletion of groundwater. In addition, regulation by government via decisions and legislation would control the water use and agriculture practices, for example regulation and control well drilling, water abstraction and control groundwater pollution practices.

In Yemen, policies to boost agriculture have brought higher water demands. Agriculture is the nation's largest user of water. Irrigation accounts for 88% of water consumption in Yemen, followed by urban uses (10%) and industrial uses (2%) (Hellegers et al. 2008). Basin irrigation (efficiency ~40%) is found throughout Wadi Zabid in Tihama coastal plain, and use of modern irrigation techniques is rare. Large quantities of water are lost, as return flows are unrecovered and mainly discharged directly into the sea. In addition, a large part of the consumed fraction is non-beneficial (Gleick, Christian-Smith, and Cooley 2011), being lost to evaporation from basin irrigation areas due to the high temperatures, which reach 40°C in the study region. The greater water demand and high water losses have led to accelerated well drilling and construction of many new dams and water diversion structures. Throughout Yemen, lands irrigated from wells expanded tenfold from 1970 to 2008, from 40,000 ha to 400,000 ha, and the number of wells rose from just a few thousand to 50,000 over the same period (Hellegers et al. 2008). According to FAO (2009), there were about 347 storage dams and 33 diversion structures. During the last thirty years, some sixty dams were built in the western mountain region of the country (Charbonnier 2009).

Tihama plain, on Yemen's western coast, is one of the regions facing severe water crisis. Groundwater levels here have been dropping for decades, and water quality has also diminished, due to rising salinity among other reasons.

There were about 12,600 wells in Tihama plain in the mid-1980s, the annual drop in groundwater levels of 0.9 m in agricultural areas, whereas the average annual drop was 0.4 m for the whole Tihama plain (TSHWC 1992).

Wadi Zabid, the study area, is one of eleven wadis that drain into the Tihama coastal plain, a fertile region characterized in the past by its shallow groundwater. To meet the growing water demand for fruit cultivation (banana, mango, papaya, watermelon) and vegetables, thousands of wells have been drilled throughout the Tihama region. According to Al-Qubatee et al. (2017), stakeholders in the coastal area of Wadi Zabid observed that groundwater levels were less than one metre below the soil surface (mbss) prior to the 1970s, while by 2013, the level had dropped to more than 12 mbss with higher water salinity in a few wells. The electric conductivity (EC), which is an indicator of total dissolved solids in groundwater and hence of quality, varied between 0.8 and 17.8 dS/m (NWRA 2009). This is much higher than the standard EC for drinking water, which is 0.2-0.8 dS/m. Stakeholders in the coastal, downstream and midstream areas ranked the leading causes of groundwater depletion as follows: (i) lack of rainfall, (ii) construction of dams and water diversion structures, (iii) changes in cropping patterns and low irrigation efficiencies and (iv) random drilling of wells with over-abstraction of groundwater.

A requirement for sustainable groundwater management is an understanding of the influence of both natural, or climatic, conditions and the effects of previous management decisions and policies (Thomas and Famiglietti 2015). As Li, Li, and Endter-Wada (2017) pointed out, water resources management concerns a complex and interrelated human and natural system. Water managers therefore need to base their activities on research studies grounded in integrative approaches and use collaborative and interdisciplinary frameworks that systematically incorporate multiple perspectives and experiences. For such studies, hydrological, hydro-meteorological data and land cover maps are invaluable, particularly series of such data over time. Analyses based on monitoring and recording can help decision-makers to better understand the situation in a region and to monitor changes over time.

For example, by using series of land cover maps, the impacts of past management decisions on a landscape can be identified to improve future decisions (Skole et al. 1997; Rindfuss et al. 2004; NOAA website https://oceanservice.noaa.gov/facts/lclu.html as of April 19, 2020). Remote sensing is a useful technology to obtain such data, especially in low income countries where continuous and reliable data are not always available or field studies are costly. Also, understanding the rainfall-runoff (surface water inflow) relationship and analysis of past hydrological data (changes in natural runoff patterns) is tremendously important to assess the impact of the human, social and economic activities on the hydrological cycle (Terakawa 2003).

Most previous work on groundwater depletion has focused on either natural or human-induced factors; few studies have focused on both types of drivers. Moreover, within this literature, many authors have examined the drivers of depletion, without considering cumulative effects or drawing links with governmental policy measures and the resulting changes in human activities. Examples of studies investigating partial drivers of groundwater depletion in Tihama plain are Al-Qubatee, Hellegers, and Ritzema (2019); Al-Qubatee et al. (2017); Nasher, Al-Sayyaghi, and Al-Matary (2013); Almhab et al. (2012); Almhab (2011); World Bank (2009); NWRA (2009); NWRA (2008); Abu-Lohom (2002); Al-Kebsi (2000) and Al-Eryani (1979). According to Graham et al. (2020), future studies are needed that analyse where and why human interventions can reduce water stress in the future, together with climate changes studies. The current research expands on past work by considering both natural and human-induced drivers of groundwater depletion and linking human activities to governmental policy measures, thus offering a more integrated and comprehensive analysis. This perspective was applied to examine the main causes of the huge drop in groundwater level in Wadi Zabid. Our combined perspective provides a more complete picture of the contributions of various factors to groundwater depletion.

To assess the drivers of groundwater depletion in Wadi Zabid, Yemen, we combined locally sourced and remote sensing data. Four research questions were posed: (1) Was there a decrease in rainfall and runoff (surface water inflow) in the 1970-2009 period? (2) To what extent has agriculture expanded? (3) What changes can be observed in the rate of well drilling, groundwater abstraction and levels and construction of water harvesting and diversion structures during the 1970-2009 period? (4) Is there a relation between groundwater depletion and water and agricultural governmental policies?

The novelty of this study is that it considers natural as well as human-induced drivers of groundwater depletion based on time-series analysis. It also links changes in human activities to governmental policy measures, so as to identify the main causes of groundwater depletion, which advancing current work in this field.

3.2 Study area

The study area is part of the Tihama coastal plain, which represents one of the important groundwater aquifers in Yemen thanks to the thick alluvial deposits through which runoff from the wadis percolates to replenish groundwater stores. Agriculture is the main activity in the region, in addition to livestock grazing and fishing. Agriculture is concentrated in three seasons: the summer season, from mid-March to end June; the autumn season, from July to end September; and the winter season, from October to end December (Personal communication, Al-Nashery, Agricultural Specialist, 12 May 2017. A variety of crops are cultivated: cereals (sorghum, pearl millet and maize), oilseed (sesame), fruit (banana, date palm, mango, watermelon, papaya, cantaloupe, guava and citrus), vegetables (tomatoes, onions, okra, legumes, zucchini, hot pepper, mulukhiyah), fodder and others such as cotton and flowering plants (Jasminum sambac and henna).

Wadi Zabid is one of the most fertile catchments of the Tihama coastal plain. The wadi originates in the western highlands of Ibb and Dhamar governorates, passes through the highlands of the Jabal Ras directorate and continues through Al-Jarrahi, Zabid and Al-Tuhita directorates, discharging into the Red Sea in heavy rainfall years (Figure 3.1). The wadi is about 140 km long. Most of its length, 94 km, is in the upstream mountainous areas, with the remaining 46 km in the Tihama plain. The total catchment area of the wadi is about 4,450 km^2 (Van der Gun and Ahmed 1995; Qaid 2007). For the purposes of the current study, the Tihama plain is divided into three areas: (i) the midstream of the wadi, which is the area from the foothills to weir 5 and the lands irrigated by this weirs; (ii) the downstream of the wadi, from weir 5 to the centre of Al-Tuhita directorate; and (iii) the coastal area, from the centre of Al-Tuhita directorate to the Red Sea coast.

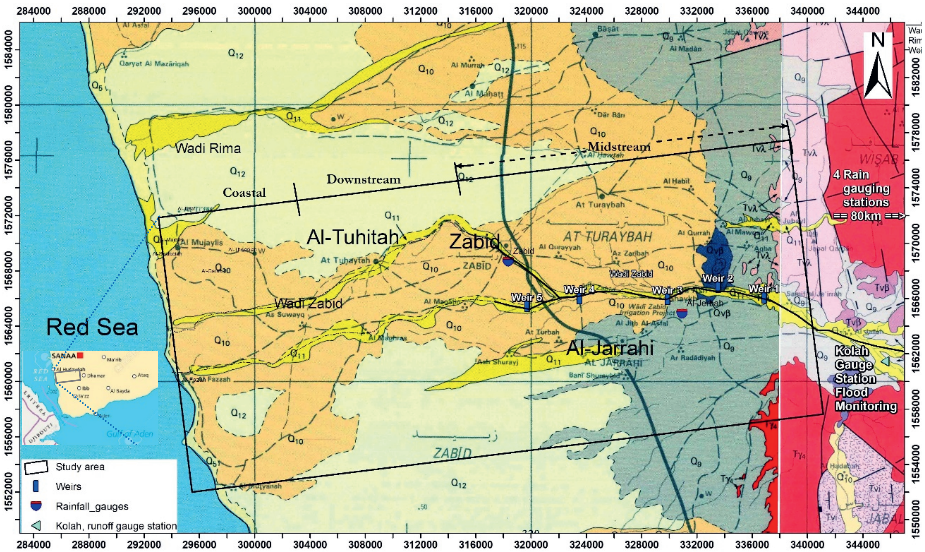

Figure 3.1 Geologic map of Wadi Zabid showing the division of the study area into midstream, downstream and coastal areas. Extracted from Al Hudaydah sheet 14F and Dhamar sheet 14G, 1:250,000 (Robertson Group 1991)

Rainfall amounts vary along the wadi and from year to year. Rainfall is greatest in the mountainous areas, averaging 550 mm/yr, decreasing to 350 mm/yr in the midstream area and 100 mm/yr near the coast. The rainy season, when the floods come, extends from end March until mid-October (about 204 days) followed by a dry season with only base flow, from mid-October until end March (about 161 days).

Average temperatures range from 18° to 40°C (NWRA 2009). The average potential evaporation is about 3,000 mm/yr (TDA 2010), which is high and exceeds rainfall amounts. The mean relative humidity is 66%, and the mean wind speed is 1.7 m/s at the Al-Jerbah meteorological station in the midstream area of the wadi (TDA 2010). The average annual water flow in the wadi from 1970 to 2009 was 122 Mm^3, recorded at Kolah gauging station (DHV 1988; TDA 2010). In the study area, irrigation depends mainly on groundwater, in addition to scarce rainfall, except in the midstream zone where spate irrigation is also used.

In the late 1970s, the Government of Yemen sought to encourage agricultural production through construction of water harvesting and diversion infrastructure. Currently there are 22 dams upstream in the wadi (Personal communication, A. A. Almhab, Ministry of Agriculture and Irrigation, 25 January 2015). In the past, farmers in the midstream area built temporary earthen diversion structures and canals prior to every flood season to distribute spate waters. In 1979, these temporary structures were replaced by five permanent weirs and an associated network of irrigation canals (some 123 km in total length) to irrigate 15,200 ha (Bahamish 2004). Distribution of spate water in the midstream of the wadi is governed by the traditional "Al-Jabarti rules", introduced by Shiekh Ismail Al-Jabarti more than 600 years ago. The rules are based on the "*al 'ala fa al 'ala*" principle; that is, the upper riparian zone has first priority for spate water use, with spate waters further shared among three midstream groups. The spate water is thus divided between three groups in the midstream area. Group one, which includes the lands located beyond weir 1 and weir 2, have spate water rights from 19 October to 2 August (288 days), with a mean water allocation of 80 Mm^3, to irrigate 4,805 ha. Group two, which includes the lands beyond weir 3 and weir 4, have spate water rights from 3 August to 13 September (42 days), with a mean water allocation of 32 Mm^3, to irrigate 10,175 ha. Group three, representing the lands beyond weir 5, have spate water rights from 14 September to 18 October (35 days), with a mean water allocation of 17 Mm^3, to irrigate 1,450 ha (Tipton and Kalmbach 1974; Bahamish 2004; IIP 2005). The rules include detailed provisions concerning water use and distribution within each group. For example, it is prohibited to irrigate land more than once every 14 days.

It is also prohibited to reclaim new land or build canals to lands that did not previously have spate water rights (Bahamish 2004). Excess water flows to the downstream and coastal areas. Runoff reaches the sea only after extreme rainfall events, which hardly ever occur (Tesco-Viziterv-Vituki 1971).

3.3 Materials and methods

3.3.1 Rainfall-runoff relation

This research investigated whether the observed fall in groundwater table in the study area was due to decreased rainfall and runoff (surface water inflow). The rainfall and runoff records were investigated over the 1970-2009 period. The topography (elevation) and climate (rainfall) varied from upstream to downstream in the wadi. Upstream rainfall data were recorded at four gauging stations, and midstream data were taken from two stations (Figure 3.1). Runoff was measured monthly at the catchment outlet, at the Kolah gauging station. The data was collected from the Tihama Development Authority (TDA) and from the literatures (e.g. DHV 1988). An excel spreadsheet was developed for data analysis.

To assess trends in rainfall-runoff over the 1970-2009 period, a three-step approach was used: (i) the median of the rainfall records from the upstream gauging stations was calculated on an annual basis and likewise for the midstream area, as the median is a more accurate than the arithmetic average in cases where the data includes extreme (high or low) values (de Nijs and Klausen 2013); (ii) the relation between rainfall and runoff was established for the upstream region over the 40-year study period, with linear trend lines derived to trace changes in rainfall and runoff; (iii) the relation between the annual runoff coefficient (*K*) and rainfall records was established to better understand the rainfall-runoff relation and the effect of other factors on the runoff coefficient.

The runoff coefficient (*K*) (Equation 3.1) was defined as the ratio between runoff (surface water inflow to midstream) and rainfall in upstream and is dimensionless (Critchley, Siegert, and Chapman 1991):

$$\text{Runoff coefficient } (K) = \frac{\text{Annual runoff (mm)}}{\text{Annual rainfall (mm)}} \tag{3.1}$$

The runoff coefficients is used to compare catchments in terms of their capability to generate runoff (Van der Gun and Ahmed 1995; Blume, Zehe, and Bronstert 2007). In our study, the (*K*) was calculated based on rainfall-runoff records for the 40 yr (1970-2009), to study the effect of other factors (e.g. the land use/ land cover) on calcuated (*K*) values for the same catchment area. Runoff is influenced by multiple factors, such as interception of rainfall by land cover, depression storage (natural or artificial, e.g., dams) and infiltration (dependent on, e.g., soil permeability, land slope and artificial barriers such as gabions and water diversion structures). In addition, the high temperatures of the region, particularly in combination with intensive agriculture, led to substantial evaporation and evapotranspiration, due for example, to open irrigation canals and dam reservoirs.

As the 40 years of runoff coefficients represent the same watershed (same soil type and same slope), they provide a good indicator of the driving forces that underlie low or high annual runoff. The question we asked was straightforward: Is low or high annual runoff caused by low or high rainfall or are other factors at work, such as changes in land cover (vegetative cover), due to changes in human activists such as agricultural practices or/ and water harvesting? No complicated rainfall-runoff model was used, as our question could be answered by means of the sample (Anderson, Woessner, and Hunt 2015) since both rainfall and runoff records were available (Seibert 1999).

3.3.2 Remote sensing and ArcGIS

This study used remote sensing technology (satellite image) to investigate the extent of the agriculture expansion in the study region. Satellite images represent an invaluable resource for monitoring land cover changes over decades. They provide detailed, precise, time saving and cost-effective information (Forkuor and Cofie 2011). Thus, remote sensing can play a key role in land and water management (DHV 1987).

The Landsat image series from the US Geological Survey capturing over 42 years was used. The images selected were those taken in December of 1972, 1984, 2009 and 2014. These years were carefully chosen to offer as high a resolution as available, especially in the earliest years) to detect changes in land cover associated with major events in the country. The images have a 30 m spatial resolution and 16-day temporal resolution. The ArcGIS Pro classification wizard and support vector machine (SVM) were used to analyse the remote sensing images. A training sample and supervised classification were used to create land cover maps and detect land cover changes in the selected years. Land cover was categorized in four classes: rocky land, bare soil, agriculture (vegetation) and desert.

3.3.3 Well inventories

To investigate changes in the rate of well drilling and groundwater abstraction and levels during the 1970-2009 period, we used data from available well inventories and historical sources, spanning local and former government authorities and private companies. The well inventories were carried out in 1972 (Tesco-Viziterv-Vituki as cited in Tipton and Kalambach 1980), 1975 (Tipton and Kalambach 1980), 1987 (DHV 1988) and 2008 (NWRA 2008). In addition, a field survey of well water levels was carried out in mid-2016 (Al-Qubatee, Hellegers, and Ritzema 2019). The well inventory carried out in 1975 (Tipton and Kalambach 1980) did not include abstraction rates. These were estimated as the annual pumping hours was known, and well yields were taken as the average of the results of pumping tests carried out by Tesco-Viziterv-Vituki (1973) for 15 wells in the midstream and downstream areas of Wadi Zabid. Abstraction volumes were missing for some wells of the well inventory carried out in 2008 (NWRA 2008) so for these average were taken from nearby wells.

The average groundwater levels in 1972 for midstream, downstream and the coastal area were obtained from the available contour map of groundwater levels. The average groundwater levels in 1987, 2008 and 2016 were obtained from the contour maps of groundwater levels (Appendix 3.1) which were drawn, for the purpose of this study, using the kriging interpolation method based on well inventories data, the above-mentioned references. Because the aquifer in the study area has lithological layers extending along the study region (with a different thicknesses) according to a geoelectric cross section of Wadi Zabid (DHV 1988), the groundwater level for the whole study region was represented by the average groundwater level of the three parts of the study region (midstream, downstream and coastal).

3.3.4 Timeline of policy measures related to water and agriculture

To investigate the relation between groundwater depletion and water and agricultural policies, data on government policies for agricultural development in the region were collected based on the literature review. Thus a historical timeline was established showing major policy decisions related to water and agriculture in Yemen over time. Major changes (events) in agriculture, such as land expansion or contraction were noted on the timeline, as well as major changes in water resources, such as changes in the rate of well drilling and changes in groundwater abstraction. The timeline therefore reveals linkages between major government policies (drivers), infrastructure development and impacts on the environment. Key political decisions include various laws and legislation enacted, such as subsidized diesel fuel, a ban on agricultural imports or exports, and facilitated imports of drilling and pumping equipment. Infrastructure development consisted mainly of agricultural schemes and water harvesting and diversion structures. Environmental impact was represented by the depletion of groundwater aquifers. The end goal of the exercise was to inform and better rationalize future decisions in land and water management (Mustard et al. 2004).

3.4 Results

3.4.1 Rainfall-runoff relation

Over the 40 years under study, a slight increase in rainfall was recorded upstream, alongside a slight decrease in runoff, according to the trend line, linear function (Figure 3.2A). Thus, less runoff (surface water inflow) reached the midstream area of the wadi. Here, two periods can be distinguished. In the first period, 1970-1979 (Figure 3.2B), there was an increase in rainfall upstream over time, resulting in a very high increase in runoff. In the second period 1980-2009 (Figure 3.2C) there was a slight increase in rainfall upstream over time; however, this was accompanied by decreased runoff.

In the midstream area, similarly, a slight increase in rainfall was recorded over the 40 years as well as in the first and second periods (Figure 3.2A-C). The increase was more or less the same as that registered in the highlands. The trend line of both rainfall and runoff indicates a very low coefficient of determination (R^2), as the amounts of rainfall and runoff were highly variable.

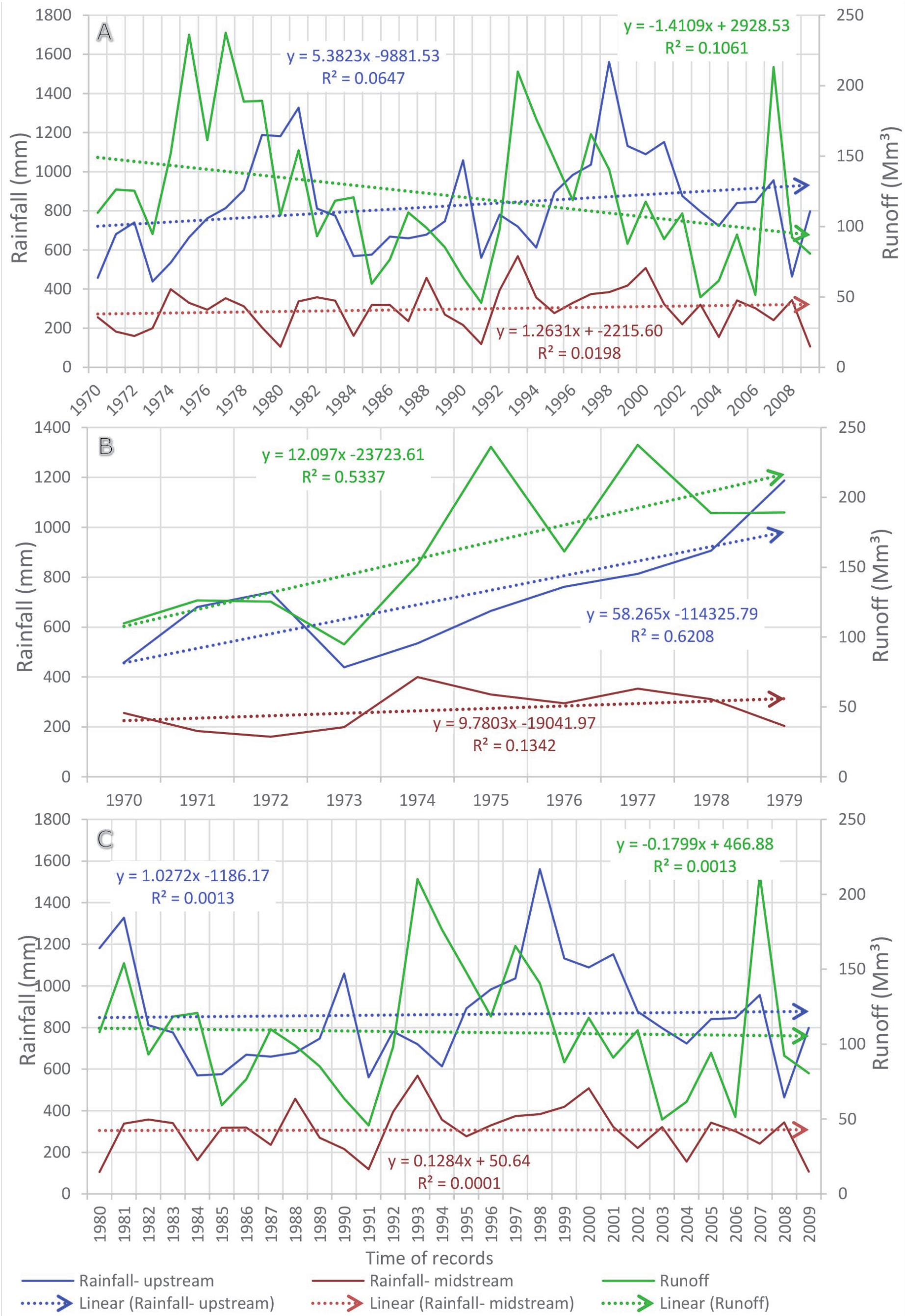

Figure 3.2 Median annual rainfall, (A) over the period 1970-2009 (B) over the period 1970-1979, and (C) over the period 1980-2009, in the upstream and midstream areas and the runoff (surface water inflow to midstream area).

This is clearly demonstrated by Figure 3.3, which plots the annual runoff coefficient (*K*) against rainfall. In that figure, the two periods can also be distinguished, based on the average runoff coefficient, which was 0.035 (standard deviation 0.017):

- In period 1, from 1970 to 1979, the runoff coefficient (*K*) was high (> 0.035), regardless of whether the amount of rainfall was high or low. This means there was high runoff in these years, due to limited human intervention.
- In period 2, from 1980 to 2009, the runoff coefficient (*K*) was low (< 0.035), again, regardless of whether the amount of rainfall was high or low. This means there was low runoff in these years which was due to the substantial human intervention in this period.

Note that a number of irregular years was observed (1984, 1993, 1994, 2007 and 2008) that deviate from these characteristic distributions, but these can be considered very few.

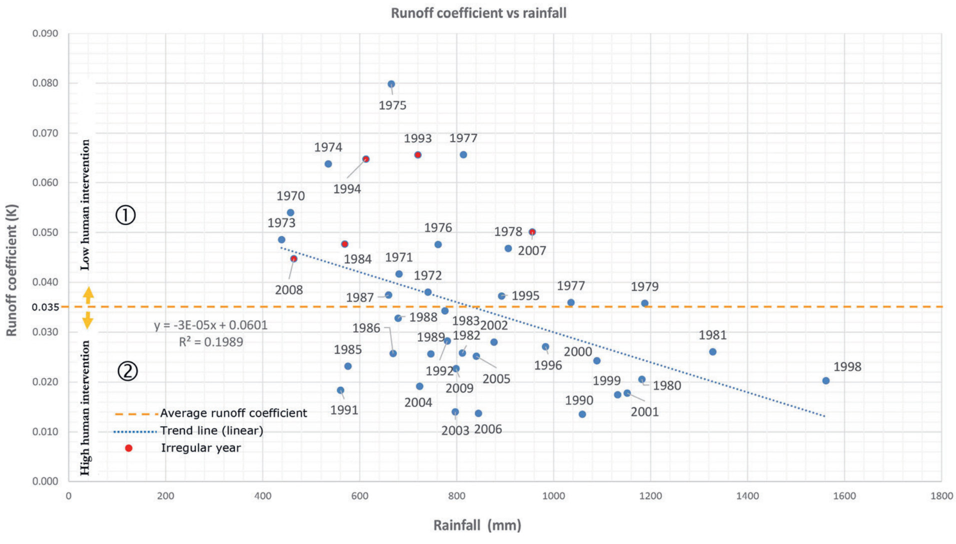

Figure 3.3 Relation between the annual rainfall in the upstream area and the resulting runoff coefficient. Two periods can be distinguished. Period 1, the years from 1970 to 1979, comprises the years characterized by a high runoff coefficient (*K*), meaning high runoff, likely due to limited human intervention. Period 2, the years from 1980 to 2009, comprises the years characterized by a low runoff coefficient (*K*), meaning low runoff, likely because of human intervention. Five irregular years over the 40-year period were observed (1993, 1994, 2007, 1984 and 2008) which deviate from these characteristic distributions. Overall, the trend of the runoff coefficient (*K*) is decreasing with an increasing amount of rainfall. This indicates the reduction in the runoff due to a high water use upstream associated with increased harvesting by dams, diversion structures and agricultural activity after 1979.

The trend of the runoff coefficient (*K*) is decreasing with an increasing amount of rainfall. This indicates that runoff did not increase with increased rainfall as expected (Equation 3.1). But on the contrary, the reduced runoff was likely due to factors such as a high water use upstream associated with increased water harvesting and diversion infrastructures (dams and weirs) and intensified agricultural activity after 1979. This reduced the amount of spate water available for irrigation in the midstream and downstream areas, increasing dependence on groundwater here.

The monthly runoff figures closely track monthly rainfall averages upstream; in other words, every rainfall episode upstream produced runoff at the outlet (Figure 3.4). The average annual runoff was 122 Mm^3.

In the midstream area, rainfall tended to slightly increase over the 40 years, measured at the two rainfall gauging stations (Figure 3.2), but average rainfall over the 40 years was very low (only 297 mm/yr). For comparison purposes, rainfall upstream was about four times that in the midstream of the wadi (average rainfall upstream over the 40 years was 827 mm/yr). Despite the large differences in rainfall between the upstream and midstream areas, the ratio between them remained approximately constant over the 40 years. In both the upstream and the midstream areas, the wet season started in April and reached its height from May to October (Figure 3.4). Yet, runoff reaching the downstream areas dwindled, due to the five diversion structures built midstream. As noted earlier, spate waters were distributed via traditional rules among three groups in the midstream area of the wadi. Only water that exceeded the needs of these groups flowed downstream, and this rarely reached the coast.

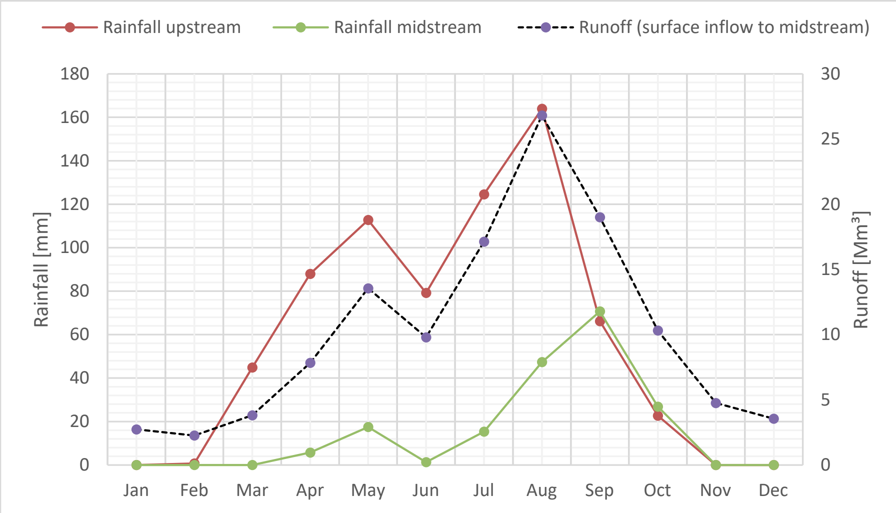

Figure 3.4 The median monthly rainfall over the period 1970-2009 in the upstream and midstream area and the average monthly surface runoff (surface water inflow to midstream) for same period.

3.4.2 Land cover

Four land cover classes were identified: rocky land, bare soil, agriculture (vegetation) and desert (Table 3.1). From 1972 to 2014, three periods were distinguished:

- From 1972 to 1984 there was an increase in agricultural land (46%) from 104 km^2 to 152 km^2. This expansion was associated with a decrease in bare soil cover.
- From 1984 to 2009 there was a large expansion of agricultural land (86%) from 152 km^2 to 283 km^2, alongside a substantial reduction in bare soil and desert cover and a small reduction in desert cover.
- From 2009 to 2014 there was a slight decrease in agricultural land (4%), from 283 km^2 to 271 km^2, alongside an increase in bare soil and a decrease in desert cover.

Table 3.1 Land cover classes and distribution, registered in Dec (1972, 1984, 2009 and 2014)

Class	Dec (1972)		Dec (1984)		Dec (2009)		Dec (2014)	
	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)
Bare soil	375	41.0	316	34.5	247	27.0	298	32.6
Desert	408	44.6	423	46.3	362	39.7	312	34.1
Rocky land	27	3.0	23	2.6	22	2.4	32	3.5
Agricultural land	104	11.3	152	16.6	283	30.9	271	29.7
Total	914	99.9	914	100	914	100	913	99.9

Total land area is smaller than the rectangular study domain because small parts are located in the Red Sea (Figure 3.1). In addition, a minor errors result from the low resolution of the Landsat images (e.g. clouds effects). Agricultural lands are less than in actuality due to our selection of Landsat images for December. These only available images with a good resolution for the selected years especially the earliest years. However cereals are not usually cultivated in December.

3.4.3 Numbers of wells, abstraction rates and groundwater levels

The number of operating wells in Wadi Zabid was 263 in 1972, with about 47.5 Mm³ of annual abstraction (Tesco-Viziterv-Vituki as cited in Tipton and Kalambach 1980) (Table 3.2, Figure 3.5A). Three years later, in 1975, the number of operating wells had increased to 831, with 81.7 Mm³ of abstraction, according to the well inventory carried out in that year (Tipton and Kalambach 1980).

The number of operational wells reached 1,221 in 1987 and 4,250 in 2008, with respectively, 240.6 Mm³ and 444.2 Mm³ of abstraction, according to DHV (1988) and NWRA (2008). From 1972 to 1975, 189 wells per year were drilled, with 144 wells per year added between 1987 and 2008. There was thus a significant increase in well numbers and groundwater withdrawals. As a result, groundwater levels fell by an average of almost 50 m from 1972 to 2016 across the wadi (Table 3.2, Figure 3.5B). The severe groundwater depletion was experienced downstream, followed by the midstream and coastal areas. According to the well inventories and field measurements (Table 3.2 and Figure 3.5B), average groundwater level depths in these areas were, respectively, 8 mbss, 20 mbss and 0.5 mbss in 1972. But recently, in mid-2016, groundwater level depths had dropped to 90, 50 and 35 mbss, respectively. The trends in expansion of agricultural lands (Table 3.1) and groundwater abstraction (Table 3.2) exhibit a parallel relation (Figure 3.5A) especially after 1980. This underlines the increasing over-reliance on groundwater for irrigation over time. In 2014 there was a decrease in agricultural land. However no data was available on the rates of groundwater abstraction in that year.

Table 3.2 Operational drilled wells, groundwater levels and abstraction rates in the study area of Wadi Zabid, 1972-2016

Years	Cumulative numbers of operational wells	Abstraction (Mm^3/yr)	Groundwater levels (mbss)			
			Coastal area	Downstream	Midstream	Whole region
1972[1]	263	47.5	0.5	8	20	9.5
1975[2]	831	81.7	-	-	-	
1987[3]	1221	240.6	10	40	25	25
2008[4]	4250	444.2	18	75	30	41
2016[5]	-	-	35	90	50	58

Sources: Data analysis for the purpose of this study based on 1. Tesco-Viziterv-Vituki (as cited in Tipton and Kalambach 1980), 2. well inventory 1975 (Tipton and Kalambach 1980), 3. well inventory 1987 (DHV 1988), 4. well inventory (NWRA 2008) and 5. Field survey in 2016 (Al-Qubatee et al, 2019).

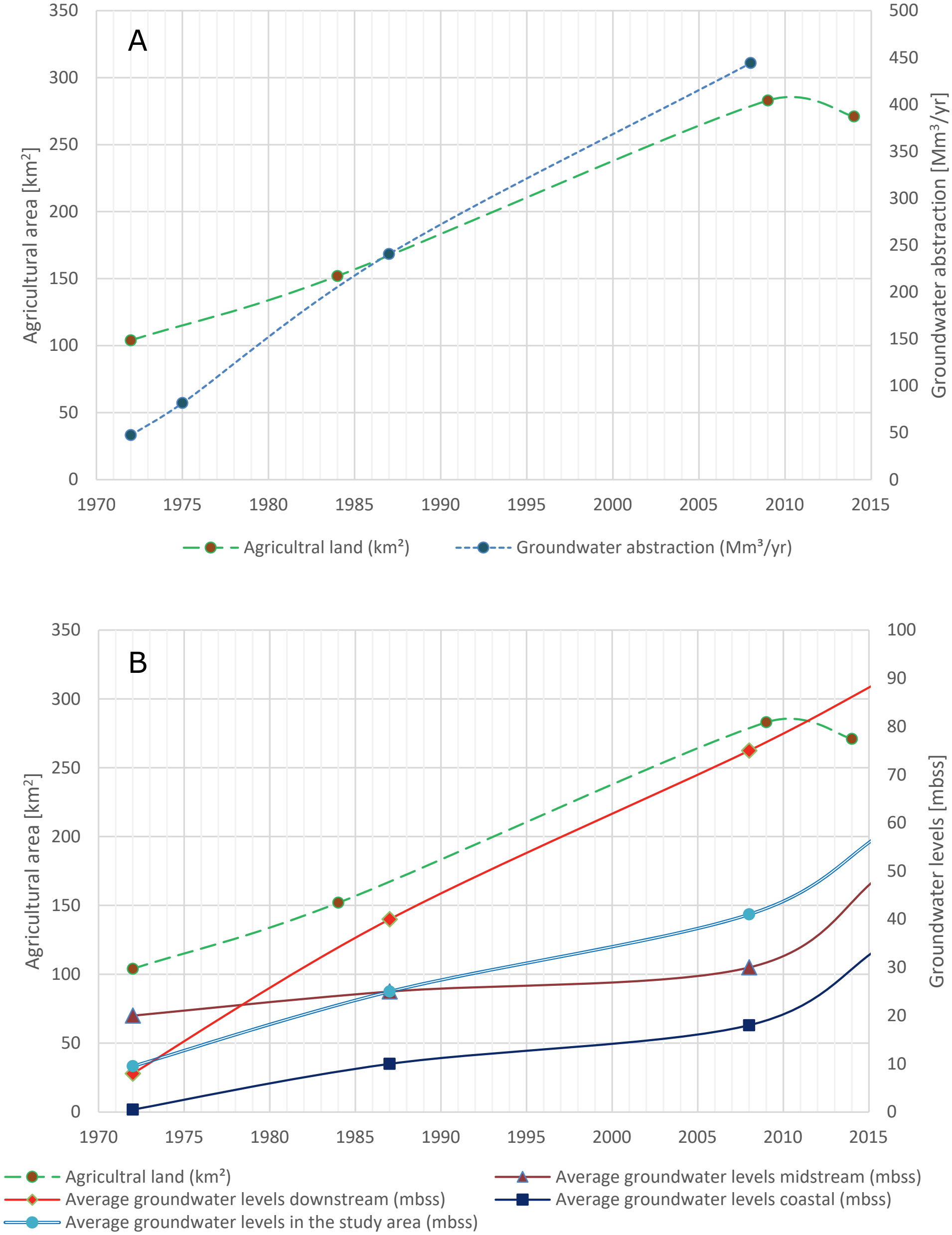

Figure 3.5 (A) Changes in agricultural land and groundwater abstraction for the whole study region over the 1972-2009 period. (B) Changes in agricultural land and groundwater levels for the midstream, downstream and coastal areas of the study region as well as for the whole study region over the 1972-2009 period (all derived from Tables 1 and 2).

3.4.4 Timeline of policy measures related to water and agriculture

Since 1970, the government has initiated a number of programmes to support farmers by enacting favourable legislation and developing infrastructure to facilitate irrigation and agriculture (Figure 3.6). These programmes have acted as an incentive to farmers throughout the country and in the study area in particular. For example, a subsidy on diesel fuel was implemented in 1970, which facilitated public and private investment in well drilling and the import of related equipment. In 1975, the Cooperative and Agricultural Credit Bank was established, giving agricultural entrepreneurs access to investment capital. In 1979, an irrigation scheme was developed in the midstream area of the wadi, with the construction of five weirs and associated canals. Twenty-two dams were built farther upstream in subsequent years. Finally, a ban on fruit imports was enacted between 1984 and 1995 to promote local cultivation. After 2011, there was a diesel crisis due to the onset of political change.

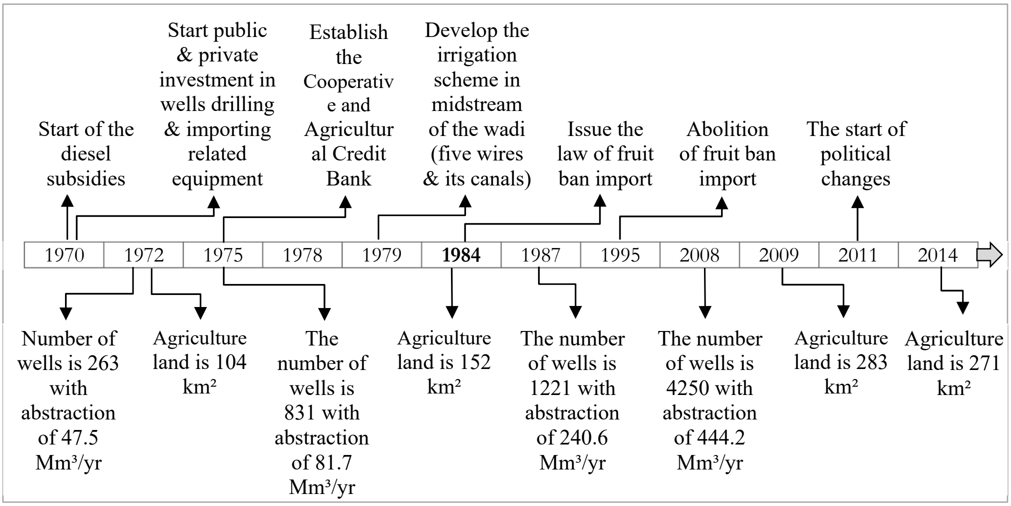

Figure 3.6 Timeline showing Governmental policy and the resulting agricultural developments and groundwater abstraction in the study area. Source: the information is based on the result of this study (see Table 3.1 and 3.2) and literature review Al-Qubatee et al (2015) and Hellegers et al (2008).

3.5 Discussion

Over the 40 years under study, rainfall actually increased on average, though slightly. This increase is evident in our rainfall time series data from 1970 to 2009, in both the upstream and midstream areas of the wadi. However, the runoff (surface water inflow), reaching the midstream area decreased. It is notable that early in our study period, from 1970 to 1979, very high runoff was measured, associated with high rainfall. After 1980, runoff reaching the midstream area decreased, despite increased rainfall upstream. Increases in rainfall are projected to continue in Yemen. A rise of about 15-20% is expected over the 2020-2050 period, relative to the benchmark, which is 2000-2009, according to climate data for the Middle East by Terink, Immerzeel, and Droogers (2013).

A number of human interventions reduced the amount of runoff that reached the downstream areas. Most important among these was the expansion of agricultural lands, in particular land planted with cash crops which have high water demands. The analysed remote sensing data (satellite images) confirm, for the study region, the significant expansion (172%) in land area under agriculture between 1972 and 2009. Van Steenbergen et al. (2010) found that banana farming in the midstream area of Wadi Zabid had expanded from 20 ha in 1980 to 3,500 ha in 2000. In addition, the Irrigation Improvement Project (IIP) (2002) confirmed that high-value crops, such as vegetables (e.g., onions, okra and tomatoes), and cash crops (e.g. banana), were replacing traditional crops (e.g. sorghum, sesame and cotton). Irrigation water application for banana in Wadi Zabid is very high: about 40,800 m^3/ha per year (Al-Qubatee, Hellegers, and Ritzema 2019). This high water demand was accommodated by increased well drilling and high groundwater abstraction rates. This reality is dictated by circumstances in most cases: humans respond to drought and water scarcity by deepening dried-up wells and building dams, despite the negative environmental consequences (Famiglietti 2014; Zetland 2014). This clearly emerged from our study, in the huge rise in well drilling and water abstraction rates. The number of operating wells in study region increased from 263 in 1972 (Tesco-Viziterv-Vituki as cited in Tipton and Kalambach 1980) to 4,250 in 2008 (NWRA 2008), with annual abstraction growing from about 47.5 Mm^3 to

444.2 Mm^3 in this period. As a result, groundwater levels fell by an average of almost 50 m from 1972 to 2016 across the wadi.

In addition, construction of water harvesting and diversion structures after 1979 reduced runoff. According to Van der Gun and Ahmed (1995), in condition such as those in Yemen, many factors influence runoff, such as catchment size and shape, rainfall, evaporation and evapotranspiration, terrain characteristics (slope, presence and characteristics of soil, rock outcrops), the groundwater system, land cover and land use (agriculture terracing, dams, spate irrigation systems and any other human intervention). In our study, the low runoff (surface water inflow) reaching the midstream area was a clear consequence of human activity upstream. Other factors that affected runoff were relatively constant in our study, as our analysis of rainfall and runoff considered just one area over time. That is why a slight decrease in the runoff coefficient was observed, despite the increase in rainfall. A study by Grum et al. (2017) found a decreased runoff coefficient for the Gule catchment and Misbar sub-catchment, in northern Ethiopia, due to the building of water harvesting techniques. The average, per event, reduction in runoff was estimated as 41% and 45% respectively. According to Bahamish (2004), construction of these concrete structures and changes in agricultural practices have contributed to a violation of the traditional spate water distribution rules, with these changes the rules no longer able to achieve fair spate water distribution. Here, human interventions were responsible for the reduction in runoff reaching downstream areas. Similar trends were observed in a study of the Zhuoshui River in Taiwan, in which Tsai et al. (2016) found that weir operations substantially affected water resources. Increased weir discharge resulted in increased groundwater levels, by about 0.1 m annually.

Our results suggest a strong link between groundwater depletion and political decisions related to water and agricultural resources. Thus, human factors were evident, not only through the practices and activities observed within the study area but also in the government policies and political decisions that acted as an engine and catalyst (drivers) for them. The timeline demonstrates that the increased area devoted to agriculture was propelled on the supply side both by the increased water availability (from wells and dams) and by political decisions related to water and agriculture. In other words, political decisions had the unintended effect of groundwater depletion. Examples of impactful decisions are the establishment of a subsidy on diesel fuel starting in 1970, facilitation of public and private investment in well drilling and import of related equipment, creation of a bank in 1975 to provide credit for agricultural activities, construction of dams after 1979 and the banning of fruit imports from 1984 to 1995. These political decisions boosted agricultural activities, hence improving farmers' incomes and creating local job opportunities (e.g., for exporters of agricultural products). However, they had negative impacts on water resources. Particularly, many farmers switched from food security crops with a low irrigation requirements to cash crops with high irrigation requirements. The leap in the number of operational wells, from 1,221 to 4,250, and expansion of agricultural lands, from 152 km² to 283 km², between 1984 and 2009, occurred after the 1984 enactment of the ban on fruit imports.

Hellegers et al. (2008) and Al-Washali et al. (2015) attributed the large increase in groundwater pumping rates for cash crop irrigation to government policy, particularly subsidies on diesel fuel. Policies and legislation acted as an incentive for agricultural expansion, reducing the cost of agricultural inputs and increasing the price of agricultural outputs. Numerous studies make similar observations on this theme. Hellegers et al. (2008) and World Bank (2010) recommended reorienting economic and other incentives towards reducing water demand. In addition, policies and regulations are needed to stem the depletion of groundwater resources. The current availability of water resources, paired with the incentives mentioned above, encourages farmers to switch more fruit crops (Hellegers, Perry, and Al-Aulaqi 2011). This study found a slight contraction of cultivated land area, by 4%, from 2009 to 2014, likely associated with the diesel crisis as a result of the unstable political situation after 2011. According to Al-Weshali et al. (2015), the instability after 2011 led to a fuel crisis and thus to substantially higher prices. This slightly eased the stress on groundwater, reducing depletion rates as well. But it has cased economic hardship and significant losses of income for farmers, affecting their food security and livelihoods (Al-Qubatee, Hellegers, and Ritzema 2019).

3.6 Conclusion

This study demonstrates the value of a research approach combining both natural and human-induced drivers of groundwater depletion. Extending earlier research, most of which investigated partial drivers of groundwater depletion, the integrative framework adopted here provided a clear picture of the contributions of the different drivers to the observed drop in groundwater table. This study indicates the crucial role that policy measures played in triggering changes in human activities and thus in water use. These results demonstrate the considerable environmental impact of policy measures affecting water use. These impacts to be factored into future planning decisions.

The current study, based on 40 years of rainfall and runoff data, found that rainfall was not a driver of groundwater depletion in Wadi Zabid. While there was a slight increase in rainfall, this was accompanied by a reduction of surface water flowing from the uplands to the midstream area of the wadi over time. This was attributed to the expansion of agricultural land and construction of water harvesting structures. Land use maps of the study region indicate that agricultural land cover increased from 104 km² in 1972 to 283 km² in 2009. That expansion was associated with a leap in the number of operational wells, from 263 to 4,250 over this period. Groundwater abstraction also grew, from 47.5 Mm³ (Tesco-Viziterv-Vituki as cited in Tipton and Kalambach 1980) to 444.2 Mm³ (NWRA 2008). Five weirs were constructed midstream in 1979 to divert water for irrigation. Followed by construction of more than 22 water harvesting structures (dams) farther upstream (Personal communication, A.A. Almhab, Ministry of Agriculture and Irrigation, 25 January 2015). Based on these findings we can conclude that human-induced factors -rather than a lack of rainfall - are the main drivers of groundwater depletion in Wadi Zabid.

A clear link was also found between the introduction of policy measures to boost agricultural activities and changes in agricultural activities, irrigation infrastructure and groundwater abstraction over time.

Policy measures related to water and agriculture succeeded in increasing agricultural lands and hence increased farmers' incomes. But this came at the expense of groundwater resources. Groundwater levels fell by an average of almost 50 m between 1972 to 2016 across the Wadi Zabid. Agricultural lands contracted slightly, by 4%, between 2009 and 2014, likely because of the diesel crisis as result of the unstable political situation after 2011.

As a recommendation, policies and decisions on economic incentives could be oriented to support reallocation of water for less consumption uses. The role of policy is particularly great in the coastal regions, which are especially vulnerable to seawater intrusion. In such regions, encouraging alternative, less water-consuming income sources is preferable to encouraging cash crop production as a livelihood strategy. The same is true for the midstream and upstream areas, in order to increase runoff and groundwater recharge for the wadi as a whole. Though cash crops may offer higher incomes in the short term, they are detrimental to sustainable livelihoods and food security, due to their greater water consumption. In addition, better management of water in the existing harvesting and diversion structures is needed, alongside greater emphasis on policies that could help to slow the current rapid groundwater depletion rates, such as improved wastewater treatment infrastructure and seawater desalination plants. Moreover water laws could be implemented to regulate well drilling and abstraction rates. With this in mind, estimation of the economic value of water would be a valuable next research step, to suggest better allocations of scarce water resources, particularly, high value activities with less water requirements.

Geolocation information

Wadi Zabid is one of the catchments of the Tihama coastal plain. The wadi originates in the western highlands of Ibb and Dhamar governorates, passes through the highlands of the Jabal Ras directorate and continues through Al-Jarrahi, Zabid and Al-Tuhita directorates, discharging into the Red Sea in heavy rainfall years. This study covered the plains area of the wadi, divided into a midstream, downstream and coastal zone (about 46 km by 20 km altogether). The centre of the study region has the coordinates 317,122UTM-E and 1,564,732UTM-N.

Acknowledgments

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Appendix 3.1

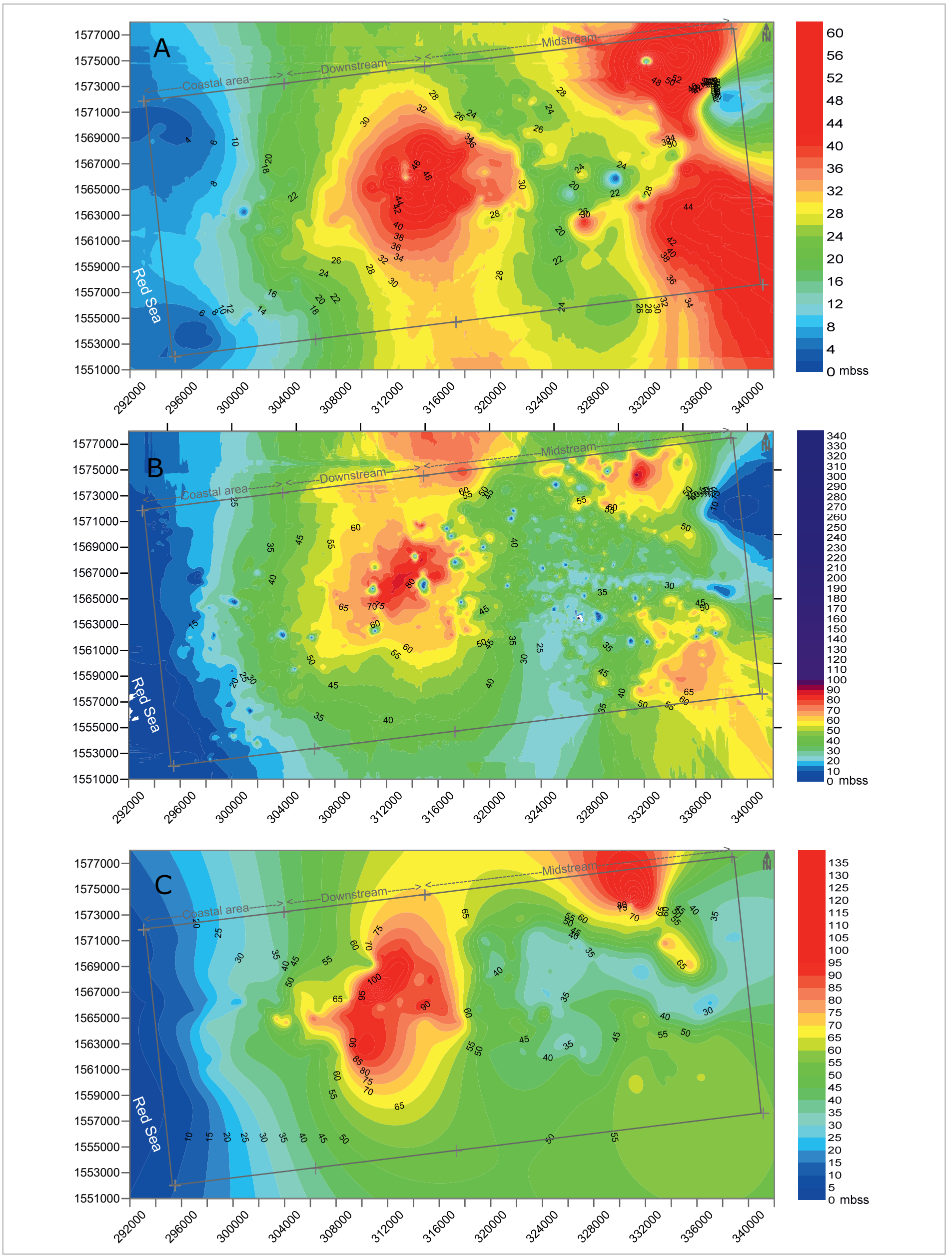

Figure A3.1 Groundwater level contour maps for the midstream, downstream and coastal areas of Wadi Zabid, obtained by kriging interpolation method: (A) in 1987, based on the well inventory by DHV (1988); (B) in 2008, based on the well inventory by NWRA (2008); and (C) in 2016, based on the field survey data of Al-Qubatee (2016).

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CHAPTER 4

The Economic Value of Irrigation Water in Wadi Zabid, Tihama Plain, Yemen

Abstract

This study used crop budgets to assess the impact of declining groundwater levels on the economic value of irrigation water in the Wadi Zabid region of Yemen. The study found that returns to land and water were highly sensitive to changes in groundwater depths over time and the free availability of spate water for irrigation. Crops differed in the amounts of irrigation water applied and in their returns to land and water. Banana had the highest irrigation requirement, but also delivered the highest return to land. Banana's return to water was greater than that of date palm and feed sorghum, but lower than that of mango and food sorghum.

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4.1 Introduction

Agricultural irrigation is the world's largest consumer of freshwater across all economic sectors, accounting for 90% of freshwater utilized globally (Siebert et al., 2010). However, irrigation efficiencies are low. In large open-canal irrigation systems, some 70% of irrigation water does not reach the intended crop (Tesfai & Stroosnijder, 2001; Hellegers et al., 2008). Nonetheless, to achieve water and food security goals in a sustainable manner, water use has to be better optimized. Moreover, to advance sustainable agriculture, approaches are needed that integrate environmental, economic, and social justice concerns (Smith & McDonald, 1998; see also http://asi.ucdavis.edu). One such approach is integrated water resources management (IWRM). IWRM is a process by which water is allocated between different uses and users in a coordinated, balanced manner (Korsgaard et al., 2008).

According to the World Bank (2015), Yemen's freshwater resources are among the lowest per capita in the world. In addition to limited freshwater supplies, the country has a growing population. Water scarcity has been further exacerbated by government policies aimed at boosting the agricultural sector, such as low-interest loans and cheap, subsidized diesel fuel. In addition, the government's institutional capacity to implement water laws has remained weak (Ward, 2001). Due to this combination of factors, Yemeni farmers have become increasingly dependent on groundwater for irrigation.

Since 1970, Yemeni lands irrigated from wells expanded 10-fold, from 40,000 ha to 400,000 ha in 2008, and the number of wells rose from just a few thousand to 50,000 over the same period (Hellegers et al., 2008). In addition, the number of harvesting and diversion structures has increased in upstream areas, which has led to reduced surface flows, dried-up wells, and water being lost from dam reservoirs through evaporation (Al-Qubatee, 2009). As a result, groundwater levels have rapidly dropped. In some cities, such as Sana'a, wells more than 1000 m in depth are sometimes needed to access the water required (Alderwish, Al-Khirbash & Mushied, 2014).

Agriculture is Yemen's third largest economic sector, after services and industry (including oil). It contributes some 20% of the country's gross domestic product (GDP), although the sector's importance is greater than its sheer size, as agriculture provides food and income for a large segment of Yemenis, especially rural populations (World Bank, 2015). Agriculture is also the country's largest user of freshwater, accounting for 93% of freshwater consumption on an annual basis. This substantial utilization of water for agriculture raises the question of whether water is being allocated to its highest value uses and if farmers are stimulated to use water efficiently. In other words, is water being utilized in such a way as to accrue the greatest benefits to society?

Conceptually, a better understanding of the economic value of water is important to support policymaking for the development, conservation, and allocation of water across places, uses, users, and time periods (Ward & Michelsen, 2002). Indeed, water allocation decisions are particularly key in areas where water is scarce and there is growing demand and competition for access to water (Hellegers & Leflaive, 2015). More efficient allocation of water to those crops that can generate the greatest value for society, and the economy can help optimize basin management as well (Al-Karablieh et al., 2012). Estimating the value of irrigation water serves not only to guide allocations of water between different crops, it can also guide the allocation of water to different production and/or irrigation techniques within a single crop type. Calculations of the economic value of irrigation water are useful both in regions with and without abundant water resources, as such calculations enable comparisons of farming profitability between regions with scarce water resources or where only rain-fed agriculture is possible versus where irrigation water is abundant. This provides an indication of the economic effect of increased irrigation (Yedra, Mesa-Jurado, López-Morales, & Castillo, 2016).

The current study sought to estimate the economic value of water for irrigation of a set of dominant crops. The aim of the study is to support water resource management and improve water allocation efficiency (Speelman et al., 2008; Hellegers, 2006). A measure of the value of water in alternative uses can substantiate policy decisions related to the development, allocation, and use of water resources (Ward & Michelsen, 2002). In a market system, water's value is represented by its price, with the price steering allocations to those uses that offer the greatest economic returns (Ward & Michelsen, 2002).

This paper argues that changing groundwater levels and the freely available spate water for irrigation in the Wadi Zabid region of Yemen are propelling changes in the production value of water and hence changes in cropping patterns. Specifically, the sensitivity of the value of water to the increased depth of groundwater pumping is investigated in the midstream, downstream, and coastal areas of the study region. To that end, we posed three research questions: (1) What is the cost of pumping one unit of groundwater from different depths? (2) What is the economic value of water in terms of the production of major agricultural crops? (3) What impacts have declining groundwater levels had on the value of water for particular crops and hence on cropping patterns?

This is very novel research, as it clarifies the impact of spate water availability and groundwater extraction from different (declining aquifer) depths on economic returns to land and water for different crops, both now and in the future. Part of this study's novelty and importance lies in the location of the study area, as Wadi Zabid, Tihama Plain, Yemen, is not a data-rich environment.

Combining the various elements to demonstrate that returns to land and water are highly sensitive to changes in groundwater depths over time, and the availability of spate water for irrigation is an important advancement of current work in this field.

Study Region

The current study focused on the Wadi Zabid region of Yemen. The wadi is one of the catchments of the Tihama coastal plain. The plain is considered one of Yemen's most fertile areas. Agriculture here provides for a large part of Yemen's food needs from cereals, vegetables, and fruits. The area is also characterized by good groundwater aquifers, which are recharged during the rainy season. The wadi originates in the western highlands of Ibb and Dhamar governorates, passes through the highlands of the Jabal Ras directorate, and continues through Al-Jarrahi, Zabid, and Al-Tuhita directorates, discharging into the Red Sea in heavy rainfall years. This study covered the plains area of the wadi, which is divided into a midstream, downstream, and coastal area (about 46 km by 20 km altogether). The center of the study region has the coordinates 317,122UTM-E and 1,564,732UTM-N (Figure 4.1).

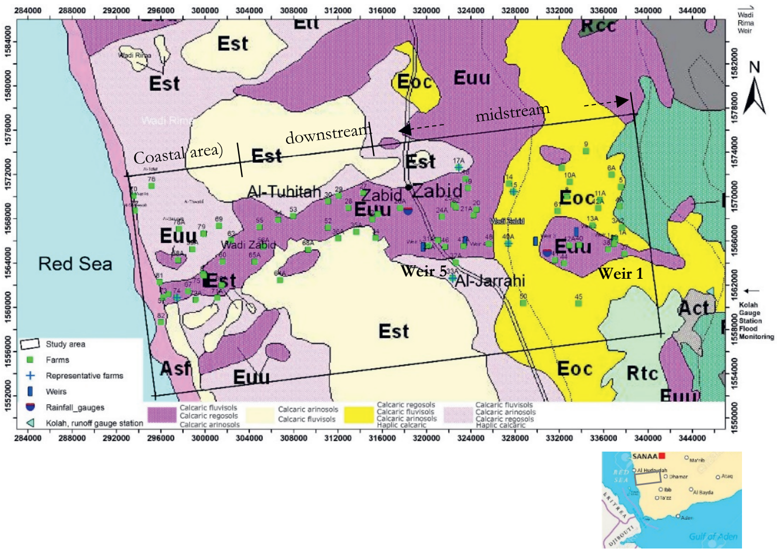

Figure 4.1. Soil map of Wadi Zabid map showing the division study area, the farms that were randomly selected for farmer interviews, and the representative farms chosen to calculate the economic value of irrigation water. Source: extracted from national soil map of Yemen sheet D38A, 1:500,000 (Agricultural Research and Extension Authority 2006).

In the study region, agricultural land use increased from 10,509 ha in 1972 to 27,786 ha, in 2014, according to remote sensing image analysis (Al-Qubatee, Al Hasan, Ritzma, Nasher, & Hellegers, submitted). The population was 312,408 at the time of the latest census, which was 2004 (Central Statistical Organization, 2005). Using a yearly population growth rate of 2% to 3%, the population can be estimated as 430,514 in 2016 (see https://www.worldometers.info).

Residents of the region depend mainly on agriculture for their livelihoods, in addition to raising livestock and fishing. Rainfall on the Tihama plain is very scarce, ranging from 100 mm per year along the coast to about 350 mm midstream in the wadi (near the foothills). Groundwater is the primary source of irrigation water, although spate flows are available in some parts of the wadi. Rules established under Sheikh Al-Jabarti more than 600 years ago gave the upper riparian area first priority for spate water use. Spate waters are divided among three groups in the midstream area of the wadi, with no water rights reserved for the downstream and coastal areas.

Wadi Zabid is known for its variety of crops, including vegetables (e.g., onions, tomatoes, okra, legumes, zucchini, hot pepper, and mulukhiyah), fruits (e.g., banana, mango, date palm, watermelon, cantaloupe, guava, papaya, and citrus), and cereals (sorghum, millet, maize, and sesame), in addition to fodder crops and crops such as cotton, *Jasminum sambac*, and henna.

The number of wells in the study region has increased significantly over time, from 859 in 1975 with abstraction rates of 81.7 Mm^3/yr (Tipton & Kalambach, 1980) to 7802 in 2008, with abstraction rates of 444.2 Mm^3/yr (NWRA, 2008).

4.2 Materials and Methods

4.2.1 Methods

The residual value method was applied to estimate the economic value of water, based on crop budgets at the farm gate. This method, a deductive approach, is the most commonly used technique for water valuation (Davidson, Hellegers & Samad, 2009). Young and Loomis (2014) presented extensive information on methods for calculating the economic value of water.

Nevertheless, the current study derived the value of water based on crop budgets (as in the Appendix 4.1), which were represented by the net profit from crop production divided by the quantity of irrigation water applied. The net profit is the total revenue earned from a crop minus the total (variable) costs incurred for its production, including the cost of irrigation (Hellegers & Roerink, 2006; Roerink & Zhovtonog, 2005).

The economic value of groundwater in irrigated agriculture was estimated separately for the midstream, downstream, and coastal areas of the study region. This enabled us to understand and compare the impact of declining groundwater levels on the profitability of crops in the various areas, due to the increased cost of pumping from greater depths.

4.2.2 Data Collection

A field survey was carried out in mid-2016 by two teams of four multidisciplinary researchers. The first team conducted questionnaire-guided interviews and discussions with farmers. The second team carried out an investigation of well water levels (measured by electronic gauge) and well yields (estimated by a hydrogeologist in the region). Changes in well depths and spate water availability were observed across the wadi. Seventy-nine farms in the midstream, downstream, and coastal areas were randomly selected to conduct the farmer interviews (Figure 4.1). We expected to find differences between farms in the quantities of agricultural inputs used and outputs produced. So, the plan for the field survey was to examine in detail changes in crop budgets on each farm—that is, the sum total of the inputs used subtracted from the earnings from the crops produced on that single farm. These results would enable us to estimate the sensitivity of returns to land and water to changes in the groundwater pumping depth.

Unfortunately, during the survey, we faced various obstacles in collecting the required data. The hard daily life circumstances experienced by the farmers at the time of the field survey in mid-2016 affected their responses during the interviews. Indeed, farmers were confronted with numerous hardships associated with the unstable political situation in the country at the time. Moreover, post-harvest losses in the study area are high; this was especially due to the high temperatures, which can reach 40º C, and the farmers' lack of cold storage facilities.

Illiteracy was another obstacle. Half of our farmer respondents were illiterate (Figure 4.2a). Therefore, many were not accustomed to precisely calculating inputs and outputs. Furthermore, the majority of the region's farmers were smallholders. Some 56% of farms occupied 3.6 ha or less (Figure 4.2b). This raised another hurdle, as some of these smallholders were discreet about sharing privileged information about the specifics of their farming operation, considering this information a trade secret. Although farmers were reluctant to talk, we were able to convince them to talk by explaining that the results can later be used to improve agricultural practices in the region. However, not all farmers gave complete answers to all the questions. They elaborated more in regard to the costs of production and costs of pumping, but gave incomplete answers regarding production and revenues.

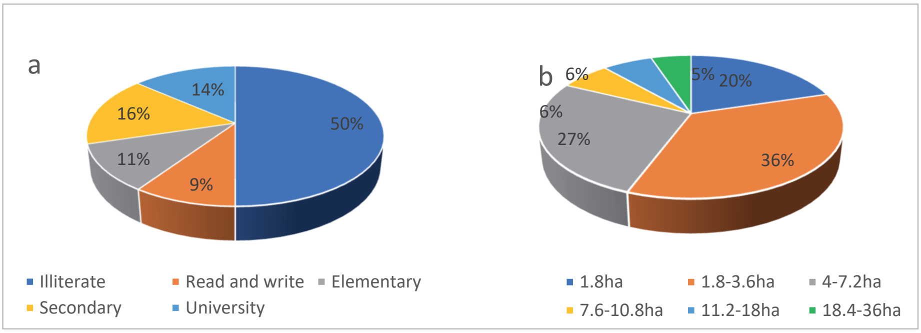

Figure 4.2 Characteristics of field survey respondents and farms in Wadi Zabid: (**a**) educational level, (**b**) farm size.

Some of these obstacles were alluded to previously by Hellegers and Perry Hellegers and Perry (2004: 33) (p. 33):

It is important to note that such returns are difficult to compute precisely in the absence of a major modelling exercise. First, the precise technical coefficients (yield/ha, water use, etc.) will vary across farms and by year. Second, some inputs are difficult to capture accurately because they are not monetized (like family labor), or may be subject to distortions due to taxes or subsidies.

To overcome the limitations of the collected data, crops were chosen in the study region for which complete data were available from representative farms, omitting farms for which exaggerated values were collected (very high and very low figures). Out of the 79 farms from which data were collected, five representative farms were selected for calculation of the crop's budgets and the return to land and water. Data from 50 farms of the 79 farms were used to calculate the cost of diesel to pump one cubic meter of groundwater from various depths. Nonetheless, many of the farmers interviewed were unable to specify crop production values in terms of quantity (kg) and price (US$ per kg), as they had sold the product in a different way, such as per tree, basket, carton, or bundle. Information related to weight (kg) could be gathered from a few farms (six farms out of 79 farms) and from two key informants. Thus, we calculated estimates based on the data that were provided. For example, banana production was estimated by multiplying the number of cartons produced per hectare according to the farmers by the average weight per carton. Other crop production figures were similarly obtained.

4.2.3 The Cost of Pumping One Unit of Groundwater

We calculated the cost of diesel to pump one cubic meter of groundwater from various depths based on data collected in mid-2016. From the results of the questionnaires and discussions with farmers, from 50 of the 79 farms, we first calculated the cost of groundwater pumping per hour (US$/hr) from a certain depth at each farm. This was done using the farmers' responses in regarding (i) pumping depths (the number of pipes installed in the well and the length of each pipe), (ii) the number of operating hours obtained using 20 liters of diesel (this is one drum, which represents a unit of volume for diesel in Yemen), and (iii) the price of per drum of diesel. After that, the cost of pumping one cubic meter of groundwater (US$/$m^3$) from a certain depth on each farm was calculated based on the cost of groundwater pumping per hour (US$/hr) at that depth and well yield (m^3/hr).

4.2.4 To Calculate the Returns to Land and Water

As the study region spans a relatively small, 46 km by 20 km area, crop budgets were assumed to be similar; that is, farm-to-farm differences in inputs for and earnings from particular crops were taken to be minimal. A more significant difference was the depths from which groundwater had to be pumped for irrigation and the availability of spate water, according to farms' location in the midstream, downstream, or coastal area. The average pumping depths for midstream, downstream, and coastal areas were obtained from the contour map of pumping depths. The map was drawn using the kriging interpolation method based on well information from the field visit, groundwater-level measurements, and the drilling depth of 248 wells, alongside well information obtained from farmers. Spate water availability was also known, which was determined by a field visit and descriptions of water distribution rules and spate water rights from the literature, as found in Tipton and Kalmbach (1974) and IIP (2005).

Spate water availability was determined as follows: (i) traditional rules dictate that only the three groups in the midstream (around the constructed weirs) had spate water rights, so the farmers downstream and in the coastal area had no spate water rights; (ii) the number of days that spate water was available annually (days/yr) was known; (iii) discussions with farmers indicated that they did not use groundwater for irrigation during the periods in which spate water was available.

4.2.5 The Effect of Increased Groundwater Pumping Depth on the Economic Value of Water

An Excel spreadsheet was used to build an economic model for investigating the impact of changes in groundwater pumping depths (mbss) on net returns to land (US $/ha) and the value of water (US $/m^3). As noted, to calculate the value of water, we subtracted the cost of all production inputs (including the cost of irrigation) from the total income from production and divided the result by the total volume of water applied. This represents the net profit gained by farmers from each unit of water applied.

4.3 Results

4.3.1 Pumping Costs

Figure 4.3 depicts the relation between the dependent variable (diesel consumption) and the independent variable (pumping depth) using different functions: (1) a linear function, (2) a power function, and (3) an exponential function. We see that the cost of pumping increases rapidly with increasing depth. This is best expressed using the exponential function as follows:

$$Y = 0.0495e^{0.0163X} \qquad R^2 = 0.5856 \qquad e = 2.71828183$$

where Y is the cost of pumping one unit of groundwater in US \$/m^3 and X is the groundwater pumping depth (mbss).

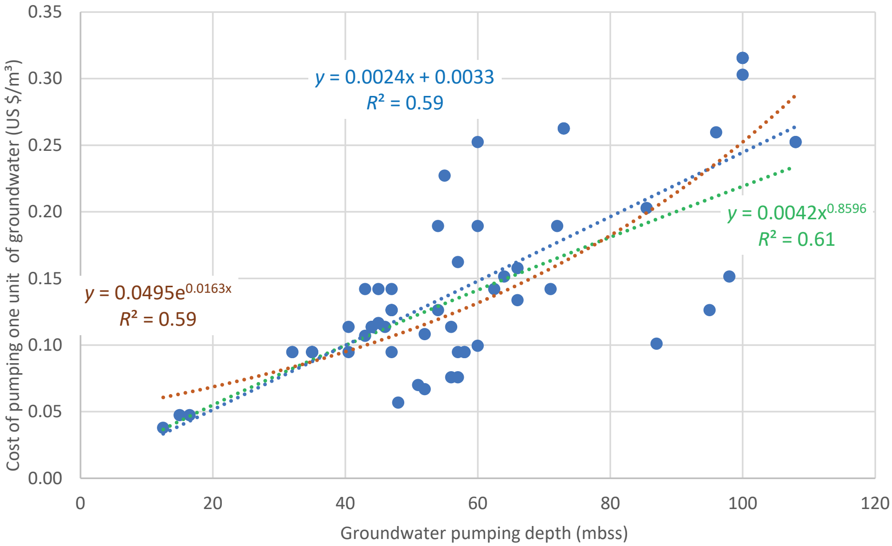

Figure 4.3 Cost of diesel to pump one unit of groundwater from different depths (US \$/m^3), 2015/2016.

The R squared of 0.59 is within the 0–1 range (1 being a perfect explanation). Capital costs (or fixed costs), such as well drilling and the purchase of a pump and engine, are not included. In addition, maintenance materials costs are not included. These additional costs are assumed to be low and without major fluctuations across the farms, as they are located within relatively small areas of the study region.

Table 4.1 presents the differences found in (i) depth of groundwater pumping levels and (ii) spate water availability across the study region. The difference in the groundwater (pumping) levels across the study region resulted in differences in the cost of pumping one unit of groundwater. These differences were especially marked in the downstream area compared to the midstream and coastal areas. Pumping costs downstream were double those in the midstream and coastal areas, namely, US $0.23/m^3 versus $0.12/m^3 and $0.10/m^3, respectively. A future scenario in which groundwater depths increase further would lead to a proportional increase in the cost of pumping one unit of groundwater, as shown in Figure 4.3 (exponential function), Figure 4.4A–C, and Figure 4.5A–C.

Table 4.1 Average pumping depth of groundwater and spate water availability in three areas of the Wadi Zabid region, 2016.

	Midstream	**Downstream**	**Coast**
Depth of groundwater pumping (mbss) *	55	95	40
Spate water availability (%) #	40	0	0

* Depth according to measuring well water levels from a survey done in mid-2016 for the purpose of this study. # As a percentage of the total irrigation water applied on an annual basis. Spate water was distributed according to Sheikh Al-Jabarti rules between three groups located in the midstream. Recently, many violations of these rules have been observed, with some asserting that the rule is socially unjust. For details, see Tipton and Kalambach (1974), Bahamish (2004), IIP (2005) and Al-Qubatee et al. (2015).

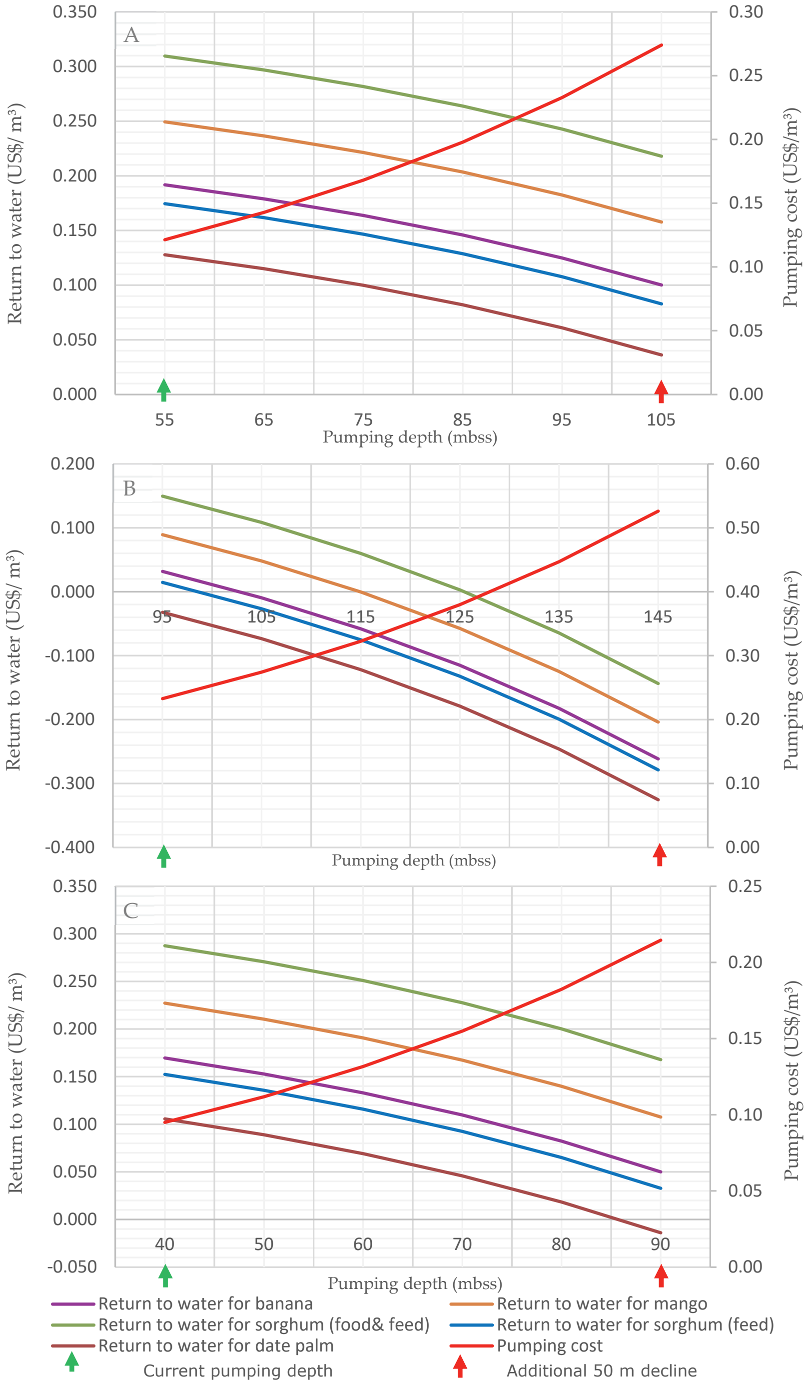

Figure 4.4 Economic returns to water in the midstream (**A**), downstream (**B**), and coastal areas (**C**) of Wadi Zabid using groundwater pumping depths in 2016 compared to a future scenario with an up to 50-m increase in groundwater pumping depths.

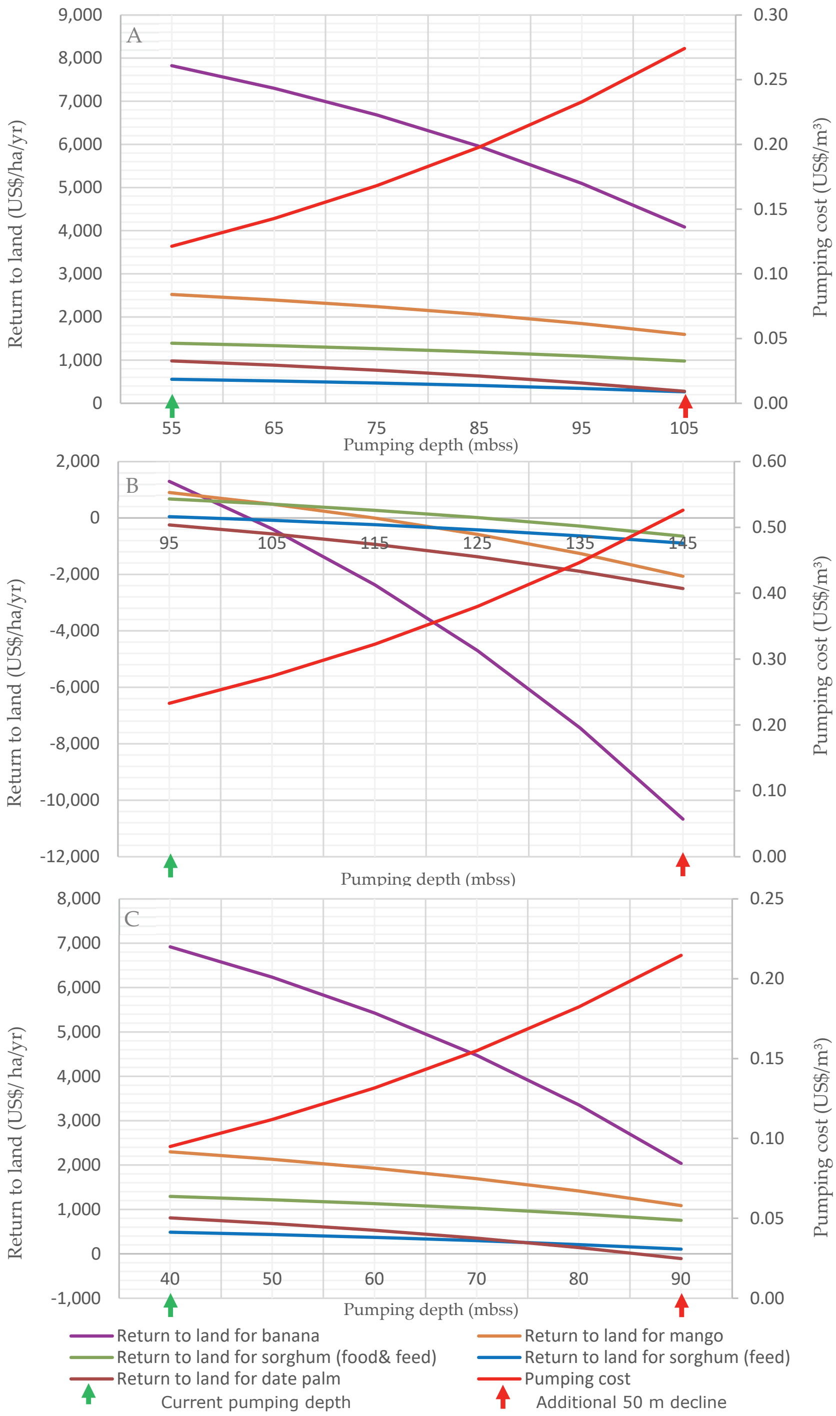

Figure 4.5 Economic returns to land in the midstream (**A**), downstream (**B**), and coastal areas (**C**) of Wadi Zabid using groundwater pumping depths in 2016 compared to a future scenario with an up to 50-m increase in groundwater pumping depths.

4.3.2 Returns to Land and Water

Table 4.1 shows the pumping depths for wells in the study region. Average spate water availability is known from the field survey and literature describing local water distribution rules and spate water rights (Tipton and Kalmbach, 1974; IIP, 2005). On average, freely available spate water makes up 40% of the total water applied for irrigation in the midstream area of the wadi, while the downstream and coastal areas had no spate water rights.

The crop budget analyses indicate that irrigation water was the most expensive crop input, which was mainly due to the high cost of the diesel fuel needed for groundwater pumping (Table 4.2). This was true for all crops and all areas studied, except for sorghum in the midstream area of the wadi and in the coastal area, where the cost of irrigation ranked second after the cost of land preparation and labor. Irrigation was the most costly input in the downstream area of the wadi, as the depth of groundwater pumping was greatest here, averaging 95 mbss.

In the downstream area, annual irrigation pumping costs varied from US $745/ha for date palm to US $9501/ha for banana. The lowest irrigation pumping costs were found in the midstream area, varying annually between US $233/ha for date palm to US $2970/ha for banana. The volumes of water applied annually for irrigation varied between 3200 m^3/ha for sorghum and 40,800 m^3/ha for banana.

Table 4.2 Crop budgets in three areas of the Wadi Zabid region, with calculated returns to land and water and total amounts of irrigation applied, 2016.

			Banana	Mango	Date Palm	Sorghum (Food)	Sorghum (Feed)
Cost of production (US$/ ha/yr)	Seeds or saplings *		69			78	39
	Land preparation and labor		1038	632	600	857	519
	Fertilizer		195	70	0	156	208
	Pesticides		363	137	130	0	0
	Cost of irrigation pumping **	Midstream (40% spate water)	2970	737	559	328	233
		Downstream (0% spate water)	9501	2357	1788	1048	745
		Coastal area (0% spate)	3876	961	730	428	304
	Total input costs	Midstream	4635	1575	1289	1419	999
		Downstream	11,166	3195	2519	2139	1511
		Coastal area	5541	1800	1460	1519	1070
Value of production	Product (tons/ha/yr)		33.33	8	13.33	3.70	0
	Price (US$/kg)		0.37	0.51	0.17	0.58	0
	By-product (US$/ha/yr)		0	0	0	649	1558
	Total returns (US$/ha/yr)		12,461	4099	2272	2812	1558
	Net returns or returns to land (US$/ha/yr)	Midstream	7826	2524	982	1394	559
		Downstream	1295	904	−247	673	47
		Coastal area	6920	2299	812	1294	488
	Total irrigation applied (m^3/ha/yr)		40,800	10,119	7680	4500	3200
	Returns to water (US$/$m^3$)	Midstream	0.19	0.25	0.13	0.31	0.17
		Downstream	0.03	0.09	−0.03	0.15	0.01
		Coastal area	0.17	0.23	0.11	0.29	0.15

* Date palm and mango saplings were not included as their life span is very long, some 100 years and 40 years, respectively. ** The average groundwater pumping depths in the midstream, downstream, and coastal areas were 55, 95, and 40 mbss, respectively.

Table 4.3 compares these quantities to the amounts of irrigation water applied in other regions and worldwide. These quantities span a considerable range, which is linked to the different agriculture practices and irrigation methods used. We see that the amounts of irrigation water applied for banana cultivation in Wadi Zabid (Yemen) and Wad Madani (Sudan) are high compared to the other regions. A reason could be that both use basin irrigation, which is supplemented by freely available spate water (in Wadi Zabid) and shallow groundwater (near the Nile River in Wad Madani).

Table 4.3 Amounts of irrigation water applied (m^3/ha) for the dominant crops in Wadi Zabid (2016), and in other places and worldwide.

Place	Banana	Mango	Sorghum (Feed and Food)	Date Palm
Wadi Zabid [1]	29,000–70,000 *	4000–27,000	500–5000	4000–25,000
Taiz [2]	16,800	18,800	6700	NA
Hadramout [2]	27,037	26,339	NA	1000
Wad Madani/Shendi [1]	60,000	7000–18,000	5000	5000–7000
Worldwide	12,000–22,000 [4]	11,200–17,000 [5]	4500–6500 [4]	15,000–35,000 [3]

Notes: NA: not available. * For 12 to 18 crops per year. Sources: 1. Field surveys conducted for this study in Yemen in mid-2016 and in Sudan in mid-2018; date palm is only in Shendi. 2. Hellegers et al. (2008). 3. In Algeria Abdelouahhab and Arias-Jiménez 1999. 4. Brouwer and Heibloem (1986). 5. Johnson and Parr (2000).

For all crops, the highest returns to land and water were registered in the midstream area of the wadi followed by the coastal area (Table 4.2, Figures 4.4A–C and 4.5A–C). In contrast, the lowest returns were found in the downstream area of the wadi.

Over the entire study region, the crops providing the highest returns to water were as follows: sorghum (food), mango, banana, sorghum (feed), and date palm. For these same crops, returns to water in the midstream area were, respectively, US \$0.31/m^3, \$0.25/m^3, \$0.19/m^3, \$0.17/m^3, and \$0.13/m^3. In the coastal area, returns to water were slightly lower (\$0.02/m^3) than in the midstream area, but the lowest returns to water were found in the downstream area. For the same crops as mentioned above, the returns to water in the downstream area were US \$0.15/m^3, \$0.09/m^3, \$0.03/m^3, \$0.01/m^3 and \$–0.03/m^3, respectively (Table 4.2 and Figure 4.4A–C). Date palm was unprofitable, representing a loss to the farmers in downstream area of the wadi.

Crop rankings according to their returns to land were different. Ordered from the highest to lowest returns, the crops ranked as follows: banana, mango, sorghum (food), date palm, and sorghum (feed) across most of the study region. The only exception was in the downstream area, where sorghum (feed) ranked higher than date palm. In the midstream area, the annual returns to land were US $7826/ha, $2524/ha, $1394/ha, $982/ha, and $559/ha, respectively, for the above-mentioned crops. In the coastal area, too, returns to land were relatively high, although a little less (by approximately 7% to 17%) than in the midstream area. Downstream, returns to land were lowest, being some 52% to 125% less than returns in the midstream area. As noted, farmers here faced losses in data palm cultivation (see Table 4.2 and Figure 4.5A–C). Our discussions with farmers indicated that the dominant crops in the midstream area were banana, mango, and sorghum, while in the downstream area they were mango, sorghum, and to a lesser extent date palm. In the coastal area, the dominant crops were date palm and sorghum. Groundwater in the coastal area was not particularly deep. However, banana and mango were rarely cultivated here due to the high salinity of some wells. Sorghum, which is a drought-resistant crop, was cultivated across the entire study region, as were vegetables. However, vegetable cultivation had decreased in recent years due to marketing difficulties resulting from the unstable political situation in the country. In addition, vegetables are particularly vulnerable to post-harvest losses (spoilage) when exposed to Tihama's high temperatures. As noted, cold storage facilities are largely absent, which is in part due to fuel shortages and electricity blackouts.

4.3.3 Sensitivity of Economic Returns to Land and Water to Falling Groundwater Levels

Increasing water scarcity is clearly apparent in the study region, and is observable in the continually falling groundwater level over the previous decades. Table 4.4 presents the water levels found in previous well inventories and the forecast for 2066. In the midstream, downstream, and coastal areas, groundwater level depths were, respectively, 20 mbss, 8 mbss, and 0.5 mbss in 1972. Recently, in mid-2016, average water levels were found to be at depths of 50 mbss, 90 mbss, and 35 mbss, respectively. Assuming continuation of the current trend over the coming five decades (to 2066), a serious groundwater level drawdown is to be expected. In Wadi Zabid, we foresee on average 50-mbss drop of the groundwater table over the next 50 years below the current levels.

The expected drop in groundwater levels will be reflected in higher pumping costs to use groundwater for irrigation. It will also impact returns to land and water, as shown in Table 4.5, Figure 4.4A–C, and Figure 4.5A–C. These effects will be felt throughout the region of study.

Table 4.4 Average groundwater depths in the study region of Wadi Zabid in previous decades and expected levels in 2066.

Year	Groundwater Levels in Wadi Zabid (mbss)		
	Midstream	Downstream	Coast
1972 [1]	20	8	0.5
1987 [2]	25	40	10
2008 [3]	30	75	18
2016 *	50	90	35
Predicted 2066	100	140	85

Sources: Data analysis in Al-Qubatee, et al. (submitted) based on 1. well inventory Tesco-Viziterv-Vituki, cited in Tipton and Kalambach (1980), 2. well inventory 1987 DHV (1988), and 3. well inventory NWRA (2008). * Based on a field survey measuring well water levels for the purpose of this study.

Midstream in the wadi. Returns to land and water show the lowest sensitivity to a drop in the groundwater level in the midstream area of the wadi compared to the other two areas. For the greatest groundwater pumping depth, returns to the dominant crops will be 30% to 72% less than the 2016 levels (Table 4.5).

Downstream in the wadi. The highest sensitivity was found in the downstream area, where a further drop in the groundwater level (assumed at 50 mbss in 50 years) would result in a 196% to 2013% reduction in returns to land and water, compared to returns in 2016. Thus, all crops would become economically unprofitable—that is, generating losses for farmers. Initially, sorghum (food) would continue to return some profit, until a 30-m drop in groundwater pumping depth is reached. Mango would also continue to be profitable, until a 10-m drop in the groundwater pumping depth is reached.

Coastal area. reductions in the economic returns to land and water here due to a further drop in the groundwater pumping depth were calculated as between 42% and 113% for the dominant crop. The date palm is very common in the coastal area due to its tolerance to salinity from other dominant crop.

The crops most vulnerable to continually falling groundwater levels—that is, those crops showing the greatest declines in returns to water across the entire study region—were ranked as follows: date palm, sorghum (feed), banana, mango, and sorghum (food) (Figure 4.4 and Table 4.5). Crops showing the greatest declines in returns to land (due to the groundwater level dropping by more than 30 m under current depths) in the midstream area of the wadi were sorghum (feed), date palm, sorghum (food), mango, and banana. For the coastal area, the ranking was similar, but with date palm coming first. In the downstream area, the crops ranked as follows from highest to lowest declines in returns to land: banana, date palm, mango, sorghum (feed), and sorghum (food) (Figure 4.5A–C and Table 4.5).

Table 4.5 Economic returns to land and water calculated for the midstream, downstream, and coastal areas of Wadi Zabid. In the current scenario, the average groundwater pumping depths are 55 mbss, 95 mbss, and 40 mbss, respectively. For the future scenario, a 50-m drop in groundwater depths was assumed, creating groundwater depths of 105 mbss, 145 mbss, and 70 mbss, respectively.

Crops	Returns to Land (US$/ha/yr)						Returns to Water (US$/m³)					
	Midstream		Downstream		Coast		Midstream		Downstream		Coast	
	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future	Current	Future
Banana	7826	4086	1295	−10,668	6920	2039	0.19	0.10	0.03	−0.26	0.17	0.05
Mango	2524	1597	904	−2063	2299	1089	0.25	0.16	0.09	−0.20	0.23	0.11
Sorghum (food)	1394	981	673	−646	1294	755	0.31	0.22	0.15	−0.14	0.29	0.17
Sorghum (feed)	559	266	47	−892	488	105	0.17	0.08	0.01	−0.28	0.15	0.03
Date palm	982	278	−247	−2499	812	−107	0.13	0.04	−0.03	−0.33	0.11	-0.01

4.4 Discussion

The cost of pumping one unit of groundwater differed across the study region due to differences in the groundwater level and thus in groundwater pumping depths. With increasing groundwater level depths, pumping costs will dramatically rise. Indeed, the cost of pumping represents a primary production cost for most crops in the study region. Our analysis found this cost to be of foremost significance in diminishing returns to land and water in the context of a falling groundwater table. The cost of pumping certainly plays a large role in determining cropping patterns in Wadi Zabid. Any incentive that reduces the cost of pumping—for example, an energy subsidy (e.g., for diesel fuel or solar panels) would dramatically increase returns to land and water. Furthermore, it could be expected to initiate a change in cropping patterns toward crops with higher water requirements. Hellegers, Perry, and Al-Aulaqi (2011) observed that direct incentives to farmers in the form of high diesel subsidies and support for more efficient irrigation techniques encourage groundwater abstraction rather than reducing irrigation demand. In contrast, raising the cost of inputs, such as energy, is an effective way to reduce demand for irrigation (Hellegers et al., 2008; He, Tyner & Siam, 2004). This is confirmed by the results of the current study, as the highest returns to land and water for the major crops were found in the midstream wadi area. The reason why is that farmers in the midstream area did not rely exclusively on groundwater for irrigation, but also had access to freely available spate water, unlike farmers in the downstream and coastal areas.

Midstream farmers would continue to make a profit from cultivating all crops, despite the expected increase in groundwater level depths. In contrast, downstream farmers were found to have the lowest economic returns to land and water, due to their total dependence on groundwater for irrigation. Moreover, in the downstream area, groundwater had to be pumped up from much greater depths: twice the depths in the midstream and coastal areas. Furthermore, no spate water reaches the downstream area.

In the downstream area, returns to land and water showed the highest sensitivity to and greatest impact of further drops in groundwater levels. In the coastal area, most crops would still continue to return some profit in the scenario of further drops in the groundwater level, except for date palm, which would become unprofitable if the current groundwater level dropped by more than 40 m. However, a further drop in groundwater levels in the coastal area would also lead to seawater intrusion. This would likely degrade water quality and risks rendering entire groundwater aquifers unfit for agriculture. Field surveys show that seawater upconing has already occurred on one date palm farm in Al-Fayza village, leading to the dying out of all the trees on the affected farm (Al-Qubatee et al., 2013; Al-Qubatee, Ritzema, Al-Weshali, Van Steenbergen & Hellegers, 2017).

Although sorghum was found to deliver the highest return to water, farmers in the midstream area of the wadi preferred banana, which also delivered a high return to water, although less than sorghum, and also delivered the highest return to land. While banana had the highest return to land, it also required application of the largest amounts of irrigation water of all the crops examined. Discussing the larger issue of the value of cash crops versus food security crops for developing countries, Achterbosch et al. (2014) indicated that as long as a balance is maintained, cash crops do have an important role in ensuring food security at both the micro and macro levels. That is because cash crops provide the income that households need to purchase other essentials required for their well-being and food security. However, these authors did note that the economic and environmental risks associated with cash crops should be guarded against and mitigated.

In regard to government incentives, Young and Loomis (2014) noted that some developing country governments have sought to keep the prices of agriculture products low in order to ensure low food prices for consumers. However, intentionally keeping prices of agriculture products low could disrupt the working of the market, diminishing the economic value of water. In fact, the current study found the opposite. Government incentives, particularly subsides on fuel, contributed to lower production costs (represented by the cost of the irrigation applied) below their costs at the global level (in a free market context). Thus, farmers earned more profit (i.e., returns to land and water were greater), and therefore, the economic value of water was higher in such cases than it would have been without such incentives. In fact, these policies encourage the expansion of agricultural lands and irrigation demand, rather than their reduction. In developed countries, production inputs such as fuel and labor are more expensive, and the prices of outputs are higher as a result.

The pumping depths were calculated based on the field measurements and information on the wells collected during the field survey and farmer interviews. The well yield data were verified by comparing them with figures from the nearest wells for which data were available from other studies in the region, the data of the well inventories of NWRA (2008) and DHV (1988). The average was found to be within the same range, between 6 l/s and 11 l/s. The availability of the spate water for the entire midstream region was assumed in this study to be equivalent to that of the group with the highest water rights, although other groups had less water rights. Moreover, even within the different water rights groups, there were differences between farms as stipulated by traditional spate water distribution rules. In fact, there is no recent, accurate map of spate water distribution in the midstream region. Thus, there is also a diminution in the returns to land and water for the farms in the midstream. The extent of that diminishment depends on the percentage of irrigation provided by spate water on the various farms. Among midstream farms with less spate water rights, the returns to land and water would be approximately equal to the returns of the farms in the coastal areas. This is because there were no substantial differences between the two areas in depths of groundwater pumping.

4.5 Conclusions

The current study found that due to differences in groundwater depths, the cost of pumping one unit of groundwater was different in the midstream, downstream, and coastal areas of the study region of Wadi Zabid. Groundwater levels were found to be especially deep in the downstream area of the wadi compared to the midstream and coastal areas. Pumping costs in the downstream area were double those in the midstream and coastal areas. The continuing fall of the groundwater level here will result in a rapidly increasing cost of pumping one unit of groundwater. The highest returns to land and water were found in the midstream area of the wadi, followed by the coastal area. Returns were lowest in the downstream area because of the greater groundwater pumping depths and lack of freely available spate water for supplementary irrigation.

Throughout the study region, crops ranked as follows, from highest to lowest returns to water: sorghum (food), mango, banana, sorghum (feed), and date palm. Regarding returns to land, the ranking was banana, mango, sorghum (food), date palm, and sorghum (feed), except in the downstream area, where sorghum (feed) came before date palm. The dominant crops in the midstream area were banana, mango, and sorghum. In the downstream area, they were mango, sorghum, and to a lesser extent, date palm. In the coastal area, the dominant crops were date palm and sorghum. Banana and mango were rarely cultivated in the coastal area because of the high salinity of some wells. Sorghum, which is a drought-resistant crop that requires the lowest quantities of irrigation water, was cultivated over the entire region.

A future scenario that assumes a continuing drop in groundwater levels would have significant impact on economic returns to land and water, particularly in the downstream area of the wadi. Here, all the cultivated crops would become economically unprofitable for farmers. A falling groundwater table would have the least effect on returns to land and water in the midstream area because of the more moderate pumping depths here, as well as the free availability of spate water. In the coastal area, although the immediate impact on economic returns would also be low, further falling groundwater levels would threaten aquifer quality due to the risk of seawater intrusion.

Regarding water reallocation, this study found sorghum (food) to provide the highest return to water but only a moderate return to land. Nonetheless, this crop has social benefit (food security), and requires less irrigation water application. Sorghum varieties for both food and feed are known to be drought-resistant crops (HWC 1992; Mahoo et al., 2007; Pistoia et al., 2010). To encourage the reallocation of water to crops with low water requirements, such as sorghum, government incentives would need to be oriented toward supporting the marketing of drought-resistant crops to assure profitable sale prices for farmers within the wadi. In addition, support for other less thirsty crops, such as peanuts and sesame, which can be cultivated with sorghum in mixed cropping, intercropping, and crop rotation systems, could enhance returns to land. Banana provides a moderate return to water and the highest return to land, but it also has a high annual requirement for irrigation water. Therefore, a groundwater balance study is recommended to further investigate the effect of banana farming on groundwater aquifers. Neighboring countries such as Saudi Arabia, according to Ouda (2014), have adopted agricultural policies oriented toward food self-sufficiency (e.g., stimulating production of wheat, vegetables, and fruit). Their encouragement and support of farmers has enabled them to achieve wheat self-sufficiency, with surpluses for export. However, those policies have also resulted in the depletion of scarce groundwater resources. Irrigation water demand increased almost threefold, from some 8 km^3 in 1980 to some 22.3 km^3 in 1994. The effect of excessive extraction of groundwater for irrigation is reflected in the decline in groundwater levels. In some aquifers, groundwater has declined by more than 200 meters in the past two decades (World Bank, 2005). It is worth mentioning here that the reduction of post-harvest losses is a promising strategy for increasing marketable output. Post-harvest losses of fruits and vegetables reach some 50% (Elik et al., 2019), and for cereal grains reach up to 60% (Kumar& Kalita, 2107). Agricultural extension offering farmers training and best practices for reducing these losses could be particularly important in regions such as the study area, where illiteracy is high and environmental conditions are harsh. Appropriate harvesting, handling, packaging, storage, and transportation can make important inroads in reducing produce losses. Indeed, preserving an existing crop constitutes a more economically and environmentally effective option than seeking to produce more agricultural produce in an area with such scarce water resources. Another policy that could be considered is e.g., the encouragement of fishing to reduce the stress on scarce water resources, especially in view of the study region's coastal proximity. Moreover, water and food production-related policies could be reoriented toward support for the marketing of agricultural products at profitable prices for farmers rather than economic incentives that do not considerably reduce water demand. As suggested by the region's farmers, any reallocation of water should consider the whole catchment of Wadi Zabid, including the upstream area, where cash crops are cultivated (Al-Qubatee et al., 2013).

Geolocation Information

Wadi Zabid is one of the catchments of the Tihama coastal plain. The wadi originates in the western highlands of Ibb and Dhamar governorates, passes through the highlands of the Jabal Ras directorate, and continues through Al-Jarrahi, Zabid, and Al-Tuhita directorates, discharging into the Red Sea in heavy rainfall years. This study covered the plains area of the wadi, which was divided into a midstream, downstream, and coastal zone (about 46 km by 20 km altogether). The center of the study region has the coordinates 317,122UTM-E and 1,564,732UTM-N.

Appendix 4.1

Crop budget formula used

Gross production value (US$/ha/yr) = yield × price.

Farmers often sold their products in different units than in kilograms, such as by maad (a locally used unit) or by number of trees, bundles, baskets, or cartons. These units were converted to conventional values where appropriate.

Costs of production * (US$/ha/yr) = seed or sapling cost + fertilizer cost + pesticide cost + land preparation and labor cost + irrigation water costs (all units in US$/ha/yr)

Cost of irrigation water (US$/ha/yr) = unit cost of pumping water (US$/$m^3$) from a particular depth (US$/$m^3$) × water quantity applied for irrigation (m^3/ha/yr)

Unit cost of pumping water (US$/$m^3$) = diesel consumed to pump one unit of groundwater (l/m^3) × cost of one liter of diesel (US$/l)

Net production value or net return to land (US$/ha/yr) = gross production value (US$/ha/yr) − costs of production (US$/ha/yr)

Value of water or net return to water# (US$/$m^3$) = net production value or net return to land (US$/ha/yr)/water quantity applied for irrigation (m^3/ha/yr)

* Not including fixed costs.

Including the cost of irrigation. The value of water (without including irrigation cost) = the value of water (including irrigation cost) + (unit cost of pumping water × percentage of groundwater applied for irrigation)

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CHAPTER 5

Present and Future Groundwater Depletion Rates in Wadi Zabid, Tihama Coastal Plain, Yemen

Abstract

This paper presents a simple water budget model that can be used to quantify present and to predict future groundwater depletion rates in areas where there is not enough data available to develop sophisticated numerical groundwater models that require a comprehensive set of long-term data. We applied the water budget model in Wadi Zabid, Yemen, a region where groundwater withdrawals have far exceeded replenishment rates for 50 years, resulting in falling groundwater levels. The results indicate that the present groundwater use in the wadi is unsustainable, mainly due to the expansion of agriculture lands. The current average groundwater depletion rate was calculated as -0.93 m/yr, which is in line with the observed average of -1.11 m/yr (1972-2016). An analysis of the expected changes in agricultural land area, surface water inflow, and increased rainfall due to climate change, showed that even marginal recovery of the groundwater system by 2060 will be impossible to achieve if local livelihoods continue to rely on agriculture. Reducing the groundwater depletion rate by two-third of the current rate would require a one-third reduction in agricultural lands in the study region, combined with a one-third increase in surface water inflow from upstream (necessitating a reduction of agriculture in the upstream region). Economic incentives to support alternative livelihoods with lower water requirements, alongside utilisation of non-conventional water sources (e.g. seawater desalination) can reduce the groundwater depletion. The simple water budget approach proved to be a useful approach to do this type of analysis in data-scarce regions.

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Al-Qubatee W, Van Lanen HAJ, Nasher G, Ritzema H, Hellegers PJGJ (will be re-submitted) Present and Future Groundwater Depletion Rates in Wadi Zabid, Tihama Coastal Plain, Yemen.

5.1 Introduction

Wadi Zabid is one of the most fertile areas of Tihama coastal plain in Yemen. Agricultural lands in Wadi Zabid expanded from 104 km^2 to 283 km^2 (172%) between December, 1972 and 2009 (Al-Qubatee et al. submitted), bringing increasing demand for irrigation water. The number of operational wells rose, from 263 in 1972 (Tesco-Viziterv-Vituki as cited in Tipton and Kalambach 1980) to 4,250 in 2008 (NWRA 2008). In that same period, five weirs were built in the midstream part of the wadi and 22 dams were constructed upstream to serve agricultural production (personal communication, A. A. Almhab, Ministry of Agriculture and Irrigation, 25 January 2015). These changes went hand in hand with weaknesses in water governance, particularly regulation, control and enforcement of water laws (World Bank 2015). The consequences of the rising number of wells in terms of groundwater depletion are clearly evident in Wadi Zabid. Groundwater levels dropped by an average of -1.11 m/yr from 1972 to 2016 (Al-Qubatee et al. submitted). This is more than twice the rate for Tihama plain as a whole. This has brought increased pumping costs, and consequently diminished net returns on land and water for the dominant crops, especially downstream (Al-Qubatee et al. 2019). Increased poverty related to diminishing returns to farming have led to greater migration away from the area (Al-Qubatee et al. 2017).

In undisturbed conditions, aquifer systems exhibit a dynamic equilibrium. Pumping groundwater from wells upsets the natural balance between recharge and discharge (e.g. Zhou 2009; Fetter 2014; Hiscock and Bense 2014). This leads to reduced natural discharge from the aquifer and depleted aquifer storage, typically observed in a falling water table.

Different approaches have been used to assess the impact of groundwater pumping on aquifer discharge, groundwater levels and the associated groundwater storage. Multi-aquifer, transient groundwater models are available that use spatially distributed weather data, groundwater pumping quantities, hydraulic parameters (e.g. transmissivity, hydraulic resistance) and stream-aquifer interaction (e.g. Anderson et al. 2015). These models combine the flow equation and the mass balance (water budget). In data-scarce regions, however, there is often not enough data to reliably simulate the groundwater system in this fashion (e.g. Spitz and Moreno 1996). The mass balance (or water budget) can be used to assess the groundwater state (Healy and Scanlon 2010), as a simpler alternative.

In the current study, we developed a simple water budget model to investigate groundwater depletion rates in Wadi Zabid, because data were not available for transient groundwater flow modelling. The overall objectives of this study were: (1) to quantify the present groundwater depletion rate in Wadi Zabid and (2) to assess the impact of a series of future changes in rainfall, land cover and surface water inflow (from upstream) on the groundwater depletion rate.

The study is novel in that it presents a means to overcome lack of comprehensive long-term data needed for sophisticated numerical groundwater models. Furthermore, the presented approach can be adapted for use in other regions that similarly lack comprehensive, long-term data to use a comprehensive numerical transient groundwater model.

5.2 Methods and data analysis

5.2.1 Methods

We developed a simple annual water budget (or mass balance) spreadsheet model of the Wadi Zabid soil and aquifer system to assess present and future groundwater storage and the associated changes in the groundwater table (i.e. the groundwater depletion/recovery rate). The water budget is a basic component of any conceptual hydrological model of an area (Healy and Scanlon 2010). It provides a link between recharge, discharge and storage processes in the hydrologic cycle.

Water budget (balance) approach to the soil and the aquifer system

Todd and Mays (2005) expressed the overall water budget (balance) by considering both surface water and the groundwater system. Our study region is arid, with a deep groundwater table, so there is no groundwater discharge to the wadi (valley) and no evapotranspiration directly from the aquifer. In accordance with Todd and Mays (2005), the annual water budget of the soil and aquifer system (Figure 5.1) can be expressed as follows:

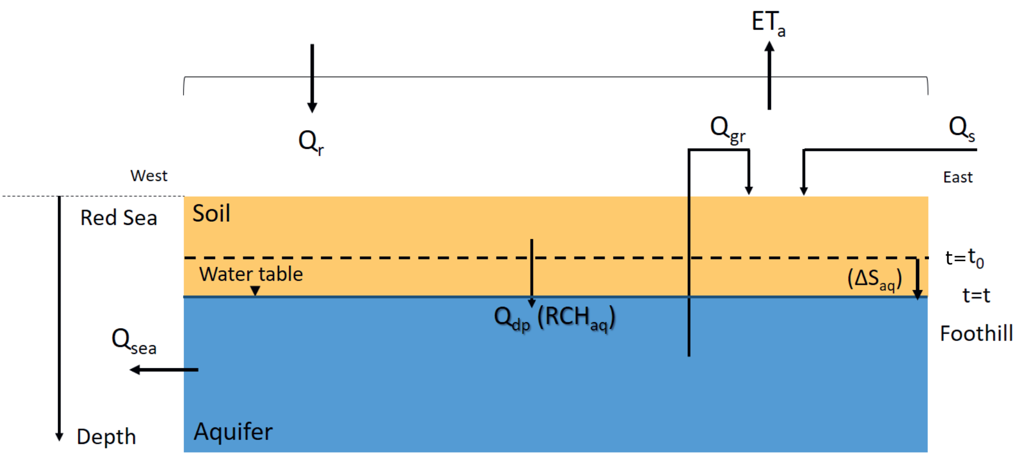

Figure 5.1 The soil and aquifer system, with $t=t_0$ representing the water table before intensive groundwater abstraction and $t=t$ being the present water table level.

(for the soil)

$$Q_{in,soil} = Q_r + Q_s + Q_{gr} \quad (5.1)$$

$$Q_{out,soil} = Q_{dp} + ETa \quad (5.2)$$

$$Q_{in,soil} = Q_{out,soil} \quad (5.3)$$

$$Q_{dp} = Q_r + Q_s + Q_{gr} – ETa \quad (5.4)$$

(for the aquifer)

$$Q_{in,aq}\ (RCH_{aq}) = Q_{dp} \quad (5.5)$$

$$\boldsymbol{RCH_{aq} = Q_r + Q_s + Q_{gr} – ETa} \quad (5.6)$$

$$Q_{out,aq} = Q_{sea} + Q_{gr} \quad (5.7)$$

$$\Delta S_{aq} = Q_{in,aq} - Q_{out,aq} \quad (5.8)$$

$$\Delta S_{aq} = RCH_{aq} – Q_{gr} – Q_{sea} \quad (5.9)$$

$$\boldsymbol{\Delta S_{aq} = Q_r + Q_s – ETa – Q_{sea}} \quad (5.10)$$

where $Q_{in,soil}$ is the water inflow to the soil; Q_r is rainfall; Q_s is surface water inflow across the eastern boundary, which is applied as irrigation water; Q_{gr} is the total groundwater abstraction from wells, which is applied as irrigation water; $Q_{out,soil}$ is water outflow from the soil system; and Q_{dp} is deep percolation from the soil system into the aquifer. ETa is the actual evapotranspiration; $Q_{in,aq}$ (or RCH_{aq}) is the water flow from the soil into the aquifer or recharge from the soil, i.e. deep percolation (Q_{dp}). $Q_{out,aq}$ is water discharge from the aquifer system; Q_{sea} is groundwater discharge into the Red Sea; and ΔS_{aq} is the change in groundwater storage in the aquifer system over time, in this study, annual change. The change in storage in the soil (ΔS_{soil}) was omitted, because it is relatively small compared to ΔS_{aq} in the study region, and soil moisture is regularly replenished in wet years. All units are L/T; thus, water budget terms are in units of mm/yr. The annual water budget was solved for wet, mean and dry years to incorporate climate variability.

Study area

The midstream, downstream and coastal area of the Wadi Zabid region of the Tihama plain in western Yemen, was selected for study because of the observed drop in groundwater levels. The study region is rectangular shaped, some 46 km by 20 km, with a total area of 920 km^2 (Figure 5.2). The average annual air temperature is 29.6°C (NWRA 2009). Average potential evaporation (*Eo*) is about 3,000 mm/yr (TDA 2010). Annual average precipitation (*P*) varies from 100 mm on the western coast, to 350 mm in the foothills and more than 550 mm in the upstream mountain area to the east. The region is arid ($0.03 < P/Eo < 0.25$), with a dry season that lasts from mid-October until late March (about 160 days). The average annual surface water inflow at the eastern boundary of the study area was 122 Mm^3 from 1970 to 2009 (DHV 1988; TDA 2010).

The study region is located within three directorates: Zabid, Al-Tuhita and Al-Jarrahi. Population in these directorates grew by some 3% annually, increasing from 312,400 in 2004 to around 472,500 in 2018 (Central Statistical Organization 2005). Most inhabitants rely mainly on crop production, in addition to livestock and fishing. Various crops are grown, such as fruits, vegetables, cereals, fodder crops, cotton, Jasminum sambac and henna.

Beneath Tihama plain is an extensive unconfined aquifer consisting of Quaternary sediments with some Tertiary sediments underneath. Aquifer thickness varies from <50 m near the foothills to 250–350 m near the Red Sea coast (DHV 1987). The Tihama aquifer system is recharged by rainfall and infiltration of surface water (Van der Gun and Ahmed 1995).

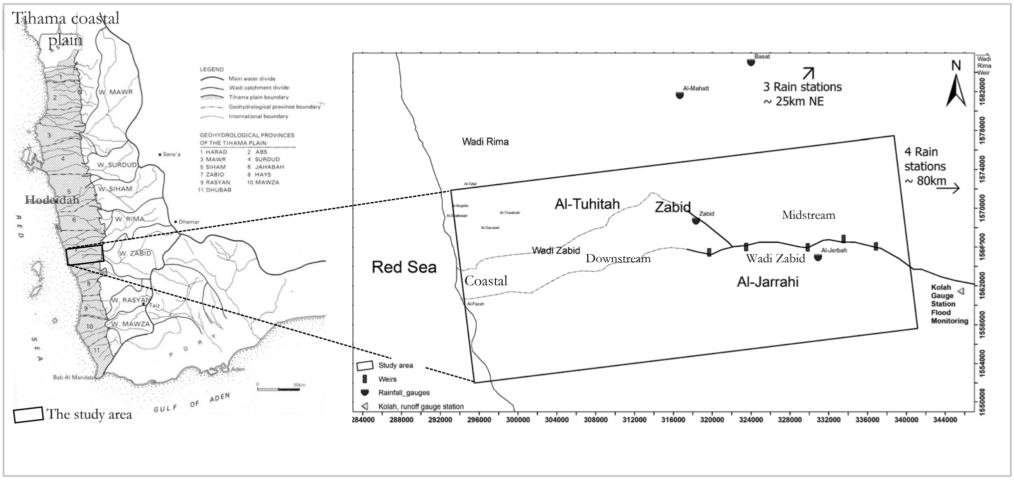

Figure 5.2 Map of the study region in Wadi Zabid (map source DHV 1988).

Boundary condition

The soil domain of the study region is open at the top with inflows of rainfall and irrigation water and outflows of evapotranspiration. The bottom of the soil, which coincides with the top of the aquifer, is also open. Horizontal flow in the soil, which is unsaturated, is negligible. For the aquifer system we assume the following:

East boundary. The aquifer's boundary condition in the east (foothills) represents a no groundwater flow condition because of the outcrop of volcanic rocks (Quaternary and Tertiary basalt and rhyolite), though in other areas the bedrock is shallow, according to a geoelectric cross section of Wadi Zabid (DHV 1988).

West boundary. At the west boundary of the aquifer system, groundwater discharges into the Red Sea (Q_{sea}) due to the difference in hydraulic head between the aquifer and the sea. The groundwater discharge into the Red Sea (Q_{sea}), i.e. of 309 mm/yr, was calculated using Darcy law using a hydraulic head difference of 244 m over the study area based on observed data of mid-2016 (Al-Qubatee et al. 2019), median hydraulic conductivity (k= 31.5 m/d) (TESCO-Viziterv-Vituki 1973), and an average aquifer thickness of 220 m (DHV 1988). The discharge was assumed to be rather constant over time, as hydraulic gradient changes only slowly (with no difference between wet and dry years).

North-south boundaries. The north and south boundaries are groundwater divides. Hence, no groundwater flows between Wadi Zabid and Wadi Rima in the north or between Wadi Zabid and Wadi Hyas in the south.

The bottom boundary. The bottom of the aquifer is represented by impermeable bedrock and consolidated rocks in the east, Tertiary alteration of clays, silt, fine sand, evaporates and weathered volcanic material (impermeable) in the central and coastal part, according to the geoelectric cross section (DHV 1988). This implies negligible groundwater flow between the aquifer and the underlying rock.

Sensitivity analysis

A sensitivity analysis is used to investigate the effect of varying some of the input data (e.g. Aguado et al 1977). In our case, the effect of temporal rainfall distribution, spatial rainfall distribution and aquifer properties on the groundwater storage deficit and groundwater depletion rate was calculated. The most reliable the input data, the more confident we can be about the water budget calculation (e.g. Singhal and Gupta 2010).

Validation of the water budget

To validate our water budget calculations, we used the water table fluctuation monitoring approach (e.g. Koïta et al. 2018), also called the water table change approach. The calculated annual average change in the water table, labelled in this study the calculated groundwater depletion rate (GDR_C), was compared to the observed annual average change in the water table, labelled the observed groundwater depletion rate (GDR_O). GDR_O, according to Al-Qubatee et al. (submitted), was derived from measured groundwater levels in the years 1972, 1987, 2008 and 2016, from Tesco-Viziterv-Vituki (as cited in Tipton and Kalambach 1980), DHV (1988), NWRA (2008) and Al-Qubatee et al. (2019). In this paper the *GDR* is negative when the groundwater storage decreases (deeper groundwater levels), and when the *GDR* is positive then storage increases, i.e. groundwater recovery rate (*GRR),* shallower groundwater levels.

The calculated change in groundwater storage (ΔS_{aq}) from the water budget cannot be straightforwardly compared to the annual average GDR_O. First, ΔS_{aq} must be converted into GDR_C. In this operation, the storativity, known as specific yield (S_y) of the unconfined aquifer (Freeze and Cherry 1979) has to be considered. Dingman (2015) provides S_y for different rock material, for example, the S_y of unconsolidated alluvial deposits and fine sand is 0.33. Thus, the GDR_C derived from the calculated change in aquifer storage (water budget results) was computed as follows:

$$GDR_C = \Delta S_{aq}/S_y \tag{5.11}$$

where GDR_C is the calculated groundwater depletion rate [L/T], ΔS_{aq} is the change in aquifer storage [L/T] and S_y is the specific yield [-].

GDR_C for wet, mean and dry years cannot be straightforwardly compared with GDR_O from monitoring wells in the same year. This is because it can take years for the deep groundwater level to respond to recharge (deep percolation) across the lower boundary of the soil.

5.2.2 Data analysis

Rainfall

Rainfall temporal distribution. Eleven monitoring stations provided rainfall data for the study region. Six of these were located in Wadi Zabid (two stations in the midstream area and four in the upstream area), and five stations were located in Wadi Rima, to the north (Figure 5.2). The eleven stations had 23 years of common rainfall records (1978-2000).

Annual rainfall data were selected to represent wet years (*P*=75%), mean years (in terms of long-term average rainfall) and dry years (*P*=25%). Here, *P* is the probability of exceedance (occurrence), calculated using the Weibull formula (Dirk 2013). First, annual averages were calculated using the rainfall data from the eleven stations. Next, the spatial distribution of rainfall for each type of year (wet, mean and dry) was determined using the data from the eleven stations (see below). We studied wet, mean and dry years to explore the effects of extreme conditions (e.g. a long series of wet or dry years) on the water budget. We focus on means, however, which by definition encompass all types of conditions.

Sensitivity analysis. We examined the influence on the water budget of applying another set of rainfall gauging stations with a longer set of common records. For this we used six of the eleven stations (in midstream and upstream area of Wadi Zabid) having 40 years of common rainfall records (1970-2009).

Rainfall spatial distribution. Several approaches can be used to interpolate point data (from rainfall gauges) to spatially distributed rainfall. For this study, we selected spline interpolation, in which a mathematical function exactly passes through the input points (in our case, the observed rainfall at each station in wet, mean and dry years). The rainfall distribution is given in isohyetes. The spline method gives negative values when annual rainfall is very low, as in dry years at the coastal area of our study region. Such negative values were taken to be zero. Spatially-averaged annual rainfall in the study region obtained from the gridded annual rainfall in wet, mean and dry rainfall years was, respectively, 433 mm, 300 mm and 165 mm.

Sensitivity analysis. We investigated the effect of applying another spatial interpolation method. Here, the Thiessen polygons method was used (e.g. Herschy and Fairbridge 1998) with the eleven rainfall stations in the study region.

Possible future changes in rainfall based on the observed historical trend. Using linear regression and data from two midstream and four upstream gauging stations (Figure 5.2), Al-Qubatee et al. (submitted) found a trend of increasing rainfall in the midstream and upstream areas of Wadi Zabid from 1970 to 2009 (Figure 5.3). Extrapolating this observed historic trend suggests a potential rise in rainfall of 18% and 26%, respectively, for the midstream and upstream areas in 2060 relative to 2014. This extrapolated rainfall trend corresponds well with results from Terink et al. (2013), using detailed prospective data from a climate model for the Middle East. They projected a 15-20% rise in annual rainfall in Yemen between 2020 and 2050, relative to the benchmark period (2000-2009). We used the projected 18% increase in rainfall, which is in line with the observed trend, in the water budget calculations in 2060, for various changes in future water use and surface water inflow.

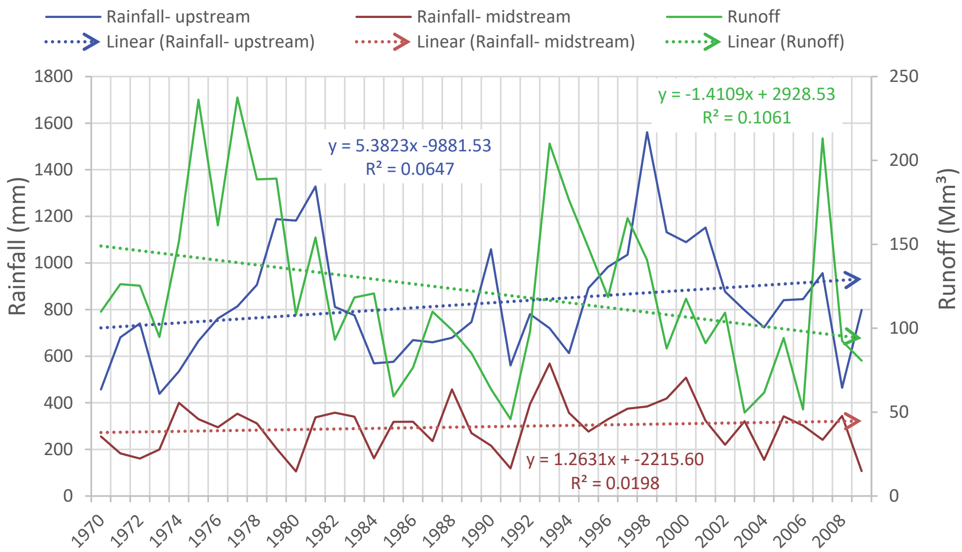

Figure 5.3 Rainfall trend (mm/yr) in the upstream and midstream areas and surface water inflow (Mm^3/yr) to the midstream area based on historical data (1970-2009) (Al-Qubatee et al. submitted), data source: (DHV 1988; TDA 2010).

Land cover and actual evapotranspiration (water consumption)

Land cover was derived from the map and data of Al Hasan (2016), which were produced using remote sensing imagery for twelve-months in 2014-2015. Actual evapotranspiration (*ETa*) was estimated in accordance with land cover, and based on Almhab (2011). *ETa* was calculated using the M-SEBAL algorithm, MODIS satellite images and Landsat7 ETM images, and meteorological data from Wadi Zabid and Wadi Rima (Almhab 2011). In 2014, about half of the land in the study region (52%) was barren and desert land (Table 5.1). These land cover types represented an area of 269 and 208 km^2, respectively. Actual evapotranspiration was low (*ETa*= 73 mm/yr) for these two covers, reflecting the dry environment. Although the area of these land covers was large, they contributed less than 10% of the total annual actual evapotranspiration (i.e. water consumption) in the study region (*ET*a= 430 mm/yr). Areas cultivated one crop per year and two crops per year, covered 34% (306 km^2) and 5% (45 km^2) of the study region, respectively, but their contribution to the total actual evapotranspiration of the study region was substantially higher (55% and 13%), due to higher actual evapotranspiration (*ETa*= 706 and 1117 mm/yr) compared to barren and desert land (Table 5.1). Perennial agriculture includes two land cover types: moderate evergreen (7% of the study region) and intense evergreen (2% of the study region). These categories and the two crops/yr category were the largest water consumers (*ETa*>1000 mm/yr). Moderate evergreen perennial covered an area of 66 km^2 and intense evergreen perennial covered just 18 km^2 in 2014-2015, yet together they contributed 23% of the total annual actual evapotranspiration.

Table 5.1 Land cover and water consumption (*ETa*)

Land cover	Total area in 2014/2015 (km²)	Total area (%)	*ETa* (mm/yr)	*ETa* cont.(mm/yr)	*ETa* cont.(%)
Desert	208	23	73	17	4
Steep lands	2	0	73	~0	0
Barren lands	269	29	73	21	5
One crop/ yr	306	34	706	237	55
Two crop/ yr	45	5	1,117	55	13
Moderate evergreen (perennial)	66	7	1,087	78	18
Intense evergreen (perennial)	18	2	1,087	22	5
Total	914	**100**		**430**	**100**
Total cultivated areas	435				

ETa is the annual actual evapotranspiration for each land cover type (Almhab et al. 2011). *ETa* cont. the area-weighted contribution of each land cover type to the total annual actual evapotranspiration from area.

The total cultivated area is 435 km^2 in 2014-2015 and the total spatially weighted actual evapotranspiration was 430 mm/yr for the present land use, which is only 15% of the potential evapotranspiration. We assumed no significant change in land cover between wet, normal and dry years, as agriculture in the study region is mainly driven by available irrigation water.

Possible future changes in land cover based on the observed historical trend. Linear regression was used to explore changes in cultivated area over the period from 1970 to 2014 and to predict agriculture land in 2060. We determined changes in cultivated area based on Landsat images for a twelve-month period in 2014-2015 (Al Hasan 2016) and land covers shown on Landsat images taken in December 1972, 1984, 2008 and 2014 (Al-Qubatee et al. submitted). December images were the only ones with a good enough resolution for the selected years, however, cereals are usually not cultivated in December (Al-Qubatee et al. submitted). Based on the observed historic trend (Figure 5.4), a 70% increase in cultivated area might be expected in 2060, relative to 2014. In the water budget for 2060 we assumed that the cultivated area could increase or decrease by 70%, which should be understood as a maximum. A series of smaller step changes was also considered.

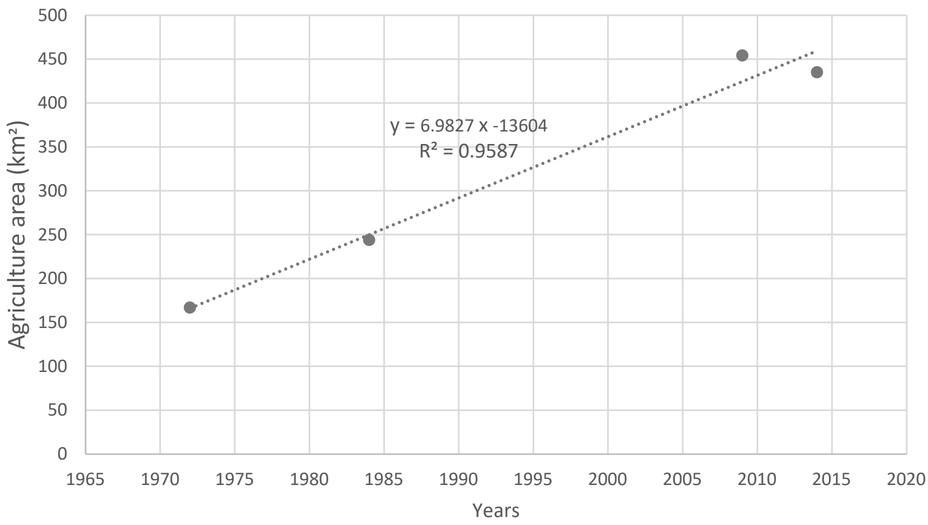

Figure 5.4 The observed historical trend in the cultivated area in the study region, based on the land cover data from Al Hasan (2016); Al-Qubatee et al. (submitted).

Surface water inflow

The Kolah gauging station has monitored surface water inflow from the mountains area (upstream area) to Tihama Plain (Figure 5.2) for the period 1970 to 2009 (DHV 1988; TDA 2010). We selected three types of years: wet, mean and dry year (using the same approach described for selecting rainfall years). The aim was to obtain. annual surface water inflow (Q_s) for the wet, mean and dry years, which were 168, 132 and 96 mm, respectively.

Possible future changes in surface water inflow based on observed historical trend. Analyses using linear regression showed a downward trend in surface water inflow at the eastern boundary of the study region over the period from 1970 to 2009 (Figure 5.3). Though the coefficient of determination was low (R^2=0.1061) we extrapolated the historical trend into the future, finding that a further decrease in surface water inflow by up to 70% could be possible by 2060. We also explored the impact of a potential increase in surface water inflow, again up to 70%. These possible changes should be understood as a maximum, though they may be too extreme. Actual changes will depend on development in agriculture and in associated water usage upstream of the study region. A series of smaller possible changes (in steps of 10%) were conceded.

Groundwater abstraction

Groundwater abstraction data for the study area were based on the well inventory carried out by NWRA in 2008 (NWRA 2008). The number of operational wells in the study region was counted at about 4,250. Well inventory data were incomplete for 853 wells (20%). For those wells, yield and pumping hours were estimated using the arithmetic average of the surrounding wells. We calculated the total water abstraction from each well by multiplying well yield by pumping hours. No data were available to differentiate groundwater abstractions by wet, mean and dry years. According to the well inventory (NWRA 2008), some 486 mm of groundwater was abstracted from the study region annually.

5.3 Results

5.3.1 Present groundwater depletion rate

The present annual water budget was calculated using Equation 5.10 considering the present groundwater exploitation and land cover. We carried out this calculation for wet, mean and dry rainfall-surface water inflow years (e.g. the wet rainfall year is combined with the wet surface water inflow year). The volume of water entering the aquifer (recharge, RCH_{aq}) was always found to be less than water leaving the aquifer (discharge, $Q_{gr} + Q_{sea}$), irrespective of year. The differences between recharge and discharge were -138, -306 and -478 mm/yr in the wet, mean and dry rainfall- surface water inflow years, respectively (Table 5.2A). The present GDR_C using Equation 5.11 for mean conditions was -927 mm/yr.

Table 5.2 Water budget and GDR_C in dry, mean and wet years (all in mm/yr): (A) with present water consumption and thus groundwater use, (B) using six rain stations with 40 years of common rainfall records to find temporal rainfall distribution, and (C) using Thiessen polygon to find the spatial distribution of rainfall

(A)

Year type	Rainfall (Q_r)	Inflow (Q_s)	Groundwater abstraction (Q_{gr})	*ETa* cont.	Q_{sea}	RCH_{aq}	ΔS_{aq}	GDR_C
Wet	433	168	486	430	309	657	-138	-415
Mean	300	132	486	430	309	489	-306	-927
Dry	165	96	486	430	309	317	-478	-1,446

(B)

Year type	Rainfall (Q_r)	Inflow (Q_s)	Groundwater abstraction (Q_{gr})	*ETa* cont.	Q_{sea}	RCH_{aq}	ΔS_{aq}	GDR_C
Wet	316	168	486	430	309	540	-255	-769
Mean	174	132	486	430	309	362	-432	-1,310
Dry	138	96	486	430	309	290	-505	-1,528

(C)

Year type	Rainfall (Q_r)	Inflow (Q_s)	Groundwater abstraction (Q_{gr})	*ETa* cont.	Q_{sea}	RCH_{aq}	ΔS_{aq}	GDR_C
Wet	495	168	486	430	309	720	-75	-226
Mean	361	132	486	430	309	549	-246	-744
Dry	200	96	486	430	309	353	-442	-1,339

ET_a cont. is the area-weighted contribution to evapotranspiration. RCH_{aq} is recharge to groundwater. Q_{sea} is discharge to the Red Sea. ΔS_{aq} is the change in groundwater storage. GDR_C is the calculated groundwater depletion rate.

Sensitivity analysis

Temporal rainfall distribution, annual rainfall was found to be lower when longer series of records (available from fewer stations) was used (compare Table 5.2B and 5.2A). The difference was 16-42% lower, dependent on the type of rainfall year. Thus, a greater GDR_C was found. For the mean conditions, it increased from -927 mm/yr (Table 5.2A) to -1,310 mm/yr (Table 5.2B).

Spatial rainfall distribution, using Thiessen polygons, the study region was only covered by polygons from two stations. The spatially-averaged areal rainfall was found to be slightly higher (14-22%) for all types of rainfall years than that was obtained using spline interpolation (compare Table 5.2C and 5.2A). This results in a smaller GDR_C for mean conditions, (about 20%) compared to that found using spline interpolation, i.e. from -927 to -744 mm/yr (Tables 5.2A and 5.2C).

Aquifer properties were used to calculate groundwater discharge into the Red Sea, as this affects groundwater storage (ΔS_{aq}, Equation 5.10), and accordingly GDR_C. From the geoelectric cross section of the Wadi Zabid (DHV 1988), we see that the hydraulic conductivity (k), and the thickness (*D*) of the aquifer underlying Tihama plain are not constant. Based on the predominant sediment texture and hydrogeological setting using the above-mentioned references, we estimated aquifer properties (Table 5.3, bold numbers). Modification of values for aquifer properties increases or decreases groundwater storage and GDR_C relative to our reference (Table 5.2A).

Table 5.3 The change in the groundwater storage and GDR_C for dry, mean and wet years applying various values for aquifer properties

k (m/day)	*D* (m)	S_y	ΔS_{aq} (mm/yr)			GDR_C (mm/yr)		
			Wet	Mean	Dry	Wet	Mean	Dry
32	**220**	**0.33**	**-137**	**-306**	**-477**	**-415**	**-927**	**-1,446**
10	**220**	**0.33**	74	-95	-267	223	-289	-808
100	**220**	**0.33**	-808	-977	-1,148	-2,448	-2,960	-3,480
32	150	**0.33**	-39	-208	-379	-118	-629	-1,149
32	350	**0.33**	-319	-488	-660	-967	-1,479	-1,999
32	**220**	0.3	-137	-306	-477	-456	-1,019	-1,591
32	**220**	0.21	-137	-306	-477	-652	-1,456	-2,273

k is the hydraulic conductivity; *D* is aquifer thickness (m); S_y is the specific yield; ΔS_{aq} is the change in the groundwater storage. GDR_C is the calculated groundwater depletion rate. Numbers in bold were applied as reference in this study.

Obviously, a smaller specific yield (S_y) increases GDR_C based on the change in aquifer storage (Equation 5.11). We investigated the effect of different S_y values, representative of different grains sizes of the sediments (Dingman 2015) that might occur in Wadi Zabid aquifer. The GDR_C, for mean condition, was found to be 10% and 57% greater, respectively, for an S_y of 0.30 and 0.21. Based on the reported hydrogeological description the former is more probable than the latter ($S_y = 0.21$ is rather extreme).

Aquifer thickness varies in Wadi Zabid. The thicker the aquifer, the greater the decrease in groundwater storage and thus the greater the GDR_C (due to more groundwater discharge into the sea) and vice versa. Hence, GDR_C for mean condition was calculated as being 32% lower for an aquifer thicknesses of 150 m and as 60% higher for an aquifer thickness of 350 m.

A decrease in the hydraulic conductivity to 10 m/d, which is extreme (representative of fine sediments, such as fine sand (Domenico and Schwartz 1998), would result in a substantial increase in groundwater storage, and hence a 70% lower GDR_C for the mean condition.

The opposite would happen if the hydraulic conductivity was 100 m/d, which is also extreme for the aquifer in Wadi Zabid (this conductivity is more representative of homogenous gravel). Inputting a hydraulic conductivity of 100 m/d yielded a 220% higher GDR_C (Table 5.3).

Validation

To validate the water budget results, we compared the GDR_C from the change in groundwater storage (ΔS_{aq}) for the mean rainfall-surface water inflow year with the annaual average GDR_O. The GDR_C for the mean rain-inflow year was -927 mm/yr (Table 5.2A) using a specific yield (S_y) of 0.33 (Equation 5.11). The average GDR_O, using observed groundwater levels collected from monotoring wells (Al-Qubatee et al. submitted) was -1,110 mm/yr over the period from 1972-2016. This corresponds well with the GDR_C, although it is about 20% lower than GDR_O. The sensitivity analysis learns that such deviation can easily be explained by uncertainties in input data (e.g. precipitation, aquifer properties, compare Table 5.2B-C and Table 5.3 with Table 5.2A).

5.3.2 Impact of changes in rainfall, land cover (water consumption) and surface water inflow on future groundwater depletion rates

According to the historical trend of rainfall (Al-Qubatee et al. submitted) and the study by Terink et al. (2013), we include an increase in rainfall of 18% in all of our water budget calculations for 2060. Also based on the historical trend, we investigated a series of decrease and increase in agriculture land cover (water consumption) and surface water inflow in 2060 relative to 2014; that is, from -70% to 70% in steps of 10%. The changes in land cover were implemented equally for all types of land cover crops (Figure 5.5). To accommodate increases, the areas cultivated one crop per year, two crops per year and to moderate or intense evergreen were assumed to expand at the expense of barren land. The opposite was applied to accommodate decrease in agricultural. In the case where agriculture land increased by 70%, all barren land would be converted to agricultural lands. As this is a rather unlikely scenario, we project that about 17% of the desert land would be reclaimed for cultivation (Figure 5.5).

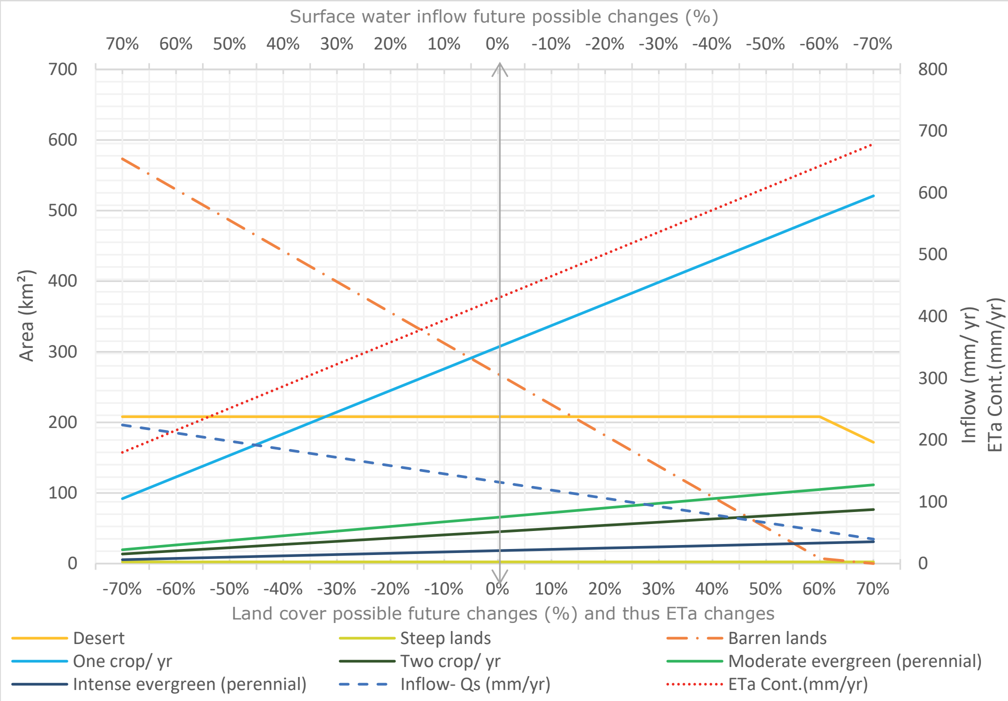

Figure 5.5 Changes in agriculture land cover (thus water consumption, *ETa*) and surface water inflow in the future (2060) relative to 2014.

Figure 5.6 presents the calculated groundwater depletion rate in 2060. The *first case* is continuation of the trend of increasing agriculture land cover, and thus water consumption, in the study region with a reduced surface water inflow (both up to 70%, investigated in steps of 10%). This case represents an absence of adequate water resources management and continuation of the historical trend of increasing rainfall (due to climate change). For this case, the *GDR* in 2060 was calculated for the following possible future changes (scenarios); (1) with an increase in the agriculture land cover in the study region of 10%, 30% and 70%, and increase in water usage upstream (mean surface water inflow decrease by 10%, relative to 2014), GDR_C is, respectively, -911, -1,127 and -1,559 mm/yr; (2) with an increase in the agriculture land cover in the study region of 10%, 30% and 70%, with some increase in water usage upstream (mean surface water inflow drops by 30%, relative to 2014), GDR_C is, respectively, -991, -1,207 and -1,639 mm/yr; and (3) with an increase in the agriculture land cover in the study region of 10%, 30% and 70%, paired with a large increase in the water usage upstream (mean surface water inflow drops by 70% relative to 2014), GDR_C is, respectively, -1,151, -1,367 and -1,799 mm/yr.

The *second case* is a reduction in agriculture land cover (thus, water consumption) in the study region, with increased surface water inflow, but continuing the historical trend of increasing rainfall (due to climate change). For this case, the *GDR* in 2060 was calculated for the following future changes (scenarios): (4) with a decrease in the agriculture land cover in the study region of 10%, 30% and 70%, and decrease in water usage upstream (mean surface water inflow increase by 10% , relative to 2014), GDR_C is -615, -399 and 34 mm/yr, respectively. As mentioned before, positive values of GDR_C represent groundwater recovery. Scenario (5) with a decrease in the agriculture land cover in the study region of 10%, 30% and 70%, and some decrease in water usage upstream (surface water inflow increase by 30% relative to 2014), GDR_C is -535, -319 and 114 mm/yr, respectively. Lastly, scenario (6) with a decrease in the agriculture land cover in the study region of 10%, 30% and 70%, and a large decrease in the water usage upstream (surface water inflow increases by 70%), GDR_C is -375, -159 and 274 mm/yr, respectively.

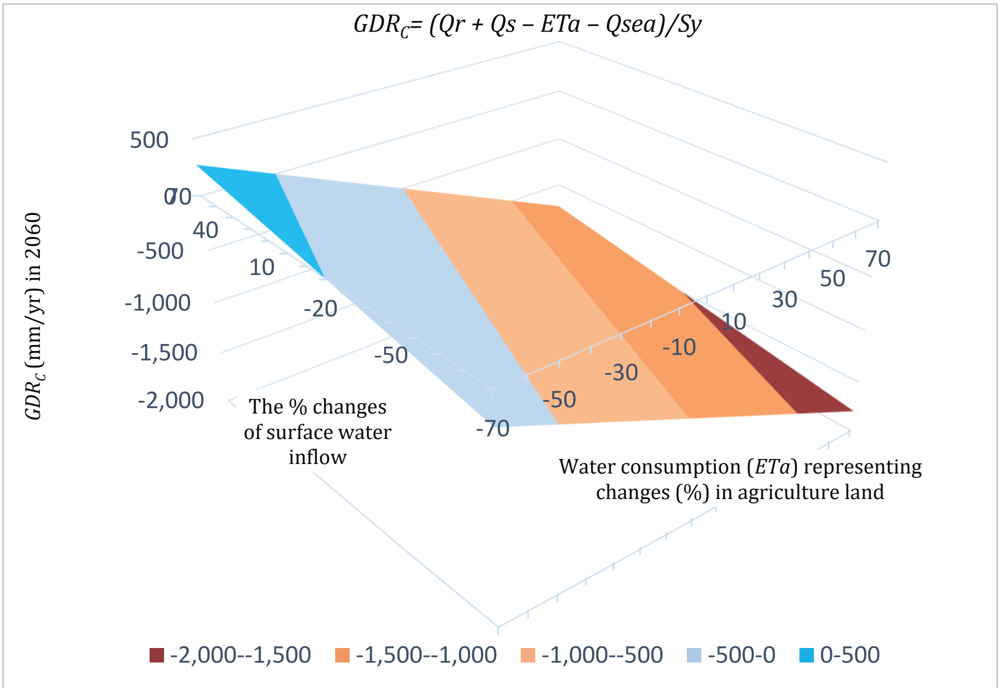

Figure 5.6 Calculated groundwater depletion rate (GDR_C), for a series of future changes (2060) in agriculture land cover (thus, water consumption) and surface water inflow relative to the situation in 2014 and including 18% increase in rainfall due to climate change.

5.4 Discussion

This study developed a simple water budget (balance) spreadsheet model to quantify the groundwater depletion rate in Wadi Zabid for the present land cover and thus groundwater use. This was done for wet, mean and dry conditions in terms of rainfall and surface water inflow. The annual deficit in the groundwater budget for mean conditions was found to be -306 mm. Water losses, comprising water consumption by agricultural crops and groundwater discharge to the Red Sea, totalled 739 mm/yr (Tables 5.2A). This far exceeds water gained via rainfall and surface water inflow from upstream (total availability ranged from 261 mm/yr in dry years to 601 mm/yr in wet years (Table 5.2A). The annual groundwater deficit is reflected in decreased aquifer storage, which results in a groundwater depletion rate (GDR_C) of -927 mm/yr for mean conditions under present land cover and thus groundwater use. The GDR_C approximates the average observed groundwater depletion rate of -1,110 mm/yr over the period from 1972 to 2016. This represents an obviously unsustainable use of land and groundwater resources in the Wadi Zabid. It is important to mention that the contribution of the evergreen crops (e.g. banana and mango) and intensive agricultural (two crops per year) to water consumption in the region was high (13% and 23%, respectively). Despite their limited area (9% and 5% of total land cover), they had the highest water consumption per unit area (*ETa*= 1087 and 1,117mm/yr, respectively, Table 5.1).

Wadi Zabid is in many aspects a data-scarce region, so shortcomings in the water budget results are expected. Our sensitivity analyses, in which we varied input data (aquifer properties and rainfall), some of which were rather extreme, shows that GDR_C is negative for mean conditions in all cases. It demonstrates that result of our simple budget approach are robust and point at the unsustainability of present land use and groundwater exploitation. GDR_C was found to be substantial, at least about -300 mm/yr (Table 5.3).

Land cover data (2014-2015) in our study (Al Hasan 2016) was compared with agriculture survey data carried out in 2006-2007 by TDA (2007). No substantial difference was found, though the increase in agriculture land cover from 2006 to 2014 was about 19% (2.3% annually). This somewhat corresponds with the trend in land cover change over the period from 1970 to 2014 which is 1.7% annually. We checked our predefined *ETa* (Table 5.1) against the study by Water Watch and Hydro-Yemen (2012) carried out in the nearby Wadi Siham (Figure 5.2). The differences were around 10%. We did not recalculate the water budget with the different land cover areas and *ETa*, but we anticipate that the effect would be similar to that of using other rainfall data records (Tables 5.2B- 5.2C).

The results of our simple water budget model provide a metric to quantify the degree of unsustainability of the present situation in the study region. It is worthy for data-scarce regions, such as Wadi Zabid, where transient numerical groundwater model is not feasible yet. The simple water budget approach developed in the current study will be useful for other data-scarce regions as well. The approach requires: (1) time series of annual areal rainfall data; (2) relative areas of land cover types; (3) actual evapotranspiration for the prevailing land cover types; (4) time series of annual surface water inflow, if occurring; and (5) incoming and outflowing groundwater, if occurring, based on hydrogeological information. Moreover, groundwater heads from different years are needed to validate the simulated groundwater depletion/recovery rate.

We investigated a series of changes in the agriculture lands cover (water consumption) and surface water inflow (from the upstream) in 2060 relative to 2014, ranging from -70% to 70% in steps of 10% and including the assumption of an 18% increase in rainfall due to climate change. Changes that would bring about recovery of groundwater resources were found to be very limited and difficult or impossible to be implemented (Figure 5.6, dark blue part). The series of changes in the agriculture land were investigated equally for all crops, which have different water consumptions (*ETa*, Table 5.1). Nevertheless investigating them otherwise would not result in substantial impacts on the groundwater depletion rate. Hence, groundwater recovery would not be initiated even by converting all agricultural lands to the crop with the lowest water consumption (e.g. one crop annually). For a long-lasting groundwater recovery, a dramatic reduction of the agricultural area – of at least 50% - is required, combined with more surface water inflow from the east. The needed reduction of the water consumption (agriculture land), however, would come at the expense of the socio-economic situation. Reduction of agriculture activity would have a dramatic effect on farmers, both in the study region and upstream, as they highly reliant on agriculture for their livelihoods. This raises the question of whether it is possible to use groundwater in Wadi Zabid in a sustainable manner, while maintaining the present expansion of agricultural activity and safeguarding local income in the region (as a major source of income). As this study found, this will be hard to achieve. A solution might be to shift towards high economic value activities that consume less water. Furthermore, the feasibility of utilizing non-conventional water sources, such as desalination of seawater in the coastal area, should be considered. Al-Sakkaf et al. (2010), in a study of the Sa’dah basin, in northwest of Yemen, concluded that sustainable groundwater use can only be achieved with reduced water demand, through water reallocation (converting from agricultural to less water-consuming activities) or use of high efficiency irrigation techniques. Greater irrigation efficiency, however, will not lead to significant water saving, as irrigation water returns to the aquifer (Gleick et al. 2011; Frederiksen and Allen 2011). In our study, we found that the annual groundwater discharge to the Red Sea was high (Tables 5.2A) but is difficult to reduce. Moreover, aquifer outflow is important to prevent further seawater intrusion and to maintain the ecological balance.

5.5 Conclusions

This study presents a simple water budget model using locally available data to quantify present and future groundwater depletion rates (*GDR*) considering series of changes in land cover and surface water inflow, assuming an increase in rainfall due to the climate change. The approach presented overcomes data scarcity, as a comprehensive set of long-term data is needed to implement sophisticated numerical groundwater models. Our approach can be used for other data-scarce regions as well. This study demonstrates quantitatively that the present groundwater use in the Wadi Zabid is unsustainable, due to the extent of agriculture both in the study region and upstream. The groundwater storage deficit for mean conditions amounts -306 mm/yr, with a GDR_C of -927 mm/yr. The GDR_C corresponds well with the average observed groundwater depletion rate (-1,110 mm/yr) over the past four decades. Our sensitivity analysis showed that, irrespective of differences in the input values, GDR_C was found to be at least -300 mm/yr. This underlines the unsustainable nature of present land use and thus groundwater exploitation in the region.

Our study investigates the impact of a series of changes in agriculture land cover (thus, water consumption) and surface water inflow (from upstream) on groundwater storage and associated GDR_C in future (2060), assuming an 18% increase in the rainfall due to climate change. Reducing GDR_C to a third (-319 mm/yr) of the current rate (-927 mm/yr) could be initiated with a 30% reduction of agricultural lands in the study region, combined with a decrease in water usage upstream (30% increase in surface water inflow). This could be envisioned if appropriate economic incentives can be provided to farmers to adopt alternative livelihoods with a lower water-requirement. Additionally, utilization of non-conventional water sources (e.g. desalination) should be sought.

With increase data availability, water budget on a monthly time scale, or a reliable transient numerical groundwater model can be developed to quantify spatially distributed groundwater storage, groundwater heads and saltwater intrusion under different environmental conditions.

Acknowledgments

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5

Chapter 6

Synthesis

6.1 Introduction

Data scarcity is a reality in much of the world, and remains a major obstacle to the use of sophisticated modelling techniques for the study of groundwater depletion. This research developed and presented an alternative, less data-intensive, combined approach to assess the extent, drivers and socio-economic impacts of groundwater depletion, and to explore scenarios for sustainable use (Figure 6.1). The approach was tested in a semi-arid and arid study region. Specifically, the research consisted of four steps, each addressing a different research question. These research questions were identified and elaborated in Chapter 1 (see Table 1.1), then further explored and answered in Chapter 2 to 5. This chapter presents an synthesis of the work, including a recap of the research questions and the answers found to them in the course of the research, alongside overall conclusions of the study and implications for future research and policy.

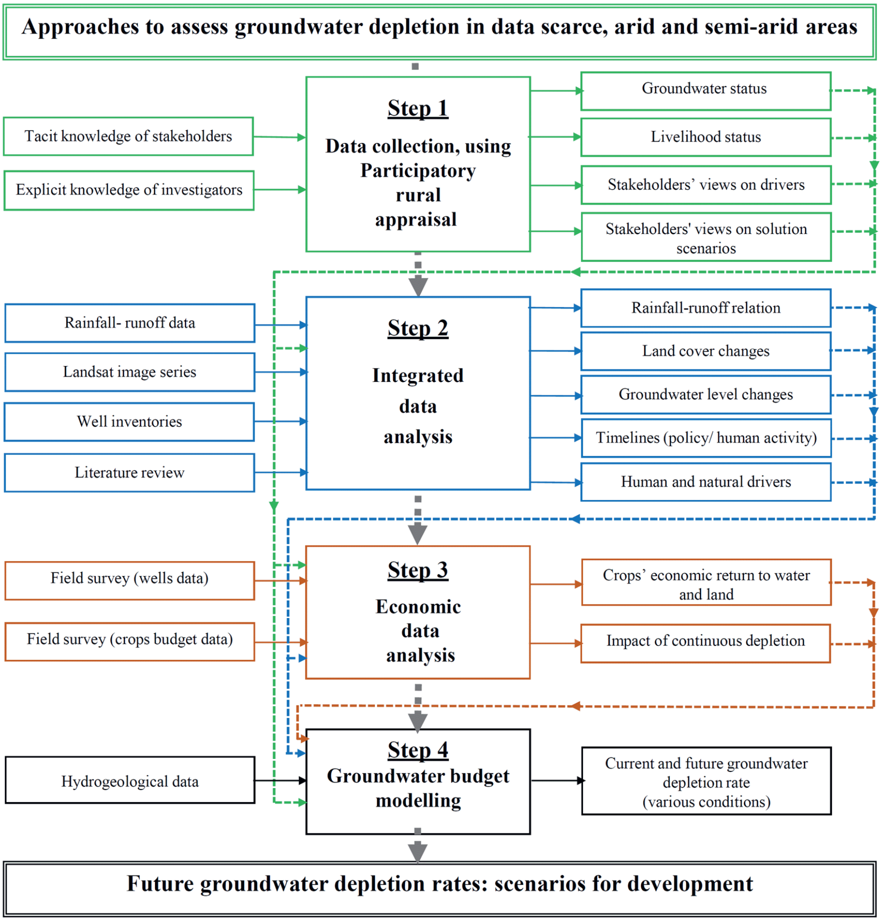

Figure 6.1 Flow chart showing the combined approach adopted in this study.

6.2 Answers to the research questions

6.2.1 Value of participatory approaches as a strategy to overcome data scarcity

Q1 What is the usefulness of participatory rural appraisal (PRA) for gaining a better understanding of the effects of groundwater depletion on livelihoods and obtaining stakeholders' points of view on the causes of and potential solutions to groundwater depletion?

Step 1 of the research (Chapter 2) centred on the value of PRA (Figure 6.1, Step 1) as a tool to overcome data scarcity. This research tested PRA in the study area of Wadi Zabid, Tihama coastal plain, Yemen. Here, despite data scarcity, PRA enabled an assessment of groundwater resource depletion, particularly changes in groundwater levels over time and the impact of these on local livelihoods. Participatory approaches also proved useful for bringing stakeholders' tacit knowledge to the fore, for a better understanding of the causes of groundwater depletion and preferred solutions from stakeholders' perspectives. Participatory approaches were effective in generating mutual learning and knowledge sharing as well, both among community members and with researchers. Particularly in areas where social water studies (Fayyad et al., 2015) are lacking, participatory approaches have been found to be valuable. PRA can empower communities to actively participate in problem assessment and express their viewpoints on solutions. However, choosing an appropriate set of PRA tools is important when addressing context-specific topics like groundwater resource depletion.

In the study area of Wadi Zabid, PRA helped overcome the problem of data scarcity, which stood in the way of sophisticated modelling methods to assess the state of groundwater resources and the impact of resource depletion on the socio-economic situation of the local population. Regarding selection of appropriate tools, this study found the most useful tools for examining the different aspects of groundwater depletion were, from the most to least useful, the following: semi-structured interviews, the transect walk combined with direct observation and group discussions, timelines, and problem and solution trees.

The group discussions and use of problem and solution trees brought out stakeholders' views on problems, their causes and proposed solutions. However, to produce a more complete picture of the causes of groundwater depletion in the study area, integrated data analysis approaches were also needed, as demonstrated in the next step of this research (Figure 6.1, Step 2). Indeed, stakeholders' perceptions were not always aligned with technical facts and expertise. Korfmacher (2001) stated arguments against public participation in watershed modelling, citing ordinary citizens' lack of technical expertise and knowledge, as well as the risk of insufficient representation and bias among participants. In addition, decision-makers may be wary of studies wherein involvement of citizens, instead of specialized studies, may cast doubt on the objectivity and scientific reliability of results. Despite these arguments, Ritzema et al. (2011) found participatory approaches to be valuable particularly for overcoming lack of data and reaching consensus among stakeholders.

6.2.2 Added value of an integrated data analysis approach

Q2 What is the added value of an integrated data analysis approach to reveal the natural and human-induced drivers of groundwater depletion?

Step 2 (Figure 6.1) of the research (Chapter 3) concerned the added value of studying the drivers of groundwater depletion using an integrated data analysis approach. Such an integrated approach includes both natural and human factors, unlike analysis approaches that pinpoint a singular aspect. The present research combined rainfall-runoff data, remote sensing data, well inventories and policy measure timelines to more clearly disclose the drivers of groundwater depletion and their impacts. Thus both natural and human-induced drivers of groundwater depletion were revealed. Moreover, this research drew a link between changes in human activities related to water and agriculture (e.g., trends in agricultural production, changes in crop patterns and evolving irrigation practices) and relevant political decisions (e.g., agricultural policies and subsidies). This underlined the catalytic role that political decisions can have in groundwater depletion and the subsequent effects on the environment. Thomas and Famiglietti (2015), similarly, found that sustainable groundwater management requires insight into the impact of both natural or climatic conditions and the effects of previous government decisions and policies.

The present research tested the integrated data analysis approach in Wadi Zabid. Here, groundwater depletion was found to be caused not by a decrease in rainfall, as stakeholders had indicated, but by human-induced factors, particularly, land cover and land use changes, such as, increasing agriculture/terraces, water harvesting and water diversion structures. These human-induced factors reduced the amount of surface water inflow to midstream and downstream zones of the study area. Drawing a link between the changes in human activities and government policy measures related to water and agriculture revealed that government policies had played a role in stimulating water-consuming activities, thus leading to increased groundwater abstraction.

Though cash crops may offer higher incomes in the short term, they were found to be detrimental to sustainable livelihoods and food security in the long term, due to their greater water consumption. With this in mind, estimation of the economic value of water was a valuable next research step (Figure 6.1, Step 3), to explore better allocations of scarce water resources, particularly, “less thirsty” but high economic value activities.

6.2.3 A simple crop budget model for assessing water allocations

> *Q3 Is a simple crop budget model sufficient for assessing the impact of an increased cost of groundwater pumping on returns to land and water for particular crops and to indicate recommended alternative water allocations?*

Step 3 of this research (Chapter 4) explored whether crop budgets are suitable for assessing the impact of spatial differences in groundwater depths and freely available spate water on the cost of irrigation and hence returns of crop production to land and water. The continuing drop in groundwater levels in the study area brought rapid increase in the cost of groundwater pumping. The share of freely available spate water for irrigation also played an important role in determining the cost of irrigation. Crop budgets were found to be a very suitable tool for assessing the sensitivity of returns to land and water assuming an increasing cost per unit of groundwater pumped and differences in the amount of spate water freely available for irrigation.

Although crop budgets provided insight into which crops had the highest return to water, this does not mean that water should be reallocated accordingly. Crop budgets were found to be less suitable for this purpose, as they only provide insight into financial returns to water, and do not consider social benefits and costs, such as food security and total annual unsustainable irrigation water requirements by the crop. Water reallocation decisions therefore require a broader interdisciplinary research basis, to ensure the feasibility of solution implementation in the long term (Marston and Cai, 2016).

Crop budget models for the study area of Wadi Zabid demonstrated the highest returns to land and water in the midstream zone of the study area, followed by the coastal zone. Returns were lowest in the downstream zone, due to the greater groundwater pumping depths there and lack of freely available spate water for irrigation. The likely future scenario, in which continued groundwater depletion can be assumed, would have significant consequences for economic returns to land and water, and thus the socio-economic status of local communities. The cost of pumping one unit of groundwater will increase rapidly as a result of the continuing drop of the groundwater levels. Furthermore, the analyses found economic returns to land and water to be very sensitive to changes in the depth of groundwater pumping, for almost all crops and research zones.

The returns to land and water in the downstream zone were most sensitive to further drops in groundwater levels. Yet, at the time of this research (mid-2016), groundwater levels in the downstream zone were already two times deeper than in the midstream and costal area. In addition, no spate water reached the downstream zone. The analysis found that all cultivated crops would become economically unprofitable for farmers in the expected future scenario; that is, with a further 50 m drop in groundwater levels over about the coming 50 years. In the coastal zone, although groundwater was relatively shallow, no spate water was available, and this part of the wadi was vulnerable to seawater intrusion. The least affected area was found to be the midstream zone, because of the more moderate pumping depths here, as well as the free availability seasonal spate water.

As a gap in knowledge, the question arose about suitable approaches for assessing, in a data-scarce region, the impact of increased agriculture, and thus increased water consumption, on aquifer storage depletion. This was the topic of the next step in the research (Figure 6.1, Step 4).

6.2.4 Quantifying groundwater depletion and recovery rates to explore scenarios for sustainable use

> *Q4 What is the usefulness of a simple water budget model to quantify groundwater depletion/recovery rates and to explore scenarios for sustainable future use?*

Step 4 of this research (Chapter 5) explored the usefulness of a simple water budget model for investigating aquifer depletion and recovery in the study region, and scenarios in this regard, as data scarcity stands in the way of application of sophisticated groundwater models. Using the water budget approach, groundwater depletion rates (GDR) were quantified for specific environmental conditions in the region (i.e., for mean conditions, for extended periods of dry and of wet conditions). The water budget approach uses as concept that groundwater storage will decrease (levels will drop) due to groundwater abstraction and groundwater discharge into the sea, and that all water (rainfall, excess spate water and abstracted groundwater) will return to the aquifer (increase groundwater storage), except the water lost due to evapotranspiration. The model also enabled prediction of the effect of future changes in land cover (e.g., agriculture) and changes in rainfall and runoff (surface water inflow from upstream) on aquifer depletion/recovery rates on the regional scale (i.e., for the study area as a whole).

A drawback of the simple water budget model developed in this study is that the outcome of the current and future scenario analysis (*GDR*) cannot be spatially (or temporally) scaled down to the sub-regional level, as lateral groundwater flow (i.e., subsurface flow between zones within a region) is not incorporated. The main reason for the missing lateral groundwater simulation is insufficient geohydrological information, which is a concern in many arid and semi-arid regions. Hence, the model cannot provide insight into the socio-economic (livelihood) implications of reductions in water use in the various zones, as it is unable to assess local (sub-regional) *GDR* in response to changes in land cover and surface water inflow in individual zones. *GDR* can only be obtained on a regional scale; that is, as a spatially-averaged quantity for the study area as a whole.

This research used the developed model to simulate the water budget for Wadi Zabid. The results indicate a -306 mm/yr decrease in groundwater storage for mean conditions, associated with a calculated groundwater depletion rate (*GDRc*) of -927 mm/yr using estimated local aquifer properties. This modelled *GDRc* corresponds rather well with the average observed groundwater depletion rate (-1,110 mm/yr) over the past four decades. The sensitivity analysis showed that, irrespective of differences in the input values, *GDRc* was at least -300 mm/yr. This underlines the unsustainable nature of present land use and groundwater exploitation at the scale of the wadi as a whole. A 30% decrease in agricultural land cover (and thus water consumption) in the future, along with a 30% increase in surface water inflow (from upstream), would lead to a reduction in *GDRc* by two thirds by 2060 (-319 mm/yr), assuming an 18% increase in rainfall due to climate change. A 70% decrease of agricultural land in the study area, combined with a 70% increase of surface water inflow, would be necessary to reverse the current groundwater depletion rate and initiate a slight recovery. However, reducing agricultural land by 70% will be impossible in the region as long as local livelihoods rely mainly on agriculture. Obviously, any further expansion of agricultural lands, in combination with less surface water coming from upstream, would lead to continuation of the present groundwater depletion and falling groundwater levels.

6.3 Main conclusions of the research

This thesis developed and tested a less complex and less data-intensive combined approach than sophisticated socio-hydrological modelling techniques? for assessing the extent, drivers and socio-economic impact of groundwater depletion, and to explore scenarios for sustainable land and water use in a data-scarce arid and semi-arid region in which the groundwater system was under heavy exploitation. The findings of the empirical chapters, summarized above, point to four key conclusions.

First, the PRA approach can be useful to overcome data scarcity, and thus for providing an adequate assessment of the different aspects of groundwater depletion. By bringing the tacit knowledge of stakeholders to the fore, combined with the expertise of investigators, PRA resulted in a better understanding of the impacts of groundwater depletion on livelihoods in the study area, and provided stakeholders' perspectives on the causes groundwater depletion as well as potential solutions. Each PRA tool used in this research had particular advantages in investigating specific aspects of groundwater depletion. Nonetheless, to complete the picture of the causes of groundwater depletion, a more integrated data analysis approach was also needed (Figure 6.1, Step 2), as stakeholders' perceptions were not always aligned with technical facts and expertise.

Second, a partial data analysis, especially when based on insufficient and uncertain data, can lead to inaccurate conclusions. This can be avoided by applying an integrated analysis approach, encompassing for example, locally sourced and remote sensing data. Such an integrated analysis, in this case, resulted in a clearer identification of the various drivers of groundwater depletion, both natural and human induced. It also revealed links between relevant policy decisions and changes in human activities related to water and agriculture. An integrated approach is particularly important in data-scarce, arid and semi-arid regions, such as Wadi Zabid, which are vulnerable to continuing depletion of already limited water supplies. Neither a purely hydrological nor a purely social science approach could have revealed such linkages; both approaches were required to do so.

Third, crop budget models are suitable for assessing the impact of spatial differences in groundwater depths and freely available spate water on the cost of irrigation and hence on returns to land and water. They were less suitable, however, for making recommendations about water reallocations, as crop budgets do not consider social benefits and costs of water.

Fourth, simple water budget models are useful for arid and semi-arid regions where long-term temporal and spatial datasets are unavailable, as comprehensive data are needed to implement sophisticated numerical groundwater models. This research showed that simple lumped water budget models can enable assessment of groundwater depletion rates and for developing scenarios on groundwater depletion at the regional scale (e.g., the whole study area) for specific long-term environmental conditions. These models were not, however, suitable for extrapolating spatial (and temporal) current and future scenarios on the sub-regional scale, and hence could not be used to derive insights into the socio-economic and livelihood implications of reductions in water use in individual sub-regions (e.g., zones within the wadi).

6.4 Discussion of the results

A less complex and less data-intensive combined approach for the study of groundwater depletion was developed and tested in this thesis to overcome data scarcity, which is an obstacle in many arid and semi-arid regions (Figure 6.1). This section discusses some implications of the main results for research and policy.

6.4.1 Research implications

This study underlines the importance and usefulness of PRA in bringing to the fore the implicit knowledge of local stakeholders. Such knowledge can be especially valuable in data-scarce arid and semi-arid regions, as local water users may have unique insights on various aspects of groundwater depletion (Figure 6.1, Step 1). Participatory approaches, in this study, contributed to mutual learning as well, as diverse opinions on the study theme were shared and collected. However, participatory approaches require that attention be paid to ensure adequate representation of different segments of society. One way to achieve this is by applying different PRA tools. As such, both individual and group interviews can be used to ensure that dialogue is not dominated by certain group, while recognizing that participants in group discussions can influence one another in beneficial ways, too, and stimulate mutual learning. Nonetheless, there is still an open debate as to whether stakeholders should be involved in knowledge production and decision-making processes (see, e.g. Moote et al., 1997; Korfmacher, 2001; Baldwin and Ross, 2012; Raadgever et al., 2012). Certainly, information gained from the community on technical aspects should be interrogated using specialized and integrated analysis techniques.

This study found that human activities, stimulated by policy measures, were the more dominant drivers of groundwater depletion in the study area compared to natural drivers. This study, however, would have benefited of a denser network of meteorological stations with longer data records. Especially when studying an arid or semi-arid region with erratic rainfall (both spatially and temporally) many data points are preferred to obtain statistical accuracies on par with temperate regions where rainfall is less variable.

This study calculated the economic returns of individual crops to land and water based on crop budgets. This method proved useful for assessing the impact of spatial differences in groundwater pumping depth and the availability of free spate water on the cost of irrigation. However, the method was less suitable for making recommendations about water reallocations, as it provided insight only into financial returns, and did not consider social benefits and costs of water, embodied in such aspects as food security, poverty alleviation and employment. Besides, farmers grew particular crops for a variety of reasons, such as for (crop) rotation purposes and food self-sufficiency. Their focus was thus not on maximizing returns to water.

The results of this study indicate that a simple water budget model is a suitable and satisfactory alternative to sophisticated groundwater models for data-scarce, arid and semi-arid regions. This is confirmed by other studies. For example, Healy and Scanlon (2010) found that the water budget can be used to assess the state of groundwater resources. The water budget is particularly suitable as a method to determine the degree of unsustainability of current groundwater use at the regional scale. Water budget models also enable exploration of differing scenarios for the future, i.e. estimation of groundwater depletion with particular changes in land cover (leading to changes in water consumption), in rainfall and in surface water inflow from upstream. However, this model studies the region for specific environmental conditions as a whole, and hence is unsuitable for analysing scenarios exploring in detail socio-economic (livelihood) implications of changes in water use at the sub-regional level and on a shorter temporal scale (e.g., monthly).

To apply the method on a sub-regional scale and with a shorter temporal span would require simulation of subsurface flows between the various sub-regions and changing the steady-state model to a transient model using a monthly time step. While implementation of these model changes are technically possible, but not relevant as a first step, due to data scarcity in the current study region. Databases with spatial and temporal data would need to be created first, which would take substantial time (i.e., years for temporal data). For example, in Wadi Zabid, only six gauging stations had more than 40-year time series of monthly rainfall data, although rainfall variability is high in such arid and semi-arid regions. Furthermore, monthly and even annual groundwater abstraction data and information of land cover, which drives water consumption, were often missing. If sufficient spatial and temporal data were available, a reliable transient numerical groundwater model could be developed to quantify spatially-distributed actual evapotranspiration, groundwater storage, groundwater heads and saltwater intrusion under different environmental conditions. This would allow assessment of the socio-economic (livelihood) implications of a change in water use at the sub-regional level.

Though the focus of this dissertation was groundwater depletion, the quality of the available water is also of essential concern. Groundwater depletion and water quality deterioration are often closely related near the coast, where groundwater over-abstraction leads to saltwater intrusion. It is important to note that some groundwater recharge in the coastal regions needs to be maintained to prevent further seawater intrusion.

6.4.2 Policy implications

The present research produced a number of findings that will be of interest to policymakers and decision-makers. The assessment conducted of the extent of groundwater depletion, its drivers, and its socio-economic impacts, as well as the scenarios and strategies explored for reducing or reversing declines in aquifer storage, provide insight into the scale and magnitude of the problem. In the study area of Wadi Zabid, the research findings point to a need to significantly reduce agricultural lands and thus water consumption along the wadi especially in midstream and upstream zones, to increase surface water flow and thus to slow the rate of depletion, in particular in the downstream and coastal areas of the wadi. Yet, because the local population depends on agriculture, reductions in agriculture would have to go hand in hand with stimulation of alternative income sources, for example, with economic incentives to achieve these. As an alternative, seawater desalination utilizing solar energy as a renewable power source could be pursued. But this is not as yet financially feasible. More spatial and temporal data would be required than is available now to develop more spatially detailed recommendations on how reductions in agricultural land and thus in water use might be implemented, their impacts (costs, benefits and risks) and how alternative income sources might be provided.

This study demonstrated that the government policy decisions and measures that have been taken over time can be studied by means of the combined approach in a more integrated manner, which tackles the various aspects related to these intervention and their immediate and future effects, whether, for example, their effects on water resources or on socio-economic aspects, in a way that serves the national interest. Such previous decisions are banning fruit import, fuel price subsidy, allowed public and private investment in well drilling and importing all related equipment (rigs, pumps etc.), provide loans to farmers, and development of irrigation-related infrastructure through building dams and canals.

In addition, the present instable political situation in the country has had wide and profound impacts, not least on the humanitarian situation and socio-economic aspects. During the field study, we found that the study area in Wadi Zabid, Tihama coastal plain, was among the regions most affected by the current situation, in terms of local food security and incomes. Inhabitants depended on agriculture as their main source of income, in addition to fisheries, yet the diesel crisis greatly affected farmers in the study area (often had to be purchased on the black market at very high prices). Also, previously farmers could easily market their agricultural products, both locally and abroad. Yet, this too had become difficult in the context of the current political situation. A larger proportion of agricultural products were therefore being lost to spoilage after harvest, especially due to the lack of cold storage facilities (with fuel shortages and electricity blackouts being contributors). Therefore, a focus on reducing post-harvest losses, particularly in view of the high temperatures in the region, would seem more economically beneficial than seeking to produce more in an area with such scarce water resources. Agricultural extension that provides training to farmers and best practices to reduce post-harvest losses could be of particular benefit in areas such as the study area, where illiteracy is high and environmental conditions are harsh.

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Summary

The overexploitation of groundwater resources, which is a problem in many arid and semi-arid regions, results into mining of groundwater and an associated continuous decline of groundwater levels impacting livelihoods. Assessing the various aspects of groundwater depletion, has become a very urgent matter. For the assessment of these aspects, comprehensive hydro-economic or socio-hydrology models are usually developed, but such models require a lot of detailed data. Data scarcity is a reality in many arid and semi-arid regions, and remains a major obstacle to the use of sophisticated numerical modelling techniques to study groundwater depletion. These regions often lack sufficient spatial data and a necessarily dense network of sufficiently long time-series data. This thesis, therefore, develops and tests the usefulness and effectiveness of an alternative less complex and less data-intensive combined approach for assessing groundwater resources, particularly the extent of groundwater depletion, the drivers of depletion and the socio-economic impact of depletion, and also develops scenarios for groundwater storage recovery. This approach was tested, in four steps, in the selected area in Wadi Zabid, that is located in the Tihama Coastal Plain, Yemen.

In the first step, the effectiveness of a participatory rural appraisal, including its various tools (e.g. semi-structured interviews, resources sketch mapping, daily calendars, timelines, transect walks and direct observation and problem and solution trees) was tested. This approach was found to be effective to assess the extent of groundwater depletion (change in groundwater levels) over the past four decades by employment of the tacit knowledge of stakeholders combined with the experience of researchers. This approach also contributed to learning about the drivers and proposed solutions of groundwater depletion from a stakeholder perspective. However, to reveal drivers of groundwater depletion an integrated data analysis approach was required.

In the next step of this research, the added value of an integrated data analysis approach to reveal the drivers of groundwater depletion was studied. Data analysis included the rainfall-runoff, remote sensing, groundwater wells, and historical timelines of policy measures and human activities. This was found to be an effective approach in revealing the effects of natural or human-induced drivers, and in disclosing the link between the changes in human activities related to water and agriculture, and the related political measures.

Human activities, represented by agriculture activities and accompanying expansion in wells drilling and construction of water harvesting and diversion structures were the main drivers

behind the continuous depletion of groundwater. Therefore, developing and testing a simple approach to calculate the economic return to land and water for the dominant crops was introduced as a third step. Its sensitivity to the continuous decline of groundwater levels and spate water availability was studied as well. It was found that the crop budget method is suitable for assessing the effect of spatial differences in the depths of groundwater and freely available spate water on the cost of irrigation and thus on the returns to land and water. However, the implemented method appeared to be less suitable to make recommendations about water reallocation, because crop budgets do not take into account the social benefits and the externality costs of groundwater depletion.

Finally, as a fourth step, a simple approach was developed to explore the impact of various scenarios on groundwater storage, including changes in land cover and availability of surface water from upstream regions (surface water inflow). The developed water budget (balance) model proved to be suitable for the regional assessment of the extent of groundwater depletion/recovery under current environmental conditions (mean, extended dry and wet periods). It confirmed the unsustainable nature of contemporary land use and groundwater exploitation in the selected test area in Wadi Zabid. The model also enabled investigation of the extent of future regional groundwater depletion/recovery for various scenarios of changes in land cover (water consumption), rainfall (considering climate change) and surface water inflow. In the test area, a decrease in agricultural land cover (and thus water consumption) by one-third and an increase in surface water inflow from upstream by one-third is required in the future to reduce the current groundwater depletion by two-third. However, such reduction of agricultural land in the test region will be difficult as long as local livelihoods rely mainly on agriculture. However, this water budget model is not suitable for assessing the depletion/ recovery at the sub-region level (e.g. zones within the test region) and thus its impact on the economic and social aspects.

The findings of this research will be of interest to policymakers and decisionmakers, as the study assessed the different aspects of the groundwater depletion and showed the link between those decisions and changes in human (water consuming) activities. Furthermore, the experiences in the test area show that a substantial investment is required in providing more spatial and temporal data than what is available now to develop complex hydro-economic or socio-hydrology models that enable comprehensive impact studies at smaller scales (e.g. sub-regions).

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Wahib Al-Qubatee was born in Taiz. He moved with his parent to Hodaidah where he finished his school education. Then he moved to Sana'a to continu his study, obtaining a bachelor degree in geology/physics from the Sana'a university, Yemen. After graduation, Wahib worked as geologist at the General Authority for Rural Water and Electricity Supply. After that he worked as geologist/ geophysics at the Yemen Geological Survey and Mineral Resources Board (GMSRB). He decided to complete his higher education, and he finished the MSc preliminary year (diploma) in Geophysics, Sana'a University. After that, he obtained a MSc in Integrated Water Resources Management from the Cologne University of Applied Sciences, Germany. After his MSc, he worked as a geophysical team leader and later a director of the Specialized Thematic Map Project at GMSRB. Later on, he worked (part time) as a researcher at the Water and Environment Center, Sana'a University and has he got admittance to do a PhD study at the Water Resources Management Group, Wageningen University and Research.

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- Scientific Publishing, Wageningen Graduate Schools (2016)
- Hydrogeology, Wageningen University (2016)

Management and Didactic Skills Training

- Supervising MSc student with thesis entitled 'The effect of land use and climate on surface water runoff in Wadi Zabid, Yemen' (2016)

Oral Presentations

- *Collaborative research to assess the degradation of groundwater resources in Al-Mujaylis, Tihama Coastal Plain, Yemen*. Social Water Studies in MENA Region,28 – 29 September 2014, Amman, Jordan
- *Participatory rural appraisal to assess the degradation of groundwater resources in Al-Mujaylis, Tihama Coastal Plain, Yemen*. Participatory research on conflicts and cooperation workshop, 20 - 22 April 2015, Kathmandu, Nepal
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