Water resources assessment under semi-arid conditions – modelling applications in a complex surface-groundwater system in Jordan

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ABSTRACT

Water scarce countries like Jordan, located in the Middle East, often fail to fulfil the water demand of different users, such as agriculture and domestic, and projections indicate that this deficit will increase. The adoption of the Integrated Water Resources Management (IWRM) approach considers all water users as interconnected consumers, competing for this resource. It provides a framework to define plans to address water resources pressures, produced not only by the nature of climate (semi-arid), but also by high population growth trends and over-extraction of groundwater for irrigation purposes. For local, basin scale planning it is essential to understand the water balance, and its elements and interactions, like for instance, land use and groundwater extraction.

In this dissertation, the groundwater system in the semi-arid southern Jordan Valley, west of the outlet of Wadi Shueib, is characterised to understand the groundwater flow dynamics and to simulate the observable trend of groundwater level depletion, using a numerical groundwater model. Future scenarios, such as possible hydrological conditions and management alternatives influencing extraction rates, are studied to evaluate their effect on groundwater levels and the water balance. This local-based numerical groundwater model is implemented with MODFLOW and is designed on a limited dataset. Values from literature, outcomes of previous studies, analytical methods and field surveys are combined to estimate unknown or unreliable abstraction rates. The principle of parsimony – keeping it as simple as possible – was applied, simplifying elements when possible (e.g. geology, distribution of hydraulic parameters) and meeting relevant assumptions when required (e.g. definitions of boundary conditions and time-series extrapolation).

In a second step, a decision support system modelling using the WEAP tool is adopted covering the two interconnected local basins of Wadi Shueib upstream and Jordan Valley downstream. Both are fed by two different main water sources (surface water and groundwater) and have two water competitors (domestic and agriculture) and hydrogeological characteristics (consolidated karst aquifer and a unconsolidated porous aquifer). Following the IWRM approach, the analysis is organized by applying scenarios, environmental indicators and a simplified visualisation decision space. Future scenarios are based on external uncertainties, such as population growth and climate, and strategies, determined mainly from the Jordanian water strategy. The water balance results from the previous numerical groundwater model in the porous aquifer are integrated in WEAP, achieving a complete water evaluation framework. The visualisation decision space, composed with the reliability of the strategies and regarding assumed acceptable standards for decision makers, is presented in the form of reliability colour grids, simplifying the final evaluation of the simulated scenarios.

The results of the numerical groundwater model show that groundwater heads present a high seasonal fluctuation at the outlet of the Wadi Shueib, which smooths towards the west. The calibrated model reproduces well the recharge processes from the northern unconsolidated and eastern consolidated aquifer and the continuous decline of water heads, especially at the eastern half of the modelled area, where most of the extraction takes place.

One of the most significant results of both numerical models is that water pressure in the Jordan Valley is caused by the current extensive groundwater pumping and it is just secondarily influenced by climate and therefore, sustainability can be only achieved by decreasing groundwater extraction rates. The overall results of the decision support system for both basins show that the implementation of strategies -with up to date unavailable financing- would be crucial, especially if decision makers aim to achieve the medium or high standards designated in this study.

The presented study presents a holistic approach to evaluate the upstream-downstream basins, defined by a surface-groundwater system, supporting an IWRM analysis. The modelling applications used in this dissertation can be updated by including new data as they become available in the future. The methodology described is transferable to other local basins in arid and semi-arid regions.

KURZFASSUNG

Länder wie Jordanien, die unter Wasserknappheit leiden, scheitern oft daran, den Wasserbedarf der verschiedenen Nutzergruppen aus dem landwirtschaftlichen und privaten Bereich zu decken. Aktuelle Prognosen deuten darauf hin, dass dieses Defizit in Zukunft noch weiter zunehmen wird. Der IWRM-Ansatz (Integriertes Wasserressourcen-Management) berücksichtigt alle Wasserverbraucher als miteinander verbundene Verbraucher, die um die Wasserressourcen konkurrieren. Er schafft einen Rahmen für die Erstellung von Plänen zur Bewältigung des Wasserressourcendrucks, der neben dem natürlichen Faktor Klima (semiarides) auch durch das zu erwartende Bevölkerungswachstum und die Überbeanspruchung des Grundwassers für die landwirtschaftliche Bewässerung aufgebaut wird. Für die lokale Planung auf Einzugsgebietsebene ist es wichtig, die Wasserbilanz sowie ihre Elemente und deren Interaktionen (z. B. die Landnutzung und die damit verbundene Grundwasserentnahme) zu verstehen.

In dieser Dissertation wird das Grundwassersystem im halbtrockenen südlichen Jordantal, westlich der Mündung des Wadi Shueibs, charakterisiert, um die Fließdynamik des Grundwassers zu verstehen und den Trend der Grundwasserspiegelsenkung mit Hilfe eines numerischen Grundwassermodells zu simulieren. Zukünftige Szenarien, wie etwa mögliche hydrologische Verhältnisse und Managementalternativen, die die Grundwasserentnahmeraten beeinflussen, werden untersucht, um ihre Auswirkungen auf den Grundwasserspiegel und die Wasserbilanz zu evaluieren. Dieses lokal basierte numerische Grundwassermodell wurde auf Grundlage eines limitierten Datensatzes entwickelt und mittels MODFLOW implementiert. Um unbekannte oder unzuverlässige Grundwasserentnahmeraten abzuschätzen, werden Werte aus der Literatur, Ergebnisse früherer Studien, analytische Methoden und Daten aus Feldmessungen herangezogen und kombiniert. Diese Arbeit wurde unter dem Prinzip der Sparsamkeit und Simplizität erstellt, wenn möglich wurden Elemente vereinfacht (z. B. Geologie, Verteilung hydraulischer Parameter) und bei Bedarf wurden, aufgrund mangelnder Datenlage, vertretbare und plausible Annahmen getroffen (z. B. Definitionen von Randbedingungen und Zeitreihenextrapolation).

In einem zweiten Schritt wird mit Hilfe von WEAP ein Entscheidungshilfesystem entwickelt, das die beiden miteinander verbundenen lokalen Einzugsgebiete, das stromaufwärts gelegene Wadi Shueib und das stromabwärts gelegene Jordantal, miteinbezieht. Beide beziehen ihr Wasser aus unterschiedlichen Bereichen (Oberflächenwasser und Grundwasser), haben zwei konkurrierenden Wassernutzer

(Privathaushalte und Landwirtschaft) und unterschiedliche hydrogeologische Eigenschaften (konsolidierter Karst-Grundwasserleiter und unkonsolidierter poröser Grundwasserleiter). Dem IWRM-Ansatz entsprechend wird die Analyse durch die Anwendung von Szenarien, Umweltindikatoren und einem vereinfachten Visualisierungsentscheidungsraum organisiert. Zukünftige Szenarien basieren auf externen Unsicherheiten wie Bevölkerungswachstum, Klima(-veränderungen) und Strategien, die primär durch die jordanische Wasserstrategie gesteuert werden. Die Wasserbilanz aus dem vorangehenden numerischen Grundwassermodell im porösen Grundwasserleiter wird in WEAP integriert und ermöglicht so den Rahmen für eine ganzheitliche Wasserbewertung. Der Visualisierungsentscheidungsraum, der sich aus der Verlässlichkeit der Strategien und angenommenen akzeptablen Standards für Entscheider zusammensetzt, wird in Form von Zuverlässigkeits-farbgittern dargestellt, was die abschließende Bewertung der simulierten Szenarien vereinfacht.

Die Ergebnisse des numerischen Grundwassermodells zeigen, dass der Grundwasserspiegel an der Mündung des Wadi Shueibs einer hohen saisonalen Schwankung unterliegt, welche sich nach Westen hin ausglättet. Das kalibrierte Modell bildet den Grundwasserzufluss aus dem nördlichen (unkonsolidierten) und östlichen (konsolidierten) Grundwasserleiter sowie die kontinuierliche Senkung des Grundwasserspiegels gut nach. Letztere findet vor allem in der östlichen Hälfte des modellierten Gebietes statt, in dem der Großteil der Grundwasserentnahme erfolgt.

Eines der bedeutendsten Ergebnisse beider numerischer Modelle ist, dass die Wasserressourcenknappheit im modellierten Gebiet primär durch die großflächige Grundwasserentnahme entsteht und das vorherrschende Klima nur eine untergeordnete Rolle spielt. Nur eine Verringerung der Grundwasserentnahmeraten ermöglicht eine nachhaltige Nutzung der vorhandenen Wasserressourcen und kann somit auch den Druck der durch die limitierten Wasserressourcen entsteht mindern. Die Gesamtergebnisse des Entscheidungshilfesystems zeigen, dass gerade jene Strategien umgesetzt werden müssten, für die aktuell keine finanziellen Mittel zur Verfügung stehen. Dies gilt vor allem, wenn die Verantwortlichen die in dieser Studie als mittelmäßig oder hoch definierten Standards erreichen möchten.

Die vorliegende Studie stellt einen ganzheitlichen Ansatz für die Umsetzung einer IWRM-Analyse vor, der die Bewertung aneinander grenzenden Einzugsgebiete, die durch ein Oberflächen-Grundwassersystem definiert werden, ermöglicht. Die im Zuge dieser Dissertation erstellten Modelle sind so gestaltet, dass die Berechnung aktueller Simulationen durch die Erneuerung oder Ergänzung von Daten möglich ist. Ebenso ist die beschriebene Methodik auf ähnliche Einzugsgebiete in trockenen und halbtrockenen Regionen übertragbar.

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LIST OF ABBREVIATIONS

BAU	Business as usual
BCF	Block-centered-flow
CIP	Capital investment plan
DSS	Decision support system
DWWTP	Decentralised wastewater treatment plant
EC	Electrical conductivity
FI	Full implementation
HRP	High resources pressure
IWRM	Integrated water resources management
LRP	Low resources pressure
MCM	Million cubic meter
MWI	Ministry of Water and Irrigation
NRW	Non-revenue water
PEST	Model-Independent Parameter Estimation and Uncertainty Analysis
SDG	Sustainable development goals
SM	Supplementary material
SMART	Sustainable Management of Available Resources with Innovative Technologies
STIM	Spatio-temporal infilling model
WEAP	Water Evaluation and Planning System
WWTP	Wastewater treatment plant
XLRM	Uncertainties-strategies-models-performance metrics

CHAPTER 1

1 INTRODUCTION

1.1 MOTIVATION/BACKGROUND

Most countries in the Middle East suffer of chronic to absolute water scarcity (Fig. 1.1), i.e. total renewable water resources per capita are less than 1000 or 500 m^3/a, respectively. Climate change and population growth are expected to worsen water availability and supply (IPCC 2014). One of the impacts of water scarcity is the inability to meet water demands for different sectors, such as domestic, industrial and environmental. Even water for irrigation for food production is insufficient (Seckler et al. 1999; Zhou et al. 2010). In Middle East countries, agriculture and livestock water-use percentage (compared with the total) to name some examples, is 60% in Lebanon, 87% in Syria, 86% in Egypt and 65% in Jordan (FAO 2016).

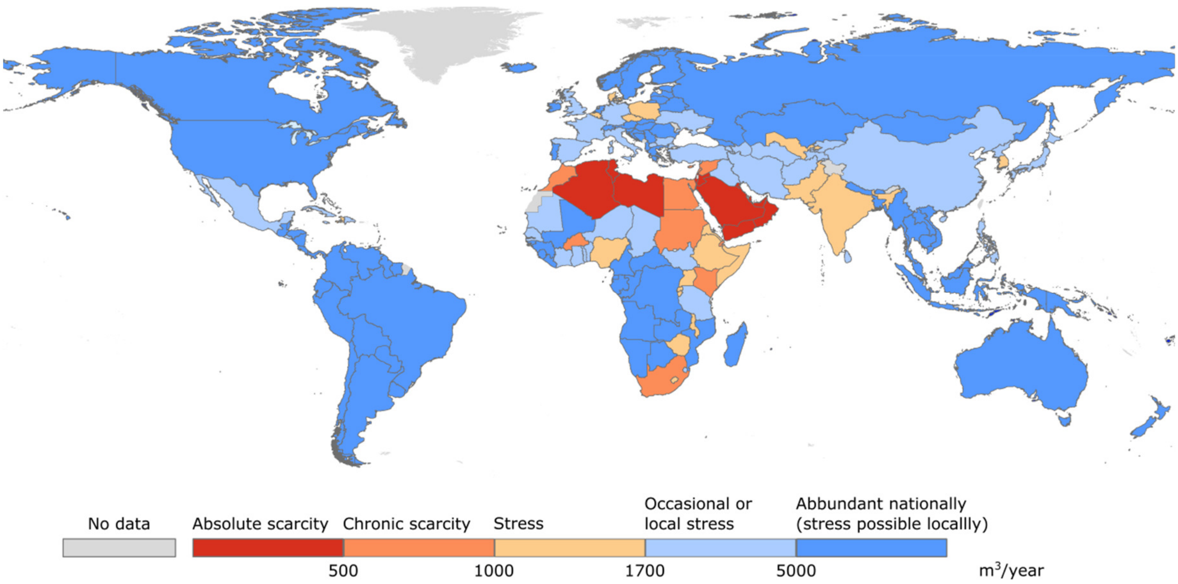


Fig. 1.1 Total renewable water resources per capita in 2014 in m^3/year. Modified after FAO AQUASTAT (2015).

In Jordan, water scarcity is attributed, among other causes, to (1) highly demographic growth and urbanisation, caused by the immigrants from neighbouring countries and internal immigration from rural to urban areas, and (2) an inappropriate agriculture development causing over-extraction of groundwater resources. For instance, the population of the sub-district of As-Salt, in Wadi Shueib, grew about 67% between 1994 and 2015 at a rate of 3% annually (DoS 1994; DoS 2015). On the other hand, despite the only 3% (in 2010) that agriculture represents of the total gross domestic product of Jordan (Transtec 2012), the Jordan Valley supplies around 70% of Jordan's total production of fruits and vegetables to the food basket of Jordan (Al-Weshah 2000a; Toll et al. 2008; Al-Omari et al. 2015). The main development of agriculture started in the mid-1970s and 1980s, when the government improved irrigation and cropping techniques; later in the 1990s, the competition between water users generated the transfer of fresh water resources from agriculture to urban areas (Venot et al. 2007) and groundwater became the main source of water destined for agriculture. Groundwater extraction for irrigation represents 70% of the total demand in the Jordan Valley (MWI 2004) and over-extraction has caused the decline of groundwater heads at a minimum rate of 1 m per year since 1992, reducing the natural storage of the aquifer and deteriorating the water quality (Al Kuisi et al. 2006).

To deal with scarce water resources, their use and allocation, management strategies should base their analysis on a holistic comprehension of the water balance, explaining each element of the basin and their interactions (Steduto et al. 2012). Sustainable management solutions to cope with a deteriorating system should be implemented, which can only be achieved by understanding the local basins and their hydrogeological conditions, considering if the water resources rely on surface water, groundwater, or both.

Many studies have addressed a water resources management approach, but most of them lacking of a detailed comprehension of the local basin to generate management strategies in smaller scales than regional. Moreover, those studies which address the hydrogeological context do not consider scenario simulations that examine the effect of possible management strategies in a local context. They also are deficient in the visualisation of results, which is usually criticised as a drawback of scientific work and how modellers communicate modelling outcomes to decision makers (Ludwig et al. 2014). In this dissertation, a flow characterisation of the groundwater system is applied to study possible future scenarios, and their results are combined within a decision support system that includes the local analysis of two interconnected water basins (upstream and downstream), with different natural water sources, surface and groundwater, and with two water competitors, domestic and agriculture, including real water strategies and applying a visualisation space to simplify the understanding of the final results.

1.2 INTEGRATED WATER RESOURCES MANAGEMENT IN ARID AND SEMI-ARID REGIONS

In regions that suffer water scarcity such as arid and semi-arid regions, the implementation of plans to manage water is essential to achieve goals like efficient allocations, cost recovery and sustainable development. Integrated water resources management (IWRM), interpreted as an approach to develop water management balancing economic efficiency, social equity and environmental sustainability (Gallego-Ayala 2013), has been in the agenda of many countries affected with water scarcity (Polak et al. 2013).

The water sector in these regions experiences several challenges that needed to be address, starting from concrete management of the resources, identifying key issues, such as weak governance (top-down institutions, which incentive competition of a limited resources), securing water for people and food production, affected ecosystems and gender disparities. The application of IWRM can contribute to solve these challenges creating coordinated strategies to tackle the causes of these issues (see Fig. 1.2). IWRM can be implemented as cycle, creating a vision, analysing the problems and defining goals and strategies, putting the plan into action and evaluating it, all this, with stakeholders participation, awareness raising and political commitments (Cap-Net et al. 2005). Moreover, the application of IWRM should be adapted to the local framework (Jeffrey and Gearey 2006) to address the issues of smaller groups and communities.

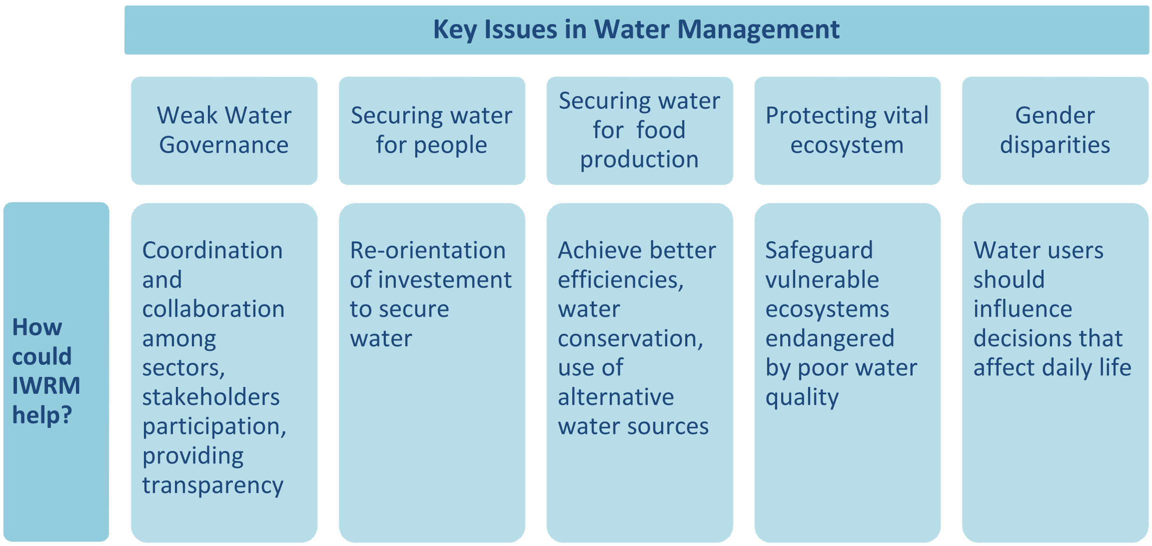


Fig. 1.2 Key issues in water management and IWRM solutions approach. Based on the text from Cap-Net et al. (2005).

Examples presenting the implementation of IWRM in water scarce countries are found in Morocco, where a policy and institutional reforms were strengthened to develop, among other measures, a long-term investment program, a water law in 2005, new legal and institutional structure to promote decentralised management and monitoring of water sources (Polak et al. 2013; USAID 2013; Martínez Santos 2014); in Yemen, improving water service availability, decentralisation and integrated management at basin level with a legal framework including IWRM since 2004 (Polak et al. 2013; Ward 2015); in Egypt, where despite the lack of a law regulating water, the Ministry of Water Resources and Regulation established a management plan adopting an IWRM approach, enhancing the irrigation system and monitoring to promote public awareness programs (Shakweer and Youssef 2007; Polak et al. 2013); and in Jordan, where since 1997 the water strategy has considered the protection of resources, use and reuse of unconventional water sources (Riepl 2013), and the current national water strategy considers explicitly IWRM as a key part of it (MWI 2015a).

These satisfactory examples, however, present also difficulties in the implementation of the appealing concept of IWRM caused, among other reasons, by geographic separation of basins, integration of other sectors that depend upon water, power struggles between institutions, weak institutional framework, disorganisation in data management and monitoring or lack of adequate and reliable data, difficulties in respecting and enforcing rules, uncertain financial sustainability, adoption of technology suitable for physical and socio-economic realities, and gaps in available knowledge and technology (IWA UNEP 2002; Shakweer and Youssef 2007; Hübschen 2011; Polak et al. 2013; Klinger et al. 2016).

Despite the difficulties to implement IWRM in these water scarce countries, the IWRM approach settles the foundation for an organised plan that deals, in some scale, with an extremely dynamic system: water scarcity in times of climate change, the globalising world, war conflicts, as well as internal and external migration.

1.3 WATER MANAGEMENT IN JORDAN

1.3.1 Water resources in Jordan

Jordan is one of the few countries falling in the category of absolute water scarcity with less than 500 m^3/year total renewable water resources per capita in 2014 (FAO AQUASTAT 2015) (Fig. 1.1). According to the national surface water budget for 2015, from the around annual 8800 million cubic meters (MCM) of rainfall, 92% is lost in evapotranspiration, 5% infiltrates to the groundwater and 3% is runoff (MWI 2016a). Projections on future water demand and supply estimate an increasing water deficit of around 450 MCM by 2020 (Table 1.1).

The main causes for the water problematic (scarcity and pollution) in Jordan are: (1) precipitation shortfall, (2) the rapid population growth combined with high urbanisation and industrialisation, (3) insufficient industrial and municipal wastewater treatment and excess of fertilizer used in agriculture, and (4) high water consumption, especially over-extraction in agriculture (Hadadin et al. 2010).

Table 1.1. Projected water demand, supply and deficit in Jordan in MCM/a (Hadadin et al. 2010).

	2020	2040
Projected water demand [MCM]		
Domestic	670	1263
Irrigation	802	803
Industrial	130	170
Total [MCM]	**1602**	**2236**
Water supply [MCM]	1152	1549
Water deficit [MCM]	450	687

Water resources are shared among domestic, agriculture, industrial and tourism users. After 2006, the municipal total annual water demand has increased from around 300 to 450 MCM in 2015; and after 2012 the domestic demand has annually increased around 30 MCM, as an effect of the significant population growth of 60% in the period 2012-2015 resulting from the immigration from neighbouring countries. By 2015, Jordan was hosting 1.4 millions of Syrians, being around 650 thousand refugees (MOPIC 2016a). The coverage of drinking water supply nationally is 94% (MWI 2015a) and it is available in shifts of 24, 48 or 60 h per week, depending on the housing density (Grimmeisen et al. 2016). Agriculture was the major user of water in Jordan; however, the increment of domestic use has rearranged this condition, becoming agriculture and municipal demand almost equal competitors for water resources (Fig. 1.3a) (DoS 2016; MWI 2016a).

Groundwater provides 60% of the total water sources for consumption in Jordan (Fig. 1.3b). The increased pressure on groundwater resources from the municipal demand has been slightly alleviated with the Disi project, where fossil water from the Disi aquifer (extended from southern Jordan to Tabuk in the northwest of Saudi Arabia) is pumped to the capital of Amman and other governorates. The Disi aquifer has an estimated capacity of billions of cubic meters and the safe yield of around 100 MCM/a, and would be proper for 100 years extraction time, as stated from results of several studies in Salameh et al. (2014). The project started pumping 90 MCM/a to Amman in July 2013 and in January 2014 began operating at full capacity with 105 MCM/a (Namrouqa 2014). However, this water is limited and other solutions must be found before it runs out.

The water supply for agriculture between 2006 and 2015 has been relatively constant with an annual average of 500 MCM and if this trend continues, the projected water demand for irrigation by 2020 indicates a deficit of around 300 MCM. In 2015, groundwater resources provided 46% of the total water demand for irrigation. The implementation of measures from the water strategy plan of 2009 has allowed the closure of 1028 illegal wells between 2009 and 2015. Furthermore, treated wastewater was introduced as an unconventional water source, with an increasing consumption from 80 MCM in 2006 to 133 MCM in 2015, representing already 26% of the water source for irrigation purposes in 2015 (MWI 2009; MWI 2016a). Other unconventional water sources have been found in water harvesting, which collects rainfall for the domestic use or irrigation, desalination of brackish water, where plants have been built for industrial purpose or agriculture with capacities between 23 and 1875 m^3/h (Mohsen 2007), and manage artificial recharge (MAR), method to store floodwater in the underground to consume it during dry seasons, and that also prevents the permanent over-exploitation of aquifers (Xanke et al. 2016).

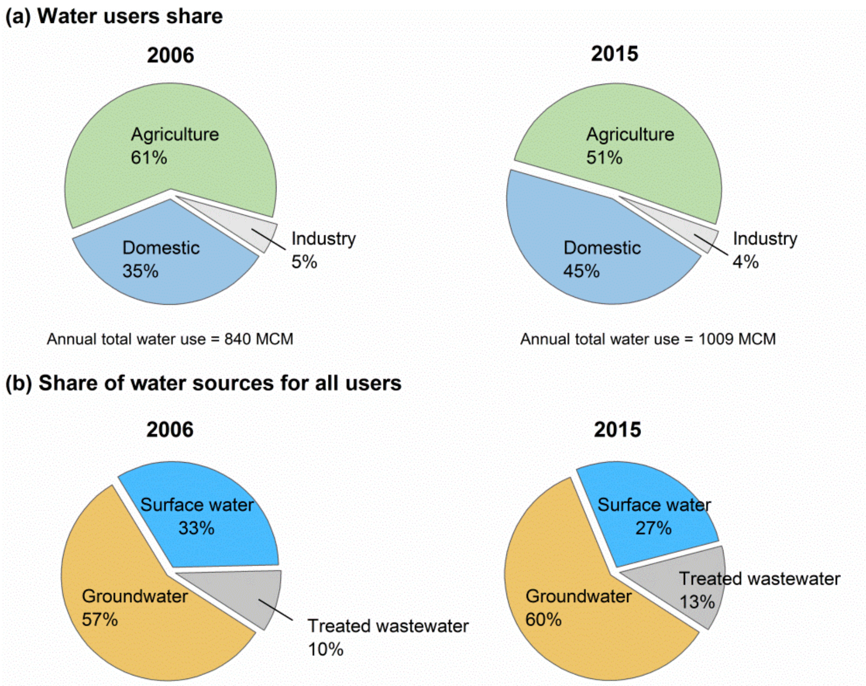


Fig. 1.3 Shares of (a) water users and (b) water sources at national level for years 2006 and 2015 (MWI 2016a).

Another issue within the water resources management in Jordan is the around 50% of non-revenue water (NRW) over time. NRW is the difference between the volume of water placed into the water distribution system and the volume that is actually billed to customers. This difference comes from physical (or real) losses (e.g. leaky supply pipes), commercial losses (e.g. data errors, illegal connections), and unbilled authorised consumption (e.g. for firefighters) (Kingdom et al. 2006). The reduction of NRW requires the efficient implementation of three elements: improvement of the supply network, operations and maintenance, and effectiveness on the public metering and billing procedures (Riepl 2013).

1.3.2 Water strategy in Jordan

After the creation of the Ministry of Water and Irrigation (MWI) in the late 1980's, the first plan "Jordan water strategy and policies" was prepared in 1997 and it was designed for water policy making in Jordan focusing on the importance of improving the management of water resources with emphasis in sustainability (Riepl 2013). The following strategy of 2009, "Water for Life", specified a vision and action plans to achieve by 2022. With "Annual Reports" the actual water situation of Jordan started being tracked and clear measures were defined to achieve objectives, such as secure drinking water supply, a sustainable use of water resources, and to understand and improve the water management (MWI 2009).

In 2015, a new water strategy was established for the period 2016-2025. Considering the Sustainable Development Goals (SDG) by the United Nations, resilience and sustainability are stated as priorities in the water sector, defining the main goal as "to ensure availability and sustainable management of water and wastewater for all Jordanians" (MWI 2015a). The new Water Sector Strategy has five essential planning areas:

1. Integrated water resources management (IWRM)
2. Water, sewages and sanitation services
3. Water for irrigation, energy and other uses
4. Institutional reform
5. Sector information management and monitoring

The water strategy is coupled to a capital investment plan (CIP) to ensure viable financing considering expansion of services, and rehabilitation and replacement of existing infrastructure (MWI 2015a). The first three planning areas are in more detailed explained in the water strategy and they are summarised as follows:

i. IWRM in the new water strategy

IWRM is defined as a national development strategy to provide a water resources management on the foundation of sustainability, economic efficiency and social equity. The MWI leads the implementation of IWRM, considering the communication and cooperation with other ministries (e.g. Ministries of Agriculture and Environment) and other water related stakeholders, such as user groups, service providers, local authorities, farmers, etc.

The IWRM strategy implementation is based on the reinforcement of three elements: water resources security, water resources development and additional amounts of supply (Fig. 1.4).

Water resources security. As response for the regional political crisis in the Middle East a Water Resource Security map was adopted and implemented to safeguard resources from risks, including terror attacks. The communication and coordination takes place among security organisation and authorities in Jordan. Infrastructure (e.g. water networks, wastewater treatment plants, dams, etc.) and water quality must be protected and monitored (MWI 2015a).

Water resources development. The water deficit should be alleviated with a strong emphasis on the efficiency of the water use and on the development of new water sources such as, water harvesting, desalination, increase of runoff storage, artificial recharge, and treated wastewater. Measures to prevent inadequate water practices are: (1) restrict groundwater over-extraction, assessing groundwater potential, (2) maximise the adoption of treated wastewater for irrigation, (3) re-allocate the water resources accordingly to national priorities and (4) develop sustainable and cost-effective treatment and desalination options (MWI 2015a).

Additional amounts of supply. Additional water supply (80 MCM by 2021 and 150 MCM by 2025) is expected from the Red Sea-Dead Sea project (a pipeline that connects both seas to supply drinking water to Jordan, Israel and Palestine). Another 15 projects (e.g. desalination, new well fields and water harvesting) should provide 187 MCM extra by 2025 (MWI 2015a).

ii. Water resources, sewages and sanitation services

Jordan covers 94% of the population with safe drinking water, of which 64% is connected to public sewer system, and about one third corresponds to septic tanks and cesspits. The water strategy focuses on sustainable water management maintaining high rates of water supply and increasing sanitation coverage. The programme considers, among other strategies, to modernise and maintain water networks, the installation of water-saving devices for domestic use and enforcement of a national standardised plan for plumbing and water products, to provide a procedure to regulate costs of operation and maintenance (MWI 2015a).

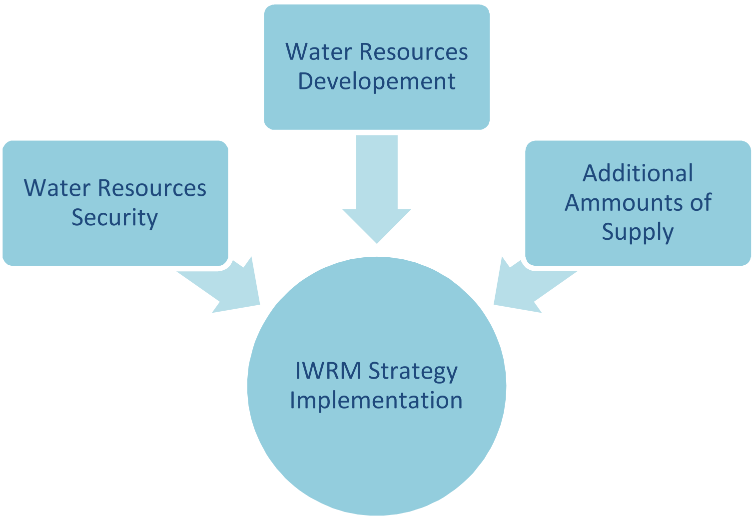


Fig. 1.4 The IWRM strategy implementation in Jordan is based on three main features (MWI 2015a).

iii. Water for irrigation, energy and other uses

The competition of different water users, domestic, food production, industrial development will be tackled by the MWI with a multi-sectoral and integrated approach, considering national priorities and the environment.

For the agriculture it is expected to increase water productivity, reduce losses and shifting cropping patterns, including the reuse of treated wastewater, decrease groundwater over-extraction to safe-yields and enforce existing regulations.

The energy sector has to work on technical inefficiencies and optimise energy consumption improving rehabilitation, operation and maintenance of distribution systems, including the option of renewable energy system.

Agriculture should be considered as a priority above other water users such as industry and tourism, and the treated wastewater should be allocated for the cooling of the two projected nuclear power plants. Finally, climate change is also seen as risk for the water system and the limited water resources should be protected by upgrading drinking water quality management system and surveillance programmes (MWI 2015a).

1.4 SIMULATION MODELLING FOR IWRM

Models, especially within the IWRM framework, should simplify the communication in the decision making process (Heinz et al. 2007). Hydrological models that represent the water system, showing water volumes and responses associated to stresses, for instance water withdrawal, help to characterise and understand the basin, for regional or local analysis. Their outputs can be combined with other data sources, e.g. survey data, creating a decision support system (DSS) to facilitate stakeholders the decision making process in management, planning and operational aspects (Andreu et al. 1996; Heinz et al. 2007). A DSS uses data and models, supporting an easy-to-use and convenient interface including decision-makers visions (Matthies et al. 2007).

Numerical modelling in IWRM should be representative of the problem, flexible and accessible, considering also a multisector integrity, namely communication between water users, governmental administrators and the scientific sector (Silva-Hidalgo et al. 2009).

In this study, two numerical tools were applied: (1) a numerical groundwater model that serves to characterise the local basin in the Jordan Valley and (2) a DSS modelling structure, the Water Evaluation and Planning system (WEAP), that covers the region of Wadi Shueib and downstream in the Jordan Valley.

1.4.1 Groundwater modelling

Numerical groundwater models are extensively used to understand the dynamics of an aquifer system, to characterise the underground water flow and to simulate impacts of different management scenarios (Zhou 2009). MODFLOW is an open source, finite-difference numerical modelling software that simulates flow through porous media. It solves the flow equation dividing the system into a grid of cells (Fig. 1.5) transforming a continuous problem in an algebraic discrete one; the water head is then calculated for each single point defined in every cell (Harbaugh et al. 2000).

Based on Darcy´s law, the governing groundwater flow equation used in MODFLOW is Equation 1.1.

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial y}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)+W=S_s\frac{\partial h}{\partial t} \quad (1.1)$$

where, K_{xx}, K_{yy}, K_{zz} are the values of hydraulic conductivity along the x, y and z coordinate axes [L/T], h is piezometric head [L], W is the volumetric flux per unit volume (sources or sinks) [1/T], S_S is the specific storage of the material [1/L] and t is time (Harbaugh et al. 2000; Anderson et al. 2015).

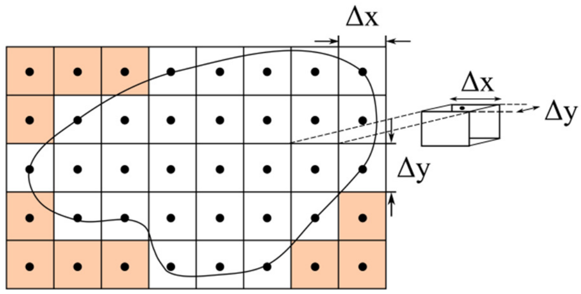


Fig. 1.5 Two-dimensional horizontal finite difference grid centred in the cell, where the contour represents the model domain, *white* cells are active and *orange* cells inactive. Based on Anderson et al. (2015).

Regarding their specific objectives, numerical groundwater models using MODFLOW are adopted as a tool to address for example: groundwater over-extraction due to irrigation (Ramireddygari et al. 2000; Mao et al. 2005; Zhang et al. 2011), groundwater availability assessments (Uddameri and Kuchanur 2006; Faunt 2009), groundwater-related subsidence (Shearer 1998), or density dependant flow due to salt water intrusion in coastal aquifers (Calvache and Pulido-Bosch 1997; Sherif et al. 2011).

Well documented groundwater modelling examples performed in Middle East countries are difficult to find. Some examples are: regional models that simulate impacts of groundwater extraction (Ebraheem et al. 2002) or determine water balances to understand the system (Margane et al. 2002; Rink et al. 2011). Basin-scale models that define scenarios based on future groundwater abstraction rates (Al Mahamid 2005; Abdulla and Al-Assa'D 2006). Especially in the southern Jordan Valley, Toll (2007) was able to characterise the water system and simulated historical events, such as the cease of pumping during war in 1967, periods of droughts and wet years events concluding that further investigation should be done in the field to model in small scale areas and that the model should simulate future abstraction strategies. Other local models are also used to characterise the hydrogeological system, but they also lack of future scenario definition (Ahmed 2009; Wu et al. 2011).

1.4.2 Decision support systems for water resources

Decision support systems provide decision makers with data and models that provide an easy-to-use and convenient interface including decision-makers insights (Matthies et al. 2007). Modelling tools for DSS in water resources, are for example AQUATOOL (Andreu et al. 1996), MIKE HYDRO BASIN (DHI 2012) and WEAP (Yates et al. 2005). They are based in interactive river-aquifer simulation platforms represented by a structure of nodes and links (Loucks et al. 2005). WEAP has a 2 years free licence for non-profit, governmental or academic organisation based in developing countries, promoting its distribution and application in Middle East countries. It executes an algorithm to allocate water among different users (e.g. municipal, agriculture) within a basin, maximising water demand supply subject to user-defined constrains, such as physical limitations or demand priorities; and integrates a hydrologic sub-model including, for instance, a rainfall-runoff analysis, where rainfall is distributed among evapotranspiration, runoff and flow to groundwater (Yates et al. 2005; Sieber and Purkey 2015).

WEAP has been applied for transboundary analysis in the Jordan River Basin, addressing environmental, technical, socio-economic, institutional and political elements using a participatory scenario development focus with stakeholders from Jordan, Israel and Palestine. Annual basin unmet demands for socio-economic demand scenarios, including climate change were projected. Challenges involving such a wide basin analysis in the region are political affairs and data heterogeneity. Results showed that population trends and economic policies are crucial factors in ensuring future water security in the Jordan River basin (Hoff et al. 2011) and infrastructure and management require improvement to cover the water demand (Bonzi et al. 2016).

Regional basin scale modelling in Jordan has been also done with WEAP. The Amman-Zarqa basin, an intensively developed and populated basin in northern Jordan, was studied with scenario simulations until 2025, including strategies regarding wastewater treatment, the Red Sea-Dead Sea project, considering conventional and unconventional water sources (e.g. reuse of treated wastewater), and integrating the socio-economic development. Results showed that the irrigation demand supply, which represents at least 50% of the total water demand in the basin, would be only covered incorporating additional unconventional water sources (Al-Omari et al. 2009). Similar results were obtained for a WEAP modelling set-up in the Jordan Valley, in all its extension from Lake Tiberias to the Dead Sea; simulations and scenario modelling showed that irrigation water shortage could only be reduced with the implementation of the Red Sea-Dead Sea pipeline and that the improvement of irrigation efficiency, the reduction of non-revenue water and additional water from the Disi project (fossil water from the Disi aquifer located in southern Jordan) would be insufficient to cover the irrigation demand (Al-Omari et al. 2015).

Local basin scale modelling was done by Riepl (2013) in Wadi Shueib, Jordan. It included areal rainfall, evapotranspiration, surface runoff, groundwater recharge, water consumption and return flows in the Wadi Shueib catchment, considering also water import from external supplies. The modelling focused mainly in the municipal supply and the management of resulting wastewater return flows. The scenario modelling until 2025 showed that the implementations of the water strategy by the time of the study are insufficient to achieve national objectives. A water balance for the Wadi Shueib basin for the year 2008 was also calculated and indicates that 80% of the rainfall is lost in evapotranspiration, 16% infiltrates in the groundwater system and merely 4% runs as runoff through the Wadi course (Riepl 2013).

i. Coupling a numerical groundwater model to WEAP

The WEAP model includes the option to be coupled to MODFLOW, making possible to analyse the influence of groundwater levels in the overall system and vice versa (Sieber and Purkey 2015). For each time-step, the simulations of one model are linked as input data to the other; WEAP calculates groundwater recharge, abstraction rates and river stages, and MODFLOW estimates groundwater heads and the water budget (Maßmann et al. 2010).

Maßmann et al. (2010) developed a coupled WEAP-MODFLOW Model in the Zabadini Basin, north-west of Damascus, Syria. They linked a three-dimensional numerical groundwater model to a WEAP model, simulating scenarios for the period 2005-2017, regarding an increase of domestic and agricultural demand, and influences of climate change, reproducing an expected groundwater drawdown. In the Haouz-Mejjate plain in Morocco, Page et al. (2012) concentrated their efforts in estimating the agriculture water requirement through remote sensing and then linked WEAP with MODFLOW, obtaining acceptable simulated groundwater heads for the period 2001-2008. However, the model does not have a calibration for surface flows and scenario modelling. In south-eastern Tunisia, the regional zone of Zeuss Koutine was modelled with a WEAP-MODFLOW link by Hadded et al. (2013), who used constant recharge from adjacent aquifers to define the boundary conditions. It reproduces groundwater heads in three observation wells and it extends the analysis until 2027 maintaining the observed tendencies and concluding that the desalination plant in operation helps to mitigate groundwater drawdown. No other scenarios were simulated.

The first two studies conclude the necessity to add more measurements to improve the models. Moreover, the three groundwater models are made at regional scale and present a clear definition of boundary conditions, allowing the link between MODFLOW and WEAP to be a straight-forward process, using a vector file that contains the dependence of each cell of the numerical groundwater model to the surface model.

1.4.3 *Challenges of modelling in semi-arid regions*

i. Data Scarcity

Dispersed and scarce data and records are a major challenge faced by modellers for most arid and semiarid regions. Certain data, such as aquifer geometry, hydraulic parameters and measured abstraction rates, are often unknown. Different authors have generated an adequate database to construct groundwater models in semiarid regions using different techniques: Laronne Ben-Itzhak and Gvirtzman (2005) constructed a three-dimensional groundwater model in the Judean Dessert in Israel gathering data from previous studies; Candela et al. (2014) generated data during field campaigns and re-evaluated the available information for the Lake Chad Basin, in Chad; Switzman et al. (2015) used previous studies and remote sensing imagery to create a spatio-temporal infilling model (STIM) determining long time series of land use for a numerical groundwater model in northern Egypt. Toll (2007) created a finite element transient model in the Lower Jordan Valley, using vertical electrical sounding and hydro-chemical charts, determined salinity distribution and variation of the composition of the groundwater flow path, which helped to define the hydraulic conductivity. For each modelled area and according to the desired spatial and temporal scale, compromises are made to fill gaps of scarce and sparse data. Traditional techniques (e.g., installation of new boreholes, pumping test) are not always possible due to time and cost constraints, and also, notably in the Middle East, due to political issues.

ii. Representing results of Decision Support Systems

The definition of future scenarios in DSS, based on the implementation of potential management strategies, supports decision makers to visualise the effects of those action plans on the water system. However, after the scenario planning a more detailed phase to evaluate results is needed (Montibeller et al. 2007). Indicators are an extensively applied tool to describe the system through attributes relevant for decision makers helping to assay the results of the scenario planning (Sullivan et al. 2003; Klug and Kmoch 2015). The selection, interpretations and use of indicators is complex (Moldan et al. 2012). Pires et al. (2016) made an extensive list classifying indicators related to water use and management that can help modellers to translate the results into understandable indices.

Moreover, most of the studies performed in the Jordan Region with WEAP (see e.g. Al-Omari et al. (2009); Hoff et al. (2011) and Al-Omari et al. (2015)) present a direct quantity output from the WEAP platform, such as unmet demand of demand sites and coverage supply. However, they lack of a comparative overview of scenarios and resulted quantity. Comair et al. (2012) and Riepl (2013) added a performance criterion to evaluate and confront scenarios. Still, there has to be an agreement of what is acceptable (Moldan et al.

2012), so that decision makers can relate to the results analysing different levels of satisfaction or tolerance. Therefore, modellers should also concentrate their efforts on presenting results as clear as possible, to avoid misinterpretations and enhancing their comprehension, since eventually, models support decision makers to make informed and evaluated decisions on water management strategies considering, in this case, the allocation and re-allocation of water.

One method to perform an organised DSS analysis is the so-called "XLRM" framework defined in Lempert et al. (2003). The "XLRM" approach, described in more detail in Chapter 4, consists on constructing a matrix that represents four features that together determine water resources management, such as the uncertainties of the system (X), strategies planned (L), how to assess the system (R) and evaluation of the system and plans (M) (Kalra et al. 2015; Forni et al. 2016). Forni et al. (2016) presented two case studies of IWRM analysis using the XLMR framework, WEAP and a visualisation tool to support the evaluation of different strategies by stakeholders.

1.5 OBJECTIVES AND RESEARCH APPROACH

The principal objective of this thesis is to evaluate an upstream-downstream water system in Jordan that is characterised for different features such as the nature of the water sources (surface and groundwater), hydrogeology (unconsolidated and consolidated aquifers) and the uses of the water resources with two strong water competitors, domestic and agriculture (Fig. 1.6). Two specific objectives for this dissertation are:

1. Characterise the groundwater system in the Jordan Valley, modelling the water flow under data scarcity, and analysing possible future scenarios based on hydrological conditions and water strategies

2. Generate a decision support system under the framework of IWRM for a local basin analysis, studying two interconnected basins and evaluating the effect of future water strategies on the water resources.

Fig. 1.6 (Left) agriculture in the Jordan Valley and (right) city of As-Salt, the main urban settlement in Wadi Shueib.

First, a local-based numerical groundwater model with MODFLOW is presented using a scarce dataset by adopting alternative methods to deal with data scarcity, to simulate the observable trend of groundwater level depletion in the southern Lower Jordan Valley (specifically, west of the outlet of Wadi Shueib) and to model different scenarios regarding possible future hydrological conditions and management alternatives influencing extraction rates. To construct the numerical groundwater flow model, a limited dataset is used and combined with outcomes of previous studies estimating unknown or unreliable abstraction rates and defining input parameters that describe the hydrogeological system. Given the uncertainty of the limited data, the principle of parsimony – keeping it as simple as possible (Hill 1998) – was adopted, simplifying elements when feasible (e.g. geology, distribution of hydraulic parameters) and meeting relevant assumptions when required (e.g. definitions of boundary conditions and time-series extrapolation).

Second, a decision support system modelling using the XLMR framework and WEAP is set-up. To account for the detailed analysis done in the porous aquifer in the Jordan Valley, the results of the numerical model are integrated in WEAP and a complete water evaluation framework for the interconnected local basins of Wadi Shueib and Jordan Valley is created. The scenario results, based mainly on the Jordanian water strategy, are then interpreted with environmental indicators and showed in a simplified visualisation decision space, based on the reliability of the strategies, regarding assumed acceptable standards for decision makers.

1.6 STRUCTURE OF THE THESIS

This thesis is organised in five different chapters. One peer-reviewed publication was accomplished within the development of this dissertation and parts of it were distributed over this thesis, organised in the following chapters:

Chapter 2 presents a characterisation of the study region - Wadi Shueib and the Jordan Valley. Portions of this chapter were taken from Alfaro et al. (2017). The chapter is divided in the sections: geographical setting, geology, hydrogeology and water quality.

Chapter 3 addresses the construction and simulation of the numerical groundwater model in the Jordan Valley using MODFLOW. This chapter is mainly based on Alfaro et al. (2017), which was partly restructured, modified and enhanced with the addition of new scenarios.

Chapter 4 focuses on the set-up and further modelling of a decision support system with WEAP, including Wadi Shueib and the Jordan Valley. It presents the results of scenario modelling with the definition of environmental indicators and a visualisation decision space system.

Chapter 5 summarises the results and conclusions of the numerical approaches addressed in Chapters 3 and 4 and discusses the potential future use of the approaches presented in this study.

CHAPTER 2

2 CHARACTERISATION OF THE STUDY REGION

2.1 GEOGRAPHICAL SETTING

The study region is located 10 km north of the Dead Sea, in the eastern part of the southern Lower Jordan Valley with its adjacent mountainous area of Wadi Shueib in the Balqa Governorate in Jordan (Fig. 2.1). The topographic elevation difference between the highlands in the east (900 m asl) and the floor of the valley (-200 m asl) results in large spatial precipitation variability. Average annual precipitation in the city of As-Salt in Wadi Shueib (station AM0001) is around 600 mm and in the Lower Jordan Valley (station AM0007) it can be less than 200 mm. The main precipitation period is from October to May. The topography also influences the temperature distribution. In the highlands, the average temperature is around 5 to 10°C less than in the Jordan Valley, where monthly average temperatures are 15.6°C in January and 32.8°C in July (Fig. 2.2).

Precipitation in the highlands partly recharges the karstified aquifer underneath; the rest flows as surface runoff downstream via the wadi, reaching its main outlet, the Wadi Shueib dam (Fig. 2.3), constructed in 1969 with a storage capacity of 1.4 million cubic meters (MCM). The dam is employed for managed aquifer recharge (MAR), since it allows infiltration of stored surface water into the aquifer. Thirteen springs are found in the study region, four of them are used for drinking water supply (Margane et al. 2010). The outflow of the other nine springs is mixed with effluent of two wastewater treatment plants and joins the Wadi Shueib runoff (Zemann et al. 2015).

Groundwater from the karstified aquifer infiltrates into the unconsolidated porous aquifer as lateral recharge at the edge of the Rift Valley (Salameh 2001). Around 200 regulated extraction wells and an unknown number of private illegal wells mainly for irrigation purposes operate in the Jordan Valley floor in the study area.

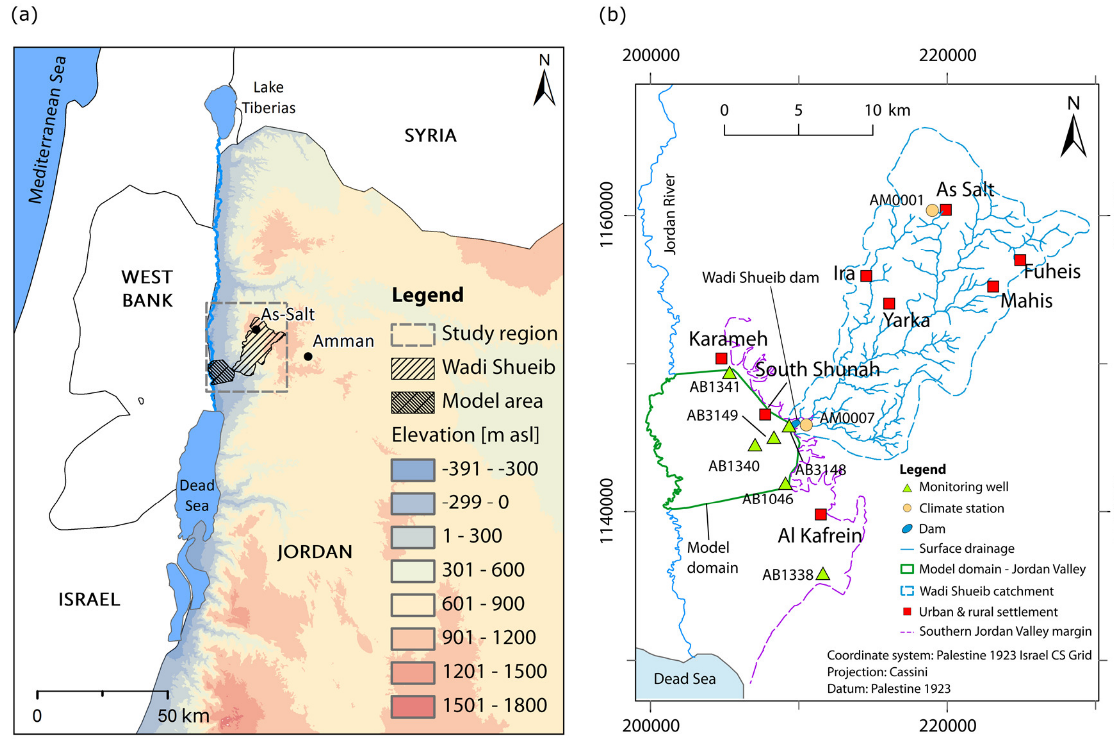


Fig. 2.1 (a) Geographical setting of northern Jordan, the study region is marked considering the modelled area at the southern Jordan Valley and the Wadi Shueib surface water catchment. (b) Delineation of the modelled area (in *green*) and Wadi Shueib surface water catchment (in *blue*), locations of urban settlements, monitoring wells and climate stations used in this study. Modified from (Alfaro et al. 2017).

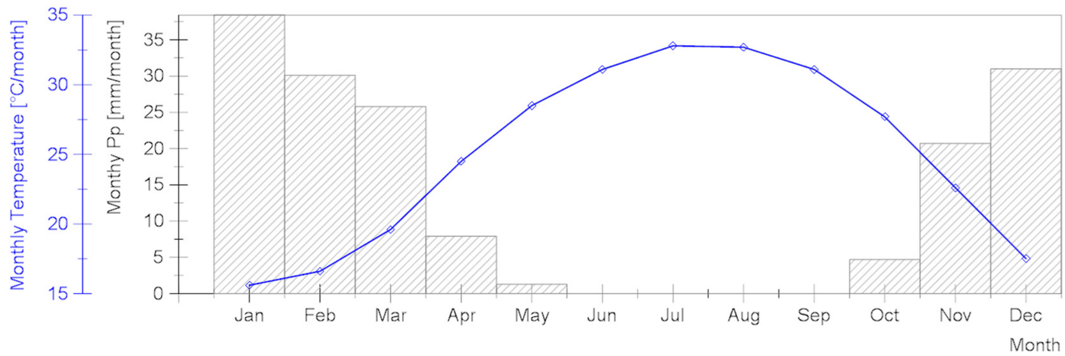


Fig. 2.2 Monthly values for precipitation (*grey bars*) and average monthly temperature (*blue line and external left y-axis*) from station AM0007. Based on data records from MWI.

Three wet years in 1979/80, 1982/83 and 1991/92 had a positive effect on groundwater levels in the Jordan Valley. The response of the wet year 1991/92 could have been intensified by the Gulf War in 1990–1991, causing a recession on profits through Jordanian agriculture (Venot et al. 2007), associated with declining groundwater abstraction rates and possibly also by the construction of the final extension of the King Abdullah Canal (KAC) in 1989. The KAC runs parallel to the Jordan River (Fig. 2.3) and provides the Jordan Valley, north of the study area, with additional water. In the study region, since the real amount of water that reaches this section is unknown, but reported as small, unregulated and polluted (Toll 2007; Al-Amoush et al. 2012), it was considered negectable for this research.

Fig. 2.3 Flow control facilities in the study region: KAC on November 9th, 2012 (left) and (right) an almost empty Wadi Shueib dam on May 2nd, 2011.

After 1993, groundwater heads start to decline (Fig. 2.4) again, as a result of a continuous increase of pumping together with the absence of wet years, with the exception of 2002/03, where a slight recovery of the water tables can be observed. The monitoring wells AB1341 and AB1340 reveal drastic depletion rates of 1 m per year on average during 1994–2002 and 2.5 m per year throughout 2003–2011 (Fig. 2.4).

The well located immediately downstream of Wadi Shueib dam (AB3148) has presented only a slight tendency of depletion since the beginning of the monitoring in 1999. Moreover, its water level is dominated by seasonal fluctuations induced by contribution to the groundwater system from the Wadi Shueib dam infiltration and the adjacent karst aquifer.

The behaviour in well AB3148 indicates that, despite the overall decline of natural recharge by precipitation after 2003, the lateral inflow to the Jordan Valley is stable and the depletion of groundwater levels in the Jordan Valley floor is most surely caused by over-extraction. This is supported by the fact that in the period of 1983–1990, with a similar sequence of eight normal to dry years as 2003–2011, groundwater levels remained stable or even slightly increased in the Jordan Valley floor (wells AB1340 and AB1341). After 2011, the closure of one or more illegal abstraction wells nearby AB1340 could have influenced groundwater tables in this monitoring well, indicated by almost constant water levels with a modest increment. No other changes in the area were able to be tracked to explain this improvement in water tables (MWI, personal communication).

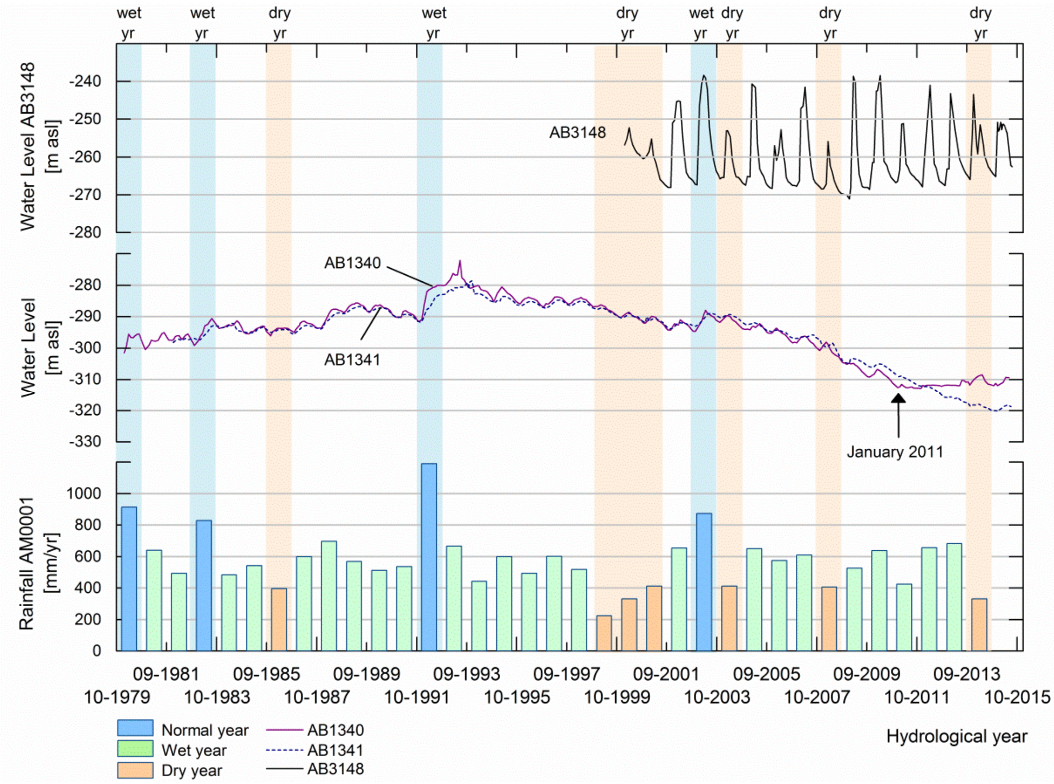


Fig. 2.4 Groundwater tables of monitoring wells and annual average precipitation in As-Salt. Hydrological years were classified as dry *(orange bars)*, average *(green bars)* and wet (*blue bars)* considering the average precipitation in a 30 years period in station AM0001: years with less than 75% of the average precipitation are denoted as dry, years with more than 125% of the average precipitation as wet. Modified after Alfaro et al. (2017).

2.2 GEOLOGICAL SETTING

The formation of the Dead Sea–Jordan Rift Valley during the middle Miocene controlled the tectonics of the study region (Sahawneh 2011). Although the surface in the Jordan Valley is relatively young, a distinct intermittent left slip fault, called the Jordan Valley fault, is found in the study area (Garfunkel 1981).

The lithology of the study region (Fig. 2.5) can be divided into two main sections, the Jordan Valley floor and the highlands. The Jordan Valley floor consists, in most parts, of unconsolidated clastic alluvial sediments and the Lisan formation (JV3) from the Holocene and Pleistocene (Fig. 2.6); the Lisan formation outcrops mainly in the western area of the Jordan Valley, but is also exposed in the incised channel of Wadi Shueib, previous to the construction of the Wadi Shueib dam. Together with the Ghor al Katar (JV1) and Samra (JV2) formations they form the Jordan Valley group. While the young Holocene alluvium overlies the Lisan, the JV2 underlies and in marginal parts interfingers with the Lisan formation (Fig. 2.5) (Toll 2007). This makes it difficult to define a unique sedimentation sequence for the whole study area, therefore, most authors show vertical profiles defining a singular Jordan Valley group (Garfunkel and Ben-Avraham 1996; El-Naser et al. 1998) or an indistinct stratification (Wolf et al. 2007; Ali et al. 2009). Al-Zoubi et al. (2006) found that the lithology of one drilling core of 1417 m depth in the study area did not match the interpretation of seismic lines. The same study showed that Late Cretaceous formations are found below -570 m asl (Al-Zoubi et al. 2006).

The highlands are composed of different formations of consolidated sediments of the Belqa, Ajlun, Kurnub and Zarqa group. The outcropping formations seen by the vertical profile in Fig. 2.5 are the Belqa and Ajlun groups, from the Paleogene and Upper cretaceous epochs. Other older formations, such as Azab (Z2) from the Jurassic period, also outcrop in the Wadi Shueib (Werz 2006). A complete stratigraphic description is presented in Fig. 2.6.

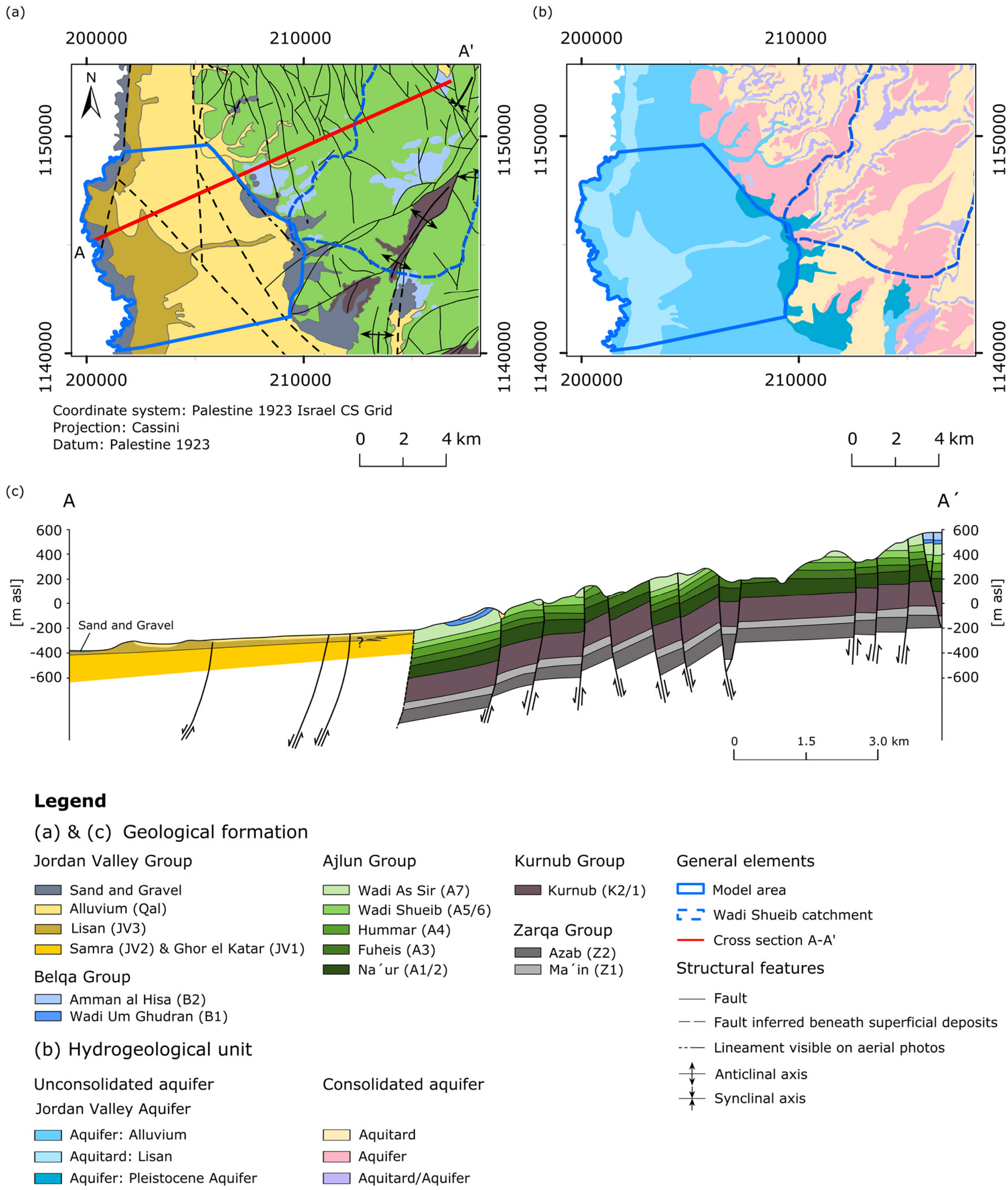


Fig. 2.5 Faults, alignments and geological formations (a) with schematic cross-section through the study area, profile A-A′, here the thickness of the Lisan formation is exaggerated vertically, which should be around 30 meter (c), and hydrogeological units (b). Extended and modified after Toll 2007 and Alfaro et al. 2017.

Era	Period	Epoch	Group	Formation (Symbol)	Hydrogeological Unit	Description
Cenozoic	Quaternary	Holocene	Jordan Valley	Alluvium (Qal)	Aquifer	Clastic sediments
		Pleistocene		Lisan (JV3)	Aquitard	Marl, clay, evaporites
				Samra (JV2)	(Pleistocene) Aquifer	Conglomerates, sands, silt, clay and marl
	Neogene	Pliocene		Ghor el Katar (JV1)	Aquifer	Cemented conglomerates
	Paleogene	Eocene	Belqa	Amman al Hisa (B2)	Aquifer	Phosphorite, silicified limestone
		Palaeocene		Wadi Um Ghudran(B1)	Aquifer	Massive chalk and marlstone, fossiliferous
Mesozoic	Cretaceous	Upper	Ajlun	Wadi As Sir (A7)	Aquifer	Limestone, dolomitic limestone, chert, marl
				Wadi Shueib (A5/6)	Aquitard	Marl and limestone
				Hummar (A4)	Aquitard/ Aquifer	Massive grey, yellowish limestone, crystalline and cavernous
				Fuheis (A3)	Aquiclude	Marlstone, limestone
				Na'ur (A1/2)	Aquitard	Grey marlstone (A1) Massive hard grey limestone and chert layers (A2)
		Lower	Kurnub	Subeihi (K2)	Aquifer	Multi-coloured sandstone
				Aardo (K1)	Aquifer	White, yellow massive sandstone
	Angular unconformity					
	Jurassic	Upper-Middle-Lower	Zarqa	Azab (Z2)	Aquitard	Marine sandstone, carbonate-shale associations
	Triassic	Upper-Middle-Lower				
Paleozoic	Permian	Lopingian-Guadalupian-Cisuralian		Ma'in (Z1)	Aquitard	

Fig. 2.6 Stratigraphy in the study area, modified after Powell 1989, Margane et al. 2002, Salameh 2002, Toll 2007, Zemann 2016 and Alfaro et al. 2017.

2.3 HYDROGEOLOGY

The mountains of Wadi Shueib consist of interstratifications of hard rocks, mainly limestone and sandstones of the Belqa, Ajlun and Kurnub group. The main karst aquifer comprises the formations A7/B2, whose sedimentary rocks present a permeability rate of around 2.3×10^{-5} m/s (Margane et al. 2002; Margane et al. 2010). Springs drain mainly through the boundaries between aquifers and the underlying aquitard (Abu-Jaber et al. 1997).

The aquifer studied in the following numerical groundwater model corresponds mainly to the Quaternary unconfined Jordan Valley complex, composed of gravels at the foot of the adjacent mountains, fine sands and silt moving towards the Jordan River. The Lisan formation, a precursor of the Dead Sea, with a thickness of around 30 m, consists primarily of marl with a high salt content. During former high water levels it caused confined conditions for the underlying JV2 aquifer. However, at the present, the water table is found below the Lisan, losing the confined characteristic acting as an aquitard (Salameh 2002; Al Kuisi et al. 2006). In some areas alluvial sediments underlie the Lisan formation, causing artesian conditions or ponding of water in shallow depths (Toll 2007). A small section, at the eastern boundary of the model area on the transition from the Jordan Valley Floor to the highlands, denoted in the geological map as “sand and gravel” (Fig. 2.5a), underneath it represents an aquifer from the Pleistocene (Fig. 2.5b), formed at the same time as part of the Lisan formation in the Jordan Valley. The alluvial aquifer can underlie or directly overlie this Pleistocene aquifer, making them hydraulically connected (Toll 2007). The presence of sand and gravel, at the western boundary of the study area as part of the Jordan Valley aquifer, it is between 1 or 2 m thick and it represents the shallow effects of erosion and deposition of a meandering Jordan River on its floodplain, engraving into the Lisan formation (Horowitz 2014). In the Jordan Valley, water exploitation takes place from the coarse clastic material of the Jordan Valley Group complex.

In the Jordan Valley section of the study area, groundwater inflow takes place from the north eastern direction along the Jordan Valley and laterally in the east, coming from the consolidated karst aquifers (Salameh 2001). Groundwater leaves the study area through discharge to the Jordan River in the north-west direction, and as subsurface flow along the Jordan Valley in the south and south-west (El-Naser et al. 1998). A direct natural recharge due to precipitation can be neglected (Toll 2007). The hydraulic gradient at the eastern central part of the modelled area is 0.015, determined with wells AB3148 and AB1340, both having their casing screens along their total depth (Table 2.1). This rather elevated hydraulic gradient can be explained by the location of these wells, directly at the alluvial fan of Wadi Shueib, with significant lateral inflow from the adjacent eastern aquifers, and by the permanent pumping in the alongside agricultural zone in the west, which affects the natural hydraulic gradient of the area.

Table 2.1. Construction data of observation wells in the model domain (MWI database). Modified after Alfaro et al. (2017).

Well	Casing layer	Top of casing screen, depth [m]	Base of casing screen, depth [m]	Top of casing screen, elevation [m asl]	Base of casing screen, elevation [m asl]	Lithology description
AB1340	1	0	70	-250	-320	Alluvium and sand
AB1341	1	0	24	-258	-282	-
	2	24	104	-282	-362	-
AB3148	1	0	24	-190	-214	-
	2	24	102	-214	-292	-
AB3149	1	0	11	-200	-211	-
	2	11	122	-211	-322	-

A schematic description of the main hydrogeological elements of the study area is shown in Fig. 2.7.

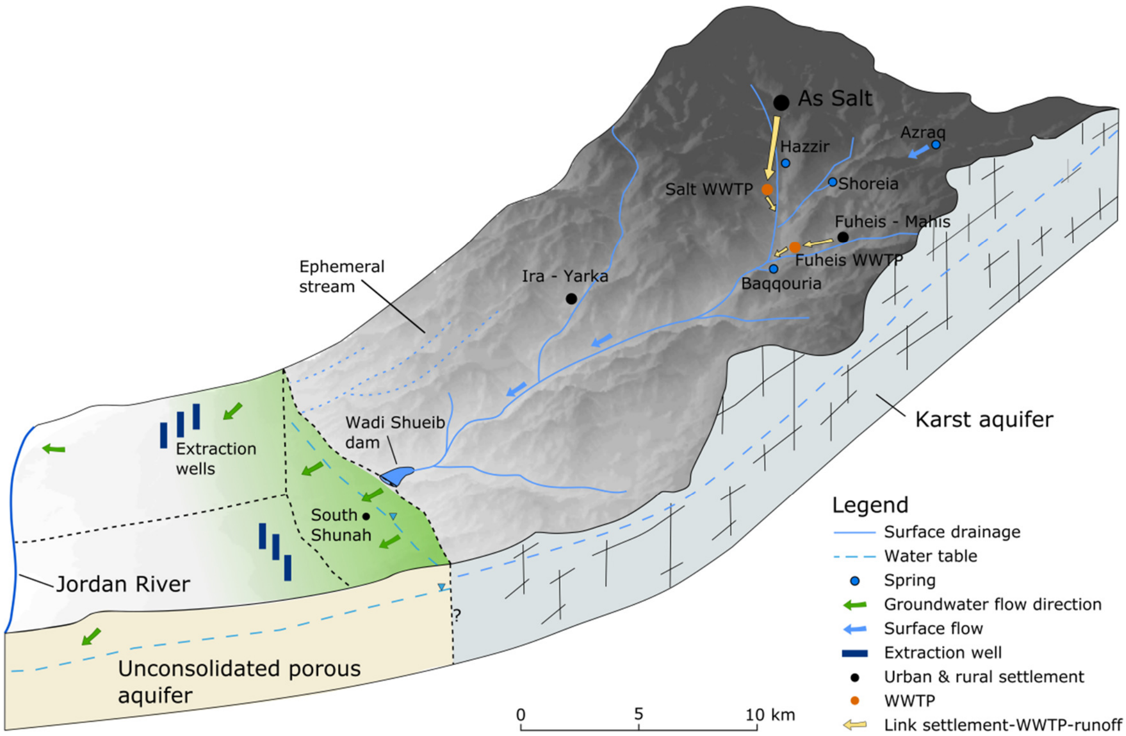


Fig. 2.7 Conceptual diagram of the study region, showing the interface between the karstic and porous aquifer, springs, the water reservoir of Wadi Shueib dam, wastewater treatment plants (WWTP) and extraction wells in the Jordan Valley floor. Geological structures are strongly generalised. Modified after Alfaro et al. (2017).

2.4 WATER QUALITY

The diverse hydrogeological characteristics (karst and unconsolidated porous aquifer) and water use (domestic and agricultural) in the study region differently affect the water quality of Wadi Shueib and the Jordan Valley.

The water quality of Wadi Shueib is mainly analysed at springs, particularly since four of them serve as drinking water sources after previous treatment. Especially in the urban parts of Wadi Shueib, e.g. As-Salt, part of groundwater recharge results from leakages from the water and sewage network, contaminating the karst aquifer with dissolved nitrate and faecal coliforms (Grimmeisen et al. 2016). Elevated concentrations of nitrate, partly higher than the maximum 50 mg/l admissible for drinking water, have been reported, indicating an input of wastewater and/or fertilizers (Abu-Jaber et al. 1997; Margane et al. 2002; Grimmeisen et al. 2016). This was also proved using isotopic signatures by Grimmeisen et al. (2017). Electrical conductivity values, used as an indicator of the soluble salt content in water (Rhoades 1996), during the period 1980-2005 in the springs Hazzir, Baqqoria and Shoreia range between 0.42 mS/cm (Shoreia) and 0.9 mS/cm (Hazzir) (Grimmeisen and Zemann 2015), classifying the springs within the range of freshwater type.

One of the main aspects of groundwater quality in intense irrigated land, such as the Jordan Valley, is water salinity; salts accumulate in the root zone preventing the crop of extracting sufficient water, slowing growth rate (Ayers and Westcot 1985) and reducing irrigation efficiencies, since more water is needed. Moreover, groundwater quality has degraded by solute recycling, that is, salts are extracted with the groundwater from the aquifer and redistributed onto irrigated fields and transferred again into the groundwater as return flow (Milnes and Perrochet 2006). For the Jordan Valley, GTZ (2003) classified the water according EC values: EC below 3 mS/cm is considered as freshwater and above 3 mS/cm is classified as brackish water, affecting the regular irrigation practices.

The groundwater composition in the Jordan Valley varies according to its location. It is influenced by water-rock interactions and recharge process coming from the inflow of the adjacent consolidated aquifers and return flow from irrigation water (Salameh 2001; Toll 2007). In general, chloride distribution follows the groundwater flow path (Toll 2007), which is consistent with the fact that the Lisan formation falls in the Sodium Chloride Type classification (Toll 2007). Chloride is present in nature as salts of sodium, potassium and calcium. The chloride ion is very mobile and intensifies the electrical conductivity of water and increasing corrosion, but it produces no health effects on humans (WHO 2003).

In the alluvial fans and debris, electrical conductivity (EC) of groundwater ranges between 0.8 and 2 mS/cm (see wells AB3148, P1 and P2 in Fig. 2.8d). The nitrate concentration is lower than 20 mg/l, although in areas with high agriculture influence, this value can reach 100 mg/l (Salameh 2001). As groundwater flows towards West, mixing processes play an important role in the increment of salinity of the water. Farber et al. (2007) found magnesium chloride water type with chloride concentrations above 960 mg/l, characteristic of a saline soil, indicating the influence of the Lisan formation, which includes precipitated aragonite, gypsum and halite.

Electrical conductivity was measured in six wells in the study region, four of them located in the Jordan Valley. Values above 3 mS/cm (brackish water) were found in three wells located within extensive irrigated zones (AB1340, AB1341 and P3), generating an inefficient and potentially high unsustainable use of the available water resources (Ben-Gal et al. 2008). Those boreholes located next to the outlet of Wadi Shueib, AB3148, P1 and P2, had values between 0.7 and 1.5 mS/cm, which indicate the inflow of freshwater from Wadi Shueib. No irrigation takes place by well P1, which provides with drinking water a Bedouin family (Fig. 2.8).

Discrete EC measurements along the depth of monitoring well AB1341 and the private wells P2 and P3 between February 2012 and November 2013 show different profiles depending on the location of the well (Fig. 2.8). Well P2 presents EC values lower than the 3 mS/cm threshold favourable for irrigation in the shallow part of the well; in February 2013, within 56 m (from -290 to -346 m asl) EC decreases 0.44 mS/cm. The variations along the depth become smoother after long periods without rainfall, since the recharge coming from the adjacent aquifers with fresh water decreases.

Another outcome is seen at 88 m depth (-345.6 m asl) in well AB1341, by measurements executed in the middle of winter, EC decreases abruptly within 5 m: 1.61 mS/cm in February 2012 and 2.3 mS/cm in March 2013, attributable to inflow of fresh water from the adjacent aquifer or flow from the underlying aquifers; this was only observed in measurements done after rainfall events.

In well P3, located 4.3 km away from the Wadi Shueib dam in a date palm farm, all values were above the brackish water threshold. Fluctuations among different measuring dates, ranging from 4.6 to 11.8 mS/cm, can be explained by the operation of neighbouring extraction wells, which induce flow movement in the high salinity formation causing these changes in the groundwater quality. Depth profiles with the largest EC values around 9 and 12 mS/cm in February 2012 (winter) and June 2013 (summer), respectively, present a curvature at about 85 m depth (-360 m asl), which might indicate the circulation of groundwater flow produced by near-by pumping. This assumption could not be verified though, since no data about the location of the well screens are available for private wells.

Additional studies about water quality in the Jordan Valley have found pharmaceutical residues, such as X-ray contrast agents, in all water types of the Jordan Valley, attributable to anthropogenic influence, e.g. hospital procedures, and the deterioration of groundwater quality over time (Zemann et al. 2014).

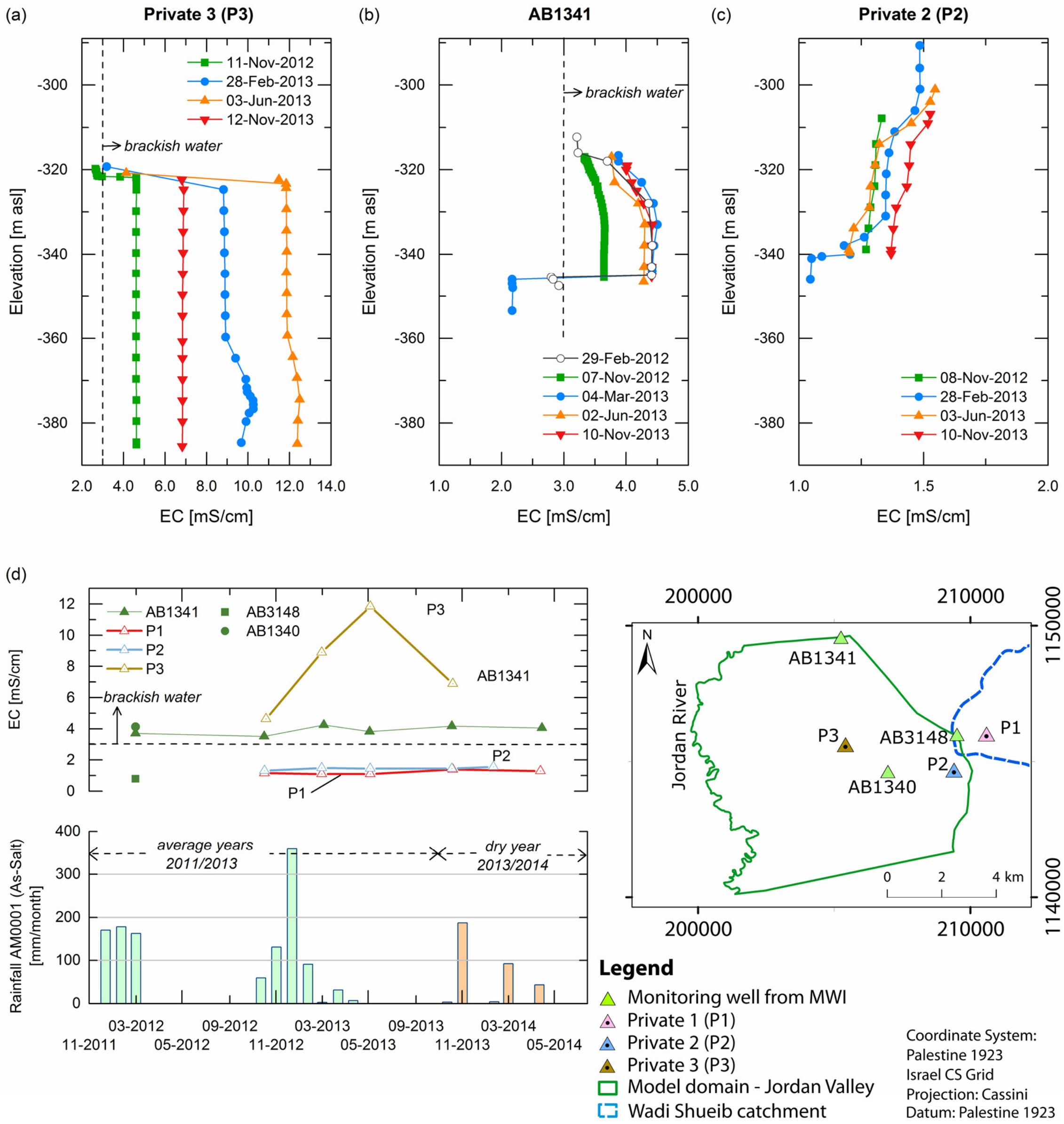


Fig. 2.8 EC depth profiles in wells (a) private 3, (b) observation well AB1341 and (c) private 2. (d) Discrete measurements of EC in wells P1, P2, P3 and AB1341 and monthly rainfall in As-Salt climate station (left) and location of wells (right). Note the different scale in the horizontal axis for Figures a, b and c.

CHAPTER 3

3 GROUNDWATER FLOW MODELLING WITH SCARCE DATA IN THE SOUTHERN JORDAN VALLEY[1]

The model area corresponds to the unconsolidated porous aquifer and the Lisan aquitard of the Jordan Valley complex (Fig. 2.1 and Fig. 2.5). Under a limited dataset context, a numerical groundwater model was developed considering different sources of information and indirect methods to generate the geometry, hydraulic parameters and sources and sinks that describe the groundwater system. After the complete set-up and calibration of the groundwater model, scenarios were built up and tested to predict the response of the aquifer to particular climatic conditions and water management alternatives.

3.1 MODEL CODE, MODEL DOMAIN AND DISCRETISATION

For the numerical model, MODFLOW (Harbaugh et al. 2000) was chosen for two reasons: the successful application to simulate groundwater flow in semi-arid environments, as proven by different studies (e.g., Candela et al., 2014; Maréchal et al., 2006; Switzman et al., 2015), and it is already used for modelling groundwater resources in the MWI, thus facilitating the transfer of information and results to the decision makers in Jordan.

The model domain coincides with the lateral extent of the unconsolidated porous aquifer in the Jordan Valley floor in the east, following a structural lineament and falling partly over the Jordan Valley margin, which defines the division between the consolidated and unconsolidated aquifers. In the west, the Jordan River is used as a natural boundary. The model boundaries in the north and south were based on a practical consideration, the

[1] This chapter was modified, enhanced and updated from Alfaro et al. (2017)

presence of observation wells for the later definition of boundary conditions, within the scarce data context (Fig. 2.1 and Fig. 2.5).

The MODFLOW model was set as two-dimensional with a heterogeneous single layer. This simplification was made because borehole logs seldom include detailed lithology to interpret a clear arrangement of hydrogeological units, since clastic sediments interfinger, overlie or underlie, in some parts, with lacustrine sediments (Toll 2007). Despite possible artesian conditions in some sectors caused by the Lisan formation, the model was defined as unconfined, as also reported by the MWI database, Al Kuisi et al. (2006) and Toll (2007).

The unconfined model domain (horizontal plane) consists of a variable and irregular grid size with 77 rows and 87 columns. The grid was refined at the most significant part, where groundwater extraction occurs, and preventing cell dimensions from changing more than 50% between cells to avoid instabilities in the model. Cell width varies from 70 m at the eastern part and increases towards the west reaching 200 m. In total, 3,786 active cells are distributed in an area of 10×9 km^2.

To simulate the continuous groundwater level depletion, the model was specified as transient and run in monthly time steps with a simulation period of nine years from January 2001 until January 2010, defined in 108 stress periods with variations of 28, 30 or 31 days.

The Block-Centered Flow (BCF) package, which considers a node located at the centre of each cell, was used to define the aquifer properties. The Direct Solver package (DE4) was chosen to calculate the finite difference equations, preventing convergence problems associated to iterative solutions (Delleur 2006).

3.2 INPUT DATA

The quantity and quality of available records in the study area are limited. Different approaches were integrated to asses this data. The model parameterisation requires a large amount of hydrological and hydrogeological information, which was collected from (1) established monitoring stations, (2) calculations with indirect methods and (3) literature. Different sources for input data are summarised in Table 3.1.

Table 3.1. Model parameters, required input information and data sources or method used to gather data. Modified from Alfaro et al. (2017).

Model parameter (MODFLOW Package)	Required input information	Data source/Method
Physical properties and initial conditions		
Model thickness	Top elevation (m asl)	Based on Sahawneh (2011)
	Bottom elevation (m asl)	Inferred from Garfunkel and Ben-Avraham (1996), El-Naser et al. (1998), Salameh (2002), Toll (2007) and datasets from MWI database
Hydraulic parameters	Hydraulic conductivity K (m/s)	Distribution according to the geological lithology and ranges of values estimated from Domenico and Schwartz (1990) and Guttman et al. (2009)
	Specific yield Sy ( )	Estimated from Morris and Johnson (1967) and Heath et al. (2004)
Model initial conditions	Initial heads (m asl)	Estimated during model calibration and MWI database
Boundary Conditions		
Hydraulic heads (CHD)	Transient water level for the northern and eastern boundary (m asl)	Estimated from MWI dataset
General Head Boundary (GHB)	Transient water level for the southern boundary (m asl)	Dataset from MWI, Klein and Flohn (1987), Bowman et al. (2007), Abu Ghazleh (2011) and Nof et al. (2012)
	Constant conductance $(m^2/d)/(m^2)$	Estimated during model calibration
Drain (DRN)	Conductivity (m^2/d) Bottom elevation of drain object (m asl)	Estimated from MWI dataset and Domenico and Schwartz (1990) and Oosterband and Nijland (1994),
Other sources and sinks		
Groundwater extraction (WEL)	Transient groundwater extraction (m^3/d)	Land classification with satellite imagery (Toll 2007; Shatnawi 2014)
		Crop water requirement after Allen et al. (1998): estimated using information from Wittwer and Honma (1979), Allen et al. (1998), GTZ (2002), Israeli et al. (2002), Zaid et al. (2002), Orloff and Putnam (2007) and Díaz-Méndez et al. (2014)
		Hydrology and climatological data from MWI dataset
Return flow (RCH)	Transient recharge (m/d)	Estimated after GTZ (2003) and Jiménez-Martínez et al. (2009)

3.2.1 *Model thickness*

Several authors have studied the geometry of the southern Lower Jordan Valley, and structural and geophysical analysis have been performed by Al-Zoubi et al. (2007), Garfunkel and Ben-Avraham (1996) and Toll (2007). Other vertical geological profiles have been sketched by El-Naser et al. (1998), Salameh (2002) and Sahawneh (2011). The depth of the complete Jordan Valley Group is estimated to be around 1000 m by Al-Zoubi et al. (2007) and 2000 m by El-Naser et al. (1998). However, the single layer of the numerical model represents the Jordan Valley Aquifer complex, where most groundwater extraction takes place; Toll (2007) interpreted this thickness between 100 and 350 m, increasing from the western border until halfway towards the Jordan River, agreeing with Salameh (2002), who depicted it as a few hundred meters depth.

Considering that extraction wells are commonly not deeper than 250 m, the thickness of the single layer was generated through interpolation of the depth values, obtained from the lithology of some deep wells and the information found in Toll (2007). The Kriging method was preferred to avoid errors by following more general spatial trends in the original data points (Hu 1995). Hence, the thickness of the MODFLOW layer varies between 50 and 250 m, increasing mainly from east towards west.

3.2.2 Boundary conditions

According to the conceptual model in Fig. 2.7, water inflows into the model domain come mainly from the adjacent mountains of Wadi Shueib. Groundwater leaves the system through the north-west boundary by the Jordan River and mainly, south-west in the direction of the Dead Sea. Moreover, pumping takes place close to the boundaries and the effects of future groundwater withdrawals will be analysed. Therefore, boundary conditions of two types were assigned: specific head (north and east) and head-dependant flux boundaries (west and south).

Time variant specified head boundary conditions or Dirichlet type (CHD Package) were set for the northern and eastern border. This type of boundary condition was chosen since (1) the potential flow, coming from the adjacent consolidated aquifer and from the northern part of the Jordan valley is unknown, and (2) a western section of the northern limit is found by the shallow “sand and gravel” formation and alluvium aquifer, where outflow through the north-west can be expected. Head stage time-series of these boundaries were tied to observed values of water level in wells AB1341 and AB3148 (Fig. 2.4). The eastern boundary condition was distributed considering hydrogeological features, such as the presence of the alluvial fan at the outlet of Wadi Shueib. Heads were defined assuming that seasonal fluctuations, seen in well AB3148, weaken as they approach the northern and southern limits. This was interpreted (1) from the pattern of groundwater heads in well AB1341, at the northern boundary of the model domain; (2) from the absence of seasonal fluctuations in observations between 1937 and 1940 in well AB1046, located south of the model area, between the drainage path of two wadis (Fig. 2.1) (Toll 2007); and (3) because no water reservoir exists and no direct water outflow from the highlands occurs in the southern edge and thus, the water level at the south limit acts similar to groundwater levels at the location of well AB1341. For the northern boundary condition, the water-level fluctuations of well AB1341 represent the sequence of the water table distributed along the border. This was assumed due to the lack of groundwater level records close to the Jordan River. It was not set as a no-flow boundary to allow flow exchange, however, since specific head conditions can simulate unreasonable flows into and out of the system (Anderson et al. 2015), water balance results were additionally checked and calibrated against groundwater head observations.

The Jordan River at the western boundary was simulated with a head-dependent flux boundary condition or Cauchy type. The southern part of the Jordan River receives mainly treated wastewater from Amman, coming from its tributary, the Zarqa River (Comair et al. 2012). Its natural base flow has decreased in part, due to the construction of a dam (Al-Abed and Al-Sharif 2008), resulting in shallow river-water levels in the southern Jordan River. 28 cm was the water level depth measured in July 2009, and for April 2009 the estimated average was 44 cm (Gafny et al. 2010). This shallow river-water level and the findings of Farber et al. (2004), who concluded through chemical analysis that groundwater contributes to the Jordan River, leads to assume that the river mostly acts like a gaining stream and any losses can be neglected. Therefore, the Jordan River is simulated using the Drain (DRN) Package, which can only remove water from the system. Drain attributes (conductance and elevation) remain constant during the simulation period. The streambed conductance is a function of the width of the river (8 m, determined from satellite pictures), the hydraulic conductivity of the riverbed material, defined between 2.3×10^{-5} and 5×10^{-5} m/s (supposing a high organic content (Oosterband and Nijland 1994)), and the thickness of the riverbed sediments, assumed as 1 m. The elevation of the drain was based on the topography at the Jordan River.

A head-dependent flux boundary through a general head boundary (GHB Package) was assigned to the southern boundary; the Dead Sea is the main feature representing the hydraulic boundary outside of the modelled area and it was used to simulate the outflow in the south-west direction, as represented in the conceptual model. Two values are necessary to define GHB, the head of the water body apart of the model domain (Dead Sea) and the conductance, which represent the resistance to the flow to move between the boundary cell (southern limit) and the source (Dead Sea) (Mace et al. 2000).

To determine head stages, the southern border was divided into two segments (Fig. 3.5). This division was done to assure that computed groundwater heads fall within the model thickness and not under the bottom elevation, considering the low values of the Dead Sea water level. Values of nodes between opposite ends within the eastern segment (Segment 1) are interpolated linearly along the grid cells. For the first node of Segment 1 at the eastern boundary, groundwater heads values of well AB1338, between 1986 and 2005, were linearly extrapolated to complete the simulated period; head values range from -275 to -282 m asl, from October 2001 to October 2009, respectively. For the second node of Segment 1 and for the complete western segment (Segment 2), water head values of the Dead Sea were used, which have decreased from -412 m asl in 1999 to -422 m asl in 2009 (Klein and Flohn 1987; Hassan and Klein 2002; Bowman et al. 2007; Abu Ghazleh et al. 2009; Nof et al. 2012). Time series of the estimated heads for GHB are shown in Fig. 3.8.

The conductance value depends on the hydraulic conductivity, the grid cells dimensions, and the distance between the boundary cell and the constant head source. In this case, the conductance was estimated during the calibration process, considering that the variable dimensions of the grid cells have widths between 80 and 200 m.

3.2.3 Sources and sinks

Continuous increase in groundwater extraction through drilled wells is one of the main characteristics of the modelled area. Information on groundwater abstraction provided by the authorities comprises a single average value for each year for every measured well, making this data unsuitable to be used as input for a numerical model with monthly time steps. Moreover, many illegal wells are in operation in the modelled area (Chebaane et al. 2004; Toll 2007; El-Naqa and Al-Shayeb 2008) and therefore, the total extracted groundwater value collected by the authorities is most likely underestimated. Surface water from the Wadi Shueib dam represents around 10% of the total irrigation water source and was subtracted from the later estimated total irrigation water demand for modelling purposes.

Values for groundwater extraction were estimated using irrigated areas and crop water requirements. Similar methods have already been applied in other studies, e.g. Casa et al. (2008) and Al-Bakri et al. (2016). Fig. 3.1 illustrates the process to determine plausible values of groundwater extraction, which then serve as input for the WEL MODFLOW package. The main steps are: (1) estimation of total irrigated area (temporal and spatial) and (2) determination of crop water requirement.

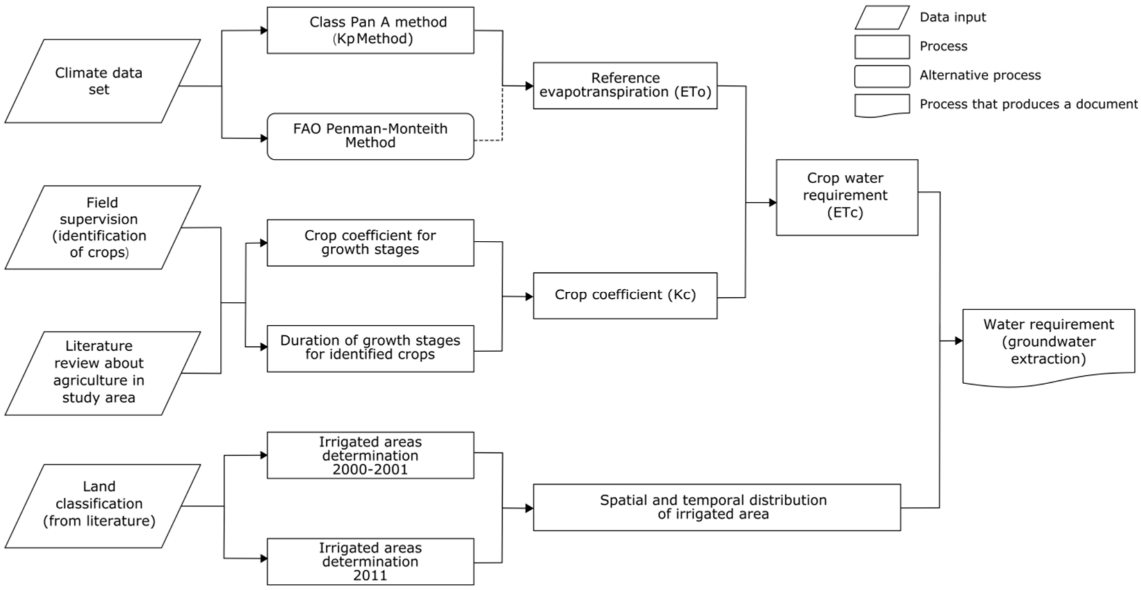


Fig. 3.1 Steps to determine plausible values for groundwater extraction in the modelled area (Alfaro et al. 2017).

To assay the spatial and temporal distribution of the irrigated area, the works of Shatnawi (2014) and Toll (2007), as well as additional information about land designation were used. Toll (2007) applied two ETM+ satellite images from May 2000 and May 2002 for a supervised classification, estimating a total irrigated land area of 17.8 and 18.0 km^2, respectively. For the year 2011, a total irrigated area of 28.5 km^2 was determined by Shatnawi (2014), who achieved a supervised land classification in the Jordan Valley, applying the maximum likelihood algorithm, using the combination of two satellite images, LANDSAT 5 (from December 2010) and LANDSAT 7 (from June 2011). To refine results, the spatial distribution of irrigated fields follows the local farm unit definition used by local authorities, where each slot comprises an area of three or four hectares (Shatanawi et al. 2003; Venot 2003). Based on data about the construction date of registered irrigation wells, most of the model's eastern area was already irrigated before or during the period 2000–2004. After the year 2005, agriculture extends towards west reaching the border of the Lisan formation (Fig. 3.4a).

In the second step, the crop water requirement (ETc) was determined as a function of the reference evapotranspiration (ET_0) and the crop coefficient (Kc) (Allen et al. 1998) with the equation:

$$ET_c = K_c \cdot ET_0 \quad (3.1)$$

Beforehand, cultivated crops in the modelled area were identified through field survey (Fig. 3.3). Duration and the crop coefficient (Kc) of growth stages – initial, development, mid, and late season – for each vegetable or fruit class were obtained using the literature listed in Table 3.1; values are presented in Table S1 of the supplementary material (SM). Reference evapotranspiration ET_0 (Fig. 3.2a) was determined with the pan coefficient method applying Equations from 3.2 to 3.6 from Allen et al. (1998) using measurements of climate station AM0007 (see location in Fig. 2.1).

$$\mathrm{ET}_0 = K_p \cdot E_{\mathrm{pan}} \tag{3.2}$$

Where ET_0 is the reference evapotranspiration [mm/d], K_p the pan coefficient [ ] and E_{pan} the pan evaporation [mm/d].

Considering that measurements in station AM0007 use the pan class A with green fetch, that is, the pan is placed in short green cropped area (Allen et al. 1998), the K_p is calculated using Equation 3.3.

$$K_\mathrm{p} = 0.108 - 0.0286 \cdot u_2 + 0.0422 \cdot \ln(\mathrm{FET}) + 0.1434 \cdot \ln(\mathrm{RH_{mean}}) - 0.000631 \cdot [\ln(\mathrm{FET})]^2 \cdot \ln(\mathrm{RH_{mean}}) \tag{3.3}$$

where u_2 is the wind speed at 2 m above ground surface [m/s], FET is FETCH or distance to the identified surface type, assumed 1 m, and RH_{mean} is the average relative humidity [%], determined with Equation 3.5. The wind speed is calculated with Equation 3.4, being z the measurement height above ground surface [m], in this case 3 m, and u_z the wind speed at the z height [m/s].

$$u_2 = u_z \cdot \frac{4.87}{\ln(67.8\, z - 5.42)} \tag{3.4}$$

$$\mathrm{RH_{mean}} = 50 \cdot \frac{e^o(T_{\min})}{e^o(T_{\max})} + 50 \tag{3.5}$$

Where, $e^o(T_{min})$ and $e^o(T_{max})$ are the saturation vapour pressure [-] at minimum and maximum daily air temperature, respectively, and defined through Equation 3.6, where T is the temperature.

$$e^o(T) = 0.6108 \cdot \exp\left(\frac{17.27\, T}{T + 273.3}\right) \tag{3.6}$$

According to Allen et al. (1998), the final ET_0 value was reduced 25% to fit the semi-arid to arid conditions of the study area. The final ET_0 values are shown in Fig. 3.2.

The FAO Penman-Monteith method was also tested resulting in an underestimation of evapotranspiration values, expected for a semi-arid environment, as shown in other studies (Garatuza-Payan et al. 1998; Berengena and Gavilán 2005; Alazard et al. 2015) and therefore, it was not used to calculate ETc.

The crop water requirements for the different crops (e.g. eggplant, tomato, banana, etc.) were calculated (see Table S2 of SM) and subsequently, the following assumptions were made: (1) crops were divided into two main categories according to their water demand: vegetables and banana/date palms, where the latter have the highest water demand, especially during the warm months (Allen et al. 1998; GTZ 2003) (Fig. 3.2b and Fig. 3.4b). This simplification was made considering the unfeasibility of identifying all vegetables during the field survey, since access to farms is restricted and some cultivation takes place close to military ground. Moreover, the identified crops might not necessarily coincide with those being cultivated at the date of image acquisition, because the cultivated crop is often changed according to market demand or for crop rotation reasons (Salman and Al-Karablieh 2001). (2) In 2000, the spatial distribution of irrigated land for vegetables and bananas/date palm was 60 and 40%, respectively, according to values reported by Toll (2007) and Venot (2003) and it varied to 68-32% in 2011, based on field observations (see Fig. 3.2c).

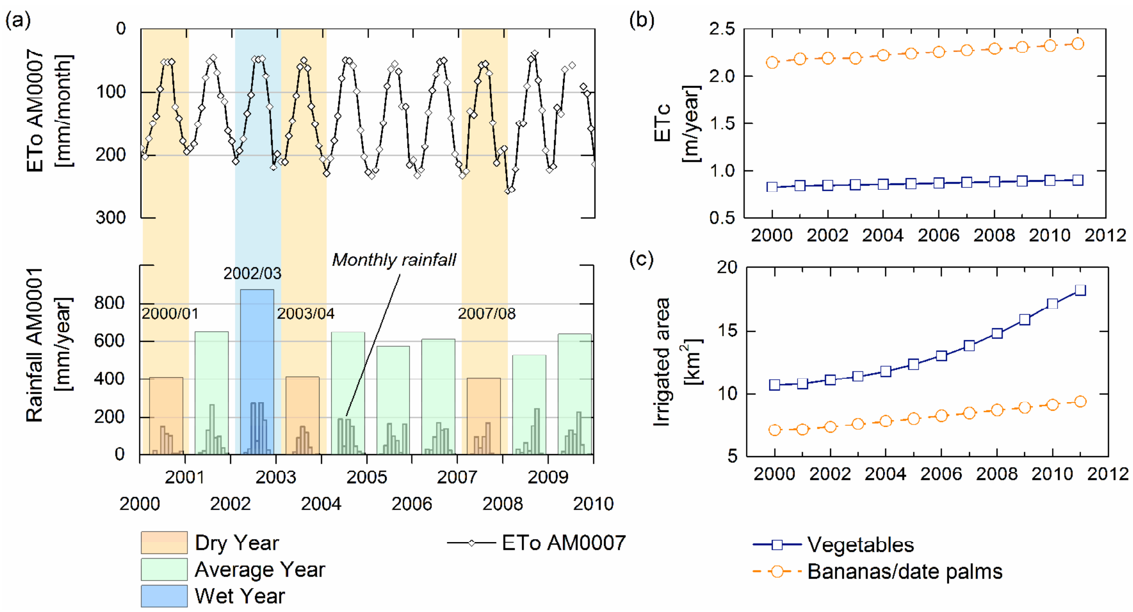


Fig. 3.2 (a) Determined ETo using the K_P method (Allen et al. 1998) in the Jordan Valley in Station AM0007; below precipitation in As-Salt, station AM0001, is represented by small bars (monthly rainfall) and larger bars show the annual rainfall average, classifying the hydrological year as dry *(orange)*, average *(green)* and wet *(blue)*. (b) ETc for vegetables and bananas/date palms as function of ETo and Kc. (c) Assumed distribution and evolution of areas.

Finally, abstraction wells were allocated to the centroids of polygons that define farm units and were assigned to the WEL MODFLOW package, since exact positions for illegal wells are unknown. It can be expected though, that wells are in the direct vicinity of cultivated areas to minimise the length of water pipes. The extraction volume was determined by the computed water requirement and area of each polygon.

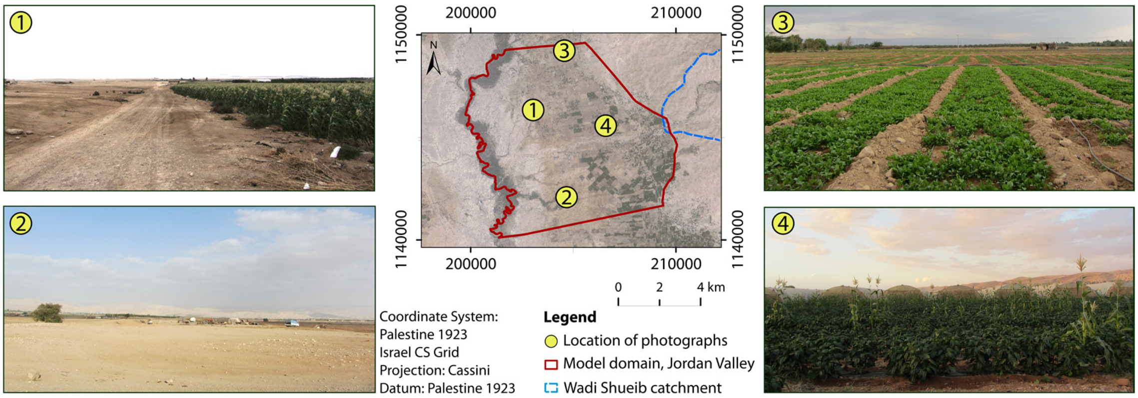


Fig. 3.3 Overview of land use and crop identification in the study area done during a field survey in November 2012. (1) Shows the interface between the Lisan formation and arable land, (2) the arid soil of the Lisan formation, (3) herbs plantation and (4) corn and green houses.

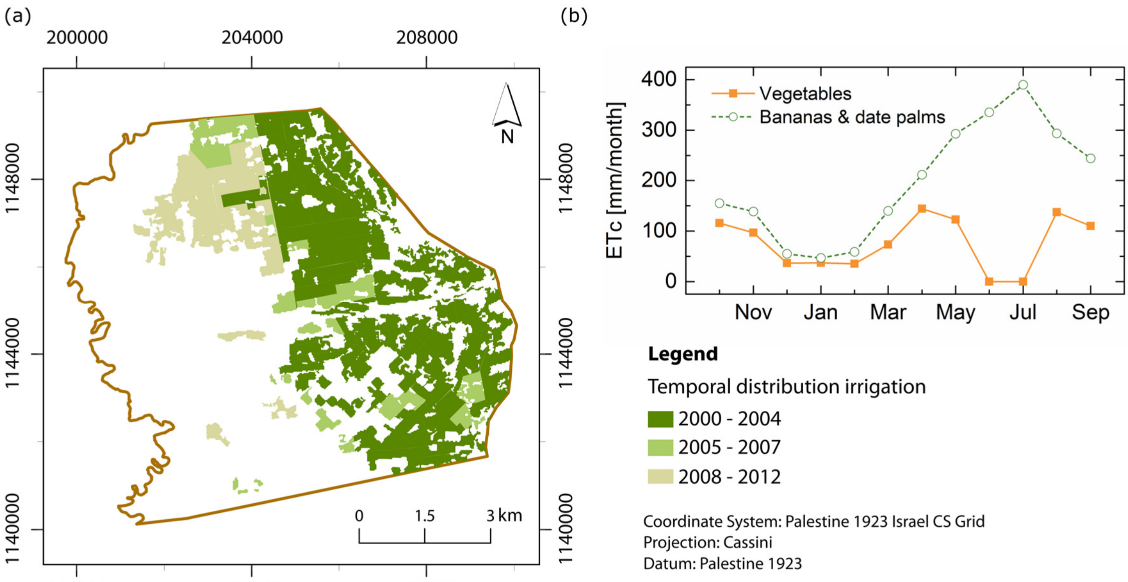


Fig. 3.4 (a) Temporal and spatial distribution of the irrigated fields. These results are based on previous studies (Toll 2007; Shatnawi 2014) and MWI database. (b) Monthly crop water requirement (ETc) for vegetables and bananas/date palms as function of the reference evapotranspiration and the crop coefficient (Equation 3.1).

Physical characteristics of soil properties and irrigation efficiency influence artificial recharge through return flow, depending on the irrigation technique in use, practices of farmers and equipment maintenance regimes (Jensen 2007; Benouniche et al. 2014). According to Toll (2007), since most crops are irrigated with drip irrigation, which can achieve efficiencies up to 95% (World Bank 2006), return flows through irrigation could be neglected; however, drip irrigation efficiencies of 56% in the Jordan Valley, due to old drop systems, were reported in a field study in 1993/1994 by Wolf et al. (1995) (cited in Jensen (2007)). Moreover, Jiménez-Martínez et al. (2009) consider the return flow to an unconfined aquifer in a semi-arid environment to be between 15 and 20% of the total irrigation. Therefore, assuming an improvement of the drip irrigation system from the 1990s and since depth to groundwater in the modelled area is larger than 40 m, the return flow, assigned to the RCH MODFLOW package, was assumed as 10-15% of the total irrigation.

3.3 CALIBRATION PROCESS AND SENSITIVITY ANALYSIS

The numerical model was first manually calibrated by varying the input parameters in plausible ranges. Predicted heads were compared to observed data from two existing observation wells (AB1340 and AB3149). Additional groundwater head observations or flow measurements for calibration purposes were unavailable. The obtained water budget at different time steps was compared to estimates given in the literature. Subsequently, the parameter optimisation Software PEST (Doherty et al. 1994) was run to determine sensitivities, to parameterise the boundary conditions, and also to apply the zone-based approach for the aquifer parameters *K* and Sy. The sensitivity analysis (Fig. 3.5) shows that sensitivity for specific head conditions (CHD) is up to 25 times higher around observations wells than at the distant points. Sensitivity values between 0.2 and 0.5 were found north of the outlet of the wadi, which coincides with the Pleistocene aquifer next to the Amman formation, by the adjacent consolidated aquifer. The southern and western boundaries were classified as insensitive. Hydraulic conductivity and storage coefficient have low sensitivity with respect to CHD; in any case, they are mostly sensitive at the centre of the model domain, where most groundwater extraction occurs (zones ID 7, ID 2 and ID 1 in Fig. 3.6).

The parameters adjusted during calibration were distribution and magnitude of the boundary condition in the east (constant head), conductance of the general head boundary, hydraulic conductivity (*K*) and storage coefficient (Sy); some changes were also made to the distribution of well nodes. Computed water levels were compared to observed groundwater heads in wells AB1340 and AB3149 during the period 2001-2010 (Fig. 3.7 a-b). A tolerance of 25% of the difference between the maximum and minimum value of water heads was defined as acceptable, that is, residuals could vary ± 5 m. Additionally, for each observation target a significant correlation coefficient r greater than 0.9, which is generally agreed as a value of a "good" calibration result (Hill 1998; Hill and Tiedeman 2007), was obtained. The manual calibration was complemented with an inverse model using PEST. The optimised solution obtained by PEST, although it minimises the model errors, resulted in an overestimated and unrealistic water budget and therefore, the forward run was preferred.

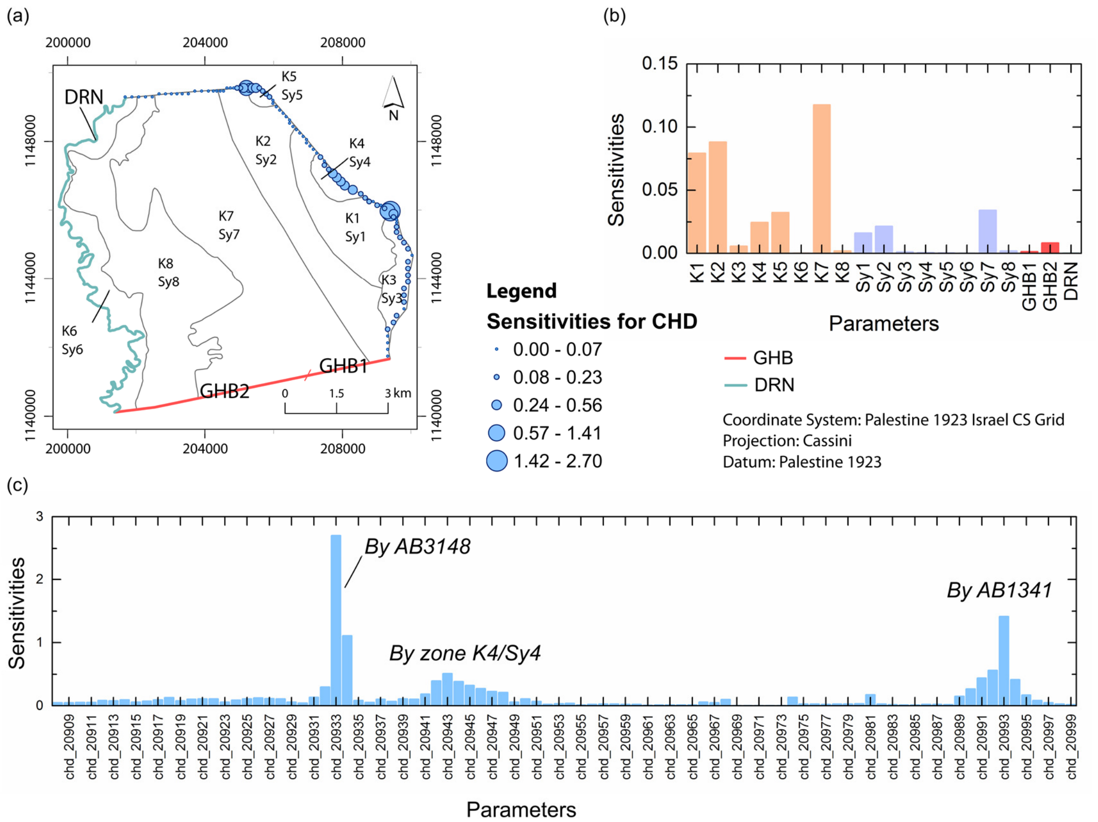


Fig. 3.5 (a) Model domain with location of parameters at the western (drains: DRN) and southern boundary (general head boundary: GHB) conditions, hydraulic conductivity (*K*) and storage coefficient (Sy). Sensitivities of the northern and eastern boundary conditions (time variant specified head: CHD) are shown with *graduated blue circles*. The defined segments of GHB are shown in the southern boundary (*red line*), (b) sensitivities for *K*, Sy, GHB and DRN, and (c) sensitivity values for CHD (eastern and northern) boundary conditions.

Visually, the residual plot of monitoring well AB1340 shows an acceptable data agreement, especially in the first years of the predicted period (Fig. 3.7c,e). The abrupt decline of measured water levels in 2008 could not be reproduced by the model; this could be explained by an overestimation of lateral inflow at the eastern boundary and its distribution along this boundary, by a change in the land use close to this well (which was not determined during land use analysis) and/or the construction of a new production well close to the monitoring well. The temporal variations of residual plot for well AB3149 shows a reasonable result, with all values within the defined tolerance of 25%, along the modelled period until June 2008, where time series data ends (Fig. 3.7d).

Hydraulic conductivity, storage coefficient and conductance

Final calibrated values for the hydraulic conductivity (*K*) and storage coefficient (Sy) are presented in Fig. 3.6 and are in accordance with ranges mentioned by Al Kuisi et al. (2006) and Guttman et al. (2009). Taking into account that hydraulic properties of the aquifer usually have a detailed spatial variability (Hunt et al. 2007), the principle of parsimony (Hill 1998) was applied to distribute the hydraulic conductivity according to the Quaternary deposits as described in Chapter 2.

K values decrease in direction to the Jordan River, as sediments become finer, with the exception of the sand and gravel found by the floodplain of the river. Maximum *K* values, between 3.5×10^{-4} and 5.0×10^{-4} m/s, are found in high-permeability zones: the north-eastern area with the high escarpment foothills formations (ID 5), the alluvial fan from Wadi Shueib in the eastern part (ID 4), and the Jordan River at the western border of the modelled area (ID 6). A moderate uniform *K* distribution between 7.9×10^{-5} and 2.3×10^{-4} m/s is defined in the central part of the modelled area (ID 1, ID 2, ID 7) following the alluvial fan gradient, where most of groundwater extraction takes place and highest sensitivities for this parameter are found. The low permeability in ID 8 represents the Lisan formation with primary low permeability (Salameh 2002).

No information about Sy was found in the literature for the model domain; however, values under 20% were expected for the unconfined aquifer, which presents mainly alluvial sediments with a natural poorly sorting degree (Toll 2007). The distribution of values was determined during the manual calibration. Most of the zones present Sy values between 0.10 and 0.13 and, the highest Sy was determined by zone ID 3, which is in the order for alluvial gravel sediments (Heath et al. 2004). By ID 8, with finer sediments than the centre of the area, the lowest Sy value of 8% was found.

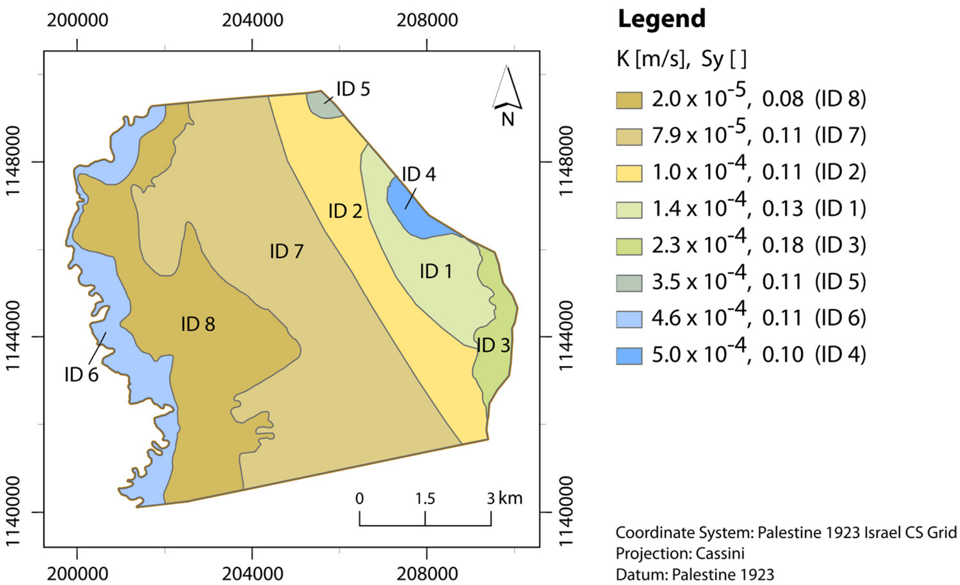


Fig. 3.6 Final values and distribution of zones for hydraulic conductivity and storage coefficient.

Conductance for the GHB boundary condition rises towards west, as cell dimensions become larger. It was estimated for each cell between 8.5×10^{-4} and 2.7×10^{-3} m^2/s. The lack of studies that integrate this parameter made not possible to compare these results. However, they are high enough to allow flow to leave the system through the southern boundary, as expected from the conceptual model.

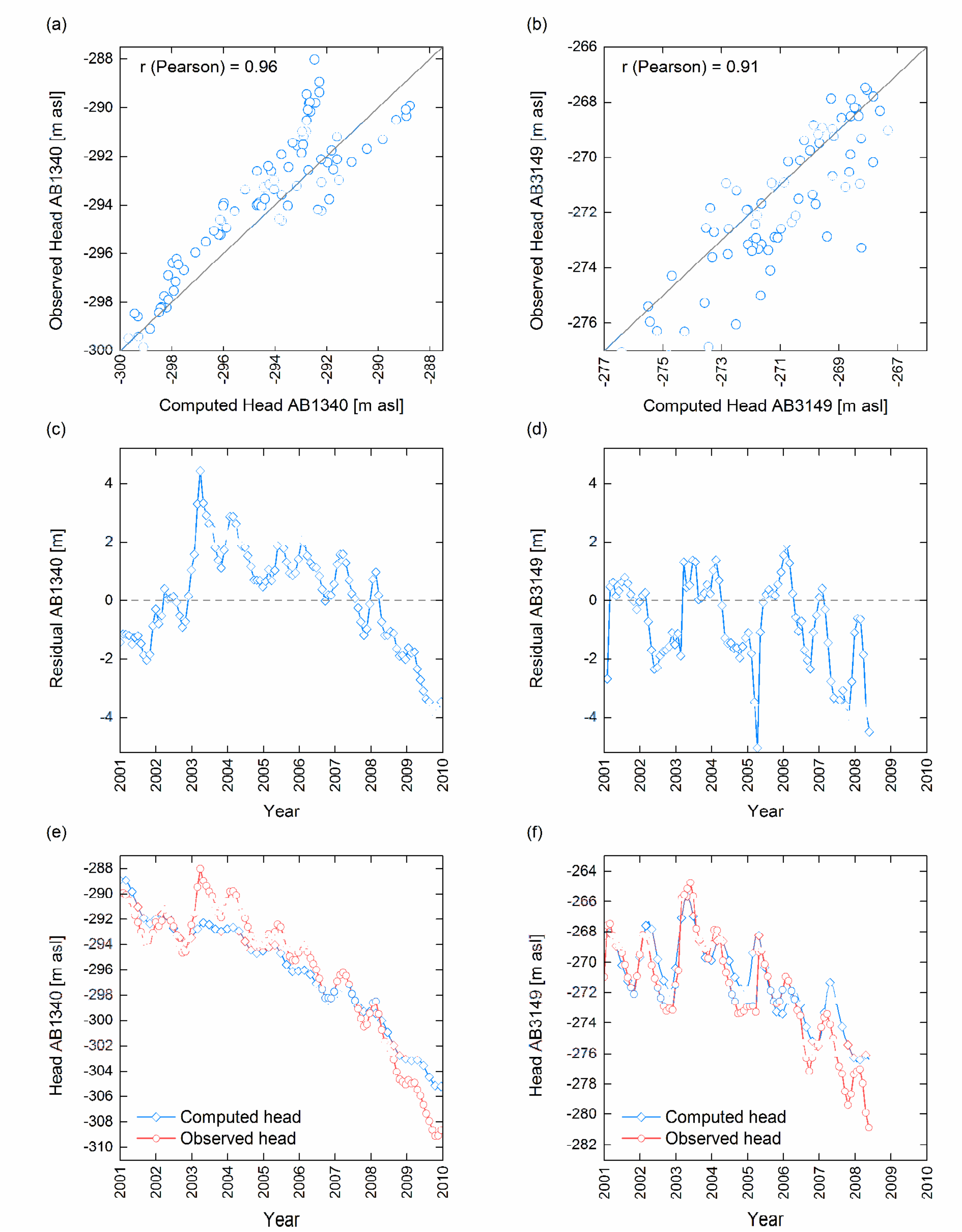


Fig. 3.7 Computed versus observed heads (a-b, e-f). Residuals of computed heads and their variation during the simulation period for observation wells (c) AB1340 and (d) AB3149.

3.4 DEFINITION OF FUTURE SCENARIOS

To use the calibrated model, six scenarios were developed and run. These scenarios were defined until October 2025, considering the hydrological conditions and management plans of local authorities. To account for the definition of the hydraulic head boundary conditions (CHD) on the eastern border, based on observation wells AB1341 and AB3148, future groundwater levels for these two monitoring wells were also assigned. Values were extrapolated from observed data of the calibration period. Due to its location on the eastern model border, AB3148 is not directly influenced by irrigated fields (compare Fig. 3.4); thus, it is feasible to estimate independent values. For AB1341, this is probably not the case and an iterative, self-reinforcing influence cannot be completely excluded. Nevertheless, a scenario definition is only possible based on these assumptions. To evaluate the impacts of the scenarios on groundwater levels, the two remaining observation wells inside the model area, AB1340 and AB3149 were used. Each scenario, based on assumed pumping rates, is simulated for average and dry hydrological years, denoted as *a* and *b* scenarios, respectively. Dry hydrological conditions are assumed, where the rainfall annual average falls under 75% of the 30-years average.

Scenario 1a & 1b: base line Agricultural development follows the same growth rate as in the period 2005–2009. Maximum arable land is reached by 2021, considering that all farm units are cultivated, and then stays constant during the last projected years (2021–2025). Based on these assumptions, a downward trend of groundwater levels in well AB1341 was extrapolated from observed data (Fig. 3.9a, d, g, h).

Scenario 2a & 2b: land use stops extending Arable agricultural land stops spreading after 2012 and remains constant until 2025, considering that agriculture only expands if treated wastewater for irrigation is available, which is currently not the case for the modelled area (MWI 2015a). If irrigation stops increasing, it is assumed that this also affects the decline rate of groundwater heads of AB1341, dropping to less than one meter per year (Fig. 3.9b, e, g, h).

Scenario 3a & 3b: groundwater extraction is reduced by 40% Agricultural development follows the same growth rate as the period 2005–2009. After national measures to gradually reduce the number of illegal wells (MWI 2009; MWI 2015b), total groundwater extraction is reduced by 40% and groundwater level in AB1341 stops declining. Therefore, a recovery in groundwater heads by the end of the forecasted period is assumed (Fig. 3.9c, f, g, h).

The calculated groundwater extraction volumes and time series for wells AB1341 and AB3148 are presented in Fig. 3.9. Moreover, to generate the model input for the calibrated model, the following conditions were applied for the respective MODFLOW package:

- CHD: groundwater recharge through heads is dependent of groundwater levels of wells AB1341 and AB3148, and is extrapolated from data of the calibration period according to the scenario definition (Fig. 3.9)

- WEL: crop water requirement values are extrapolated, and groundwater extraction is calculated according to the extension of irrigated area (scenario 1) or the reduction of water requirement (scenarios 2, 3 and 4) (Fig. 3.9)

- DRN: drain values stay constant

- GHB: water head of the Dead Sea follows a depletion of 1 m/a (Fig. 3.8)

- RCH: recharge through return flow changes accordingly to the scenario definition of land use and groundwater extraction volumes

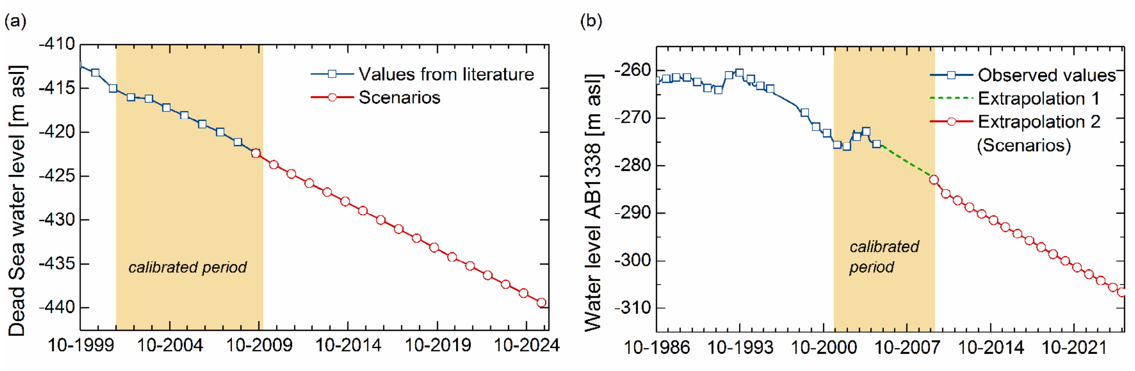
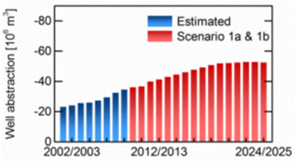
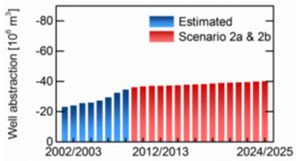
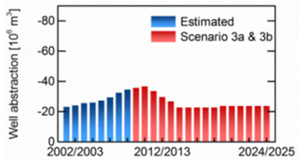
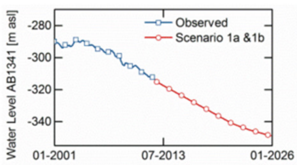
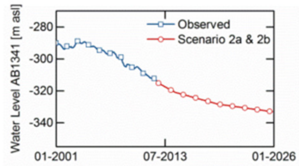
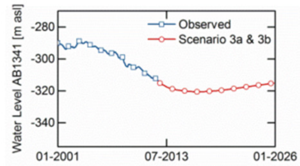


Fig. 3.8 Time series for the general head boundary for (a) the Dead Sea (GHB2 in Fig. 3.5) and (b) for well AB1338; measurements data are available until September 2005 (*blue squares*), the rest of the calibrated period (*green dash line*) and the time series for scenario modelling (*red circles*) was extrapolated.

MODFLOW Package	Scenarios 1a & 1b	2a & 2b	3a & 3b
Groundwater extraction (WEL)	Agriculture is further developed reaching the maximum arable area of 40 km^2 by 2021 (a) 	Irrigation reaches its maximum in 2012 and then stays constant until 2025 (b) 	After 2012, irrigation decreases 10% yearly and after a reduction of 40% stays constant until 2025 (c) 
Heads boundary condition (CHD) AB1341	Same depletion rate between 2004 and 2021 (d) 	Same depletion rate from 2004 until 2015. The decline rate then gradually decreases until 70 cm per year (e) 	Same depletion rate from 2004 until 2013. Then, it decreases 50% every year. In 2017, the water level starts recovering until 2025 (f) 

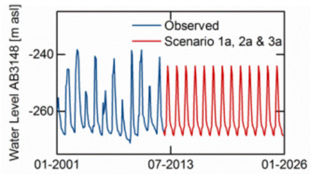
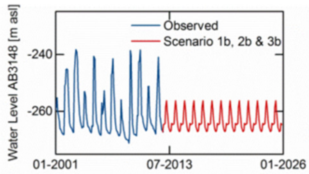
	1a, 2a & 3a	1b, 2b & 3b
Heads boundary condition (CHD) AB3148	Average groundwater levels of normal hydrological years are repeated (g) 	Average groundwater levels of dry hydrological years are repeated (h) 

Fig. 3.9 Time series for scenario simulations for the average annual extraction volumes (a, b, c); for well AB1341 tied to the northern boundary condition (d, e, f) and for well AB3148 tied to the eastern boundary condition (g, h). The slight increase in values for well abstraction (a, b, c) results from the determination of the crop water requirement as a function of evapotranspiration and therefore, this value does not stay strictly constant

3.5 RESULTS

3.5.1 Groundwater heads

Following the high dependence of the eastern boundary condition to well AB3148, groundwater heads presents a high seasonal fluctuation at the outlet of the Wadi Shueib dam, which smooths towards the west. The model reproduces the recharge processes from the northern unconsolidated and adjacent consolidated aquifer and the continuous decline of water heads. Groundwater moves in the directions north-west, west and north-south, as defined during the conceptual model (Fig. 3.10).

Between 2001 and 2009, the decline of groundwater heads occurs more drastically at the eastern half of the modelled area, where most of the extraction takes place. For instance, north of Wadi Shueib dam (by coordinates east 208,154 and north 1,146,700) and direct at the eastern boundary, groundwater levels drop 11 m in the period of October 2001 to October 2009; while at the western boundary, during the same period, water level only falls around 2 m. Moreover, the Lisan formation, represented with a lower hydraulic conductivity and storage coefficient than the rest of the modelled area, produces a steeper hydraulic gradient, slows the groundwater flow in the interface from Zone ID 7 to ID 8, and diverts, in part, the flow to the south.

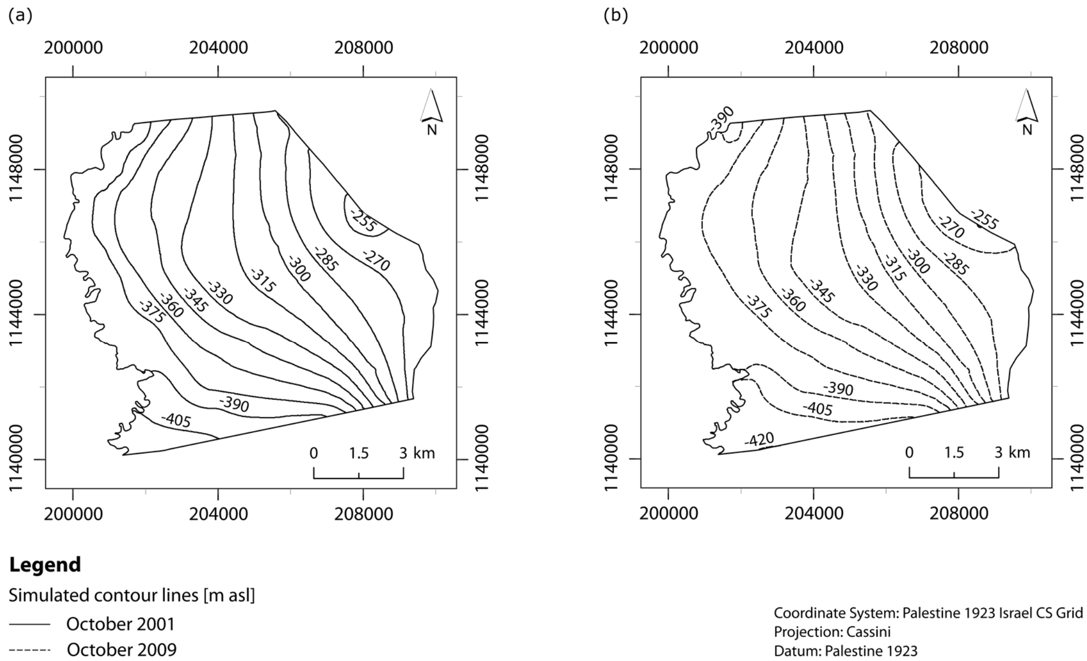


Fig. 3.10 Contour lines of computed heads for two time steps: October 2001 (a) and October 2009 (b).

3.5.2 *Water budget*

Based on the results of the calibrated model, the annual water budget for hydrological years is shown in Fig. 3.11a. A gradual increase from an annual 22 to 32 MCM is shown in the groundwater extraction component (WEL); these values were determined using the process described in Section 3.2 and are in accordance with the reported total water requirement of 63 MCM/a for the complete southern Jordan Valley (42 km^2) (Al-Weshah 2000a). Depending on well extraction, recharge through irrigation flow (RCH) shows no significant contribution to the water balance, representing a modest 5% of the total input components of the water budget.

The predominant input to the water balance is the flow resulting from the eastern boundary condition, representing the lateral recharge from the Wadi Shueib dam and the consolidated karst aquifer. The total lateral inflow is calculated as an annual average of 76 MCM. The net flow coming into cells located directly downstream of the Wadi Shueib dam is 2.7 MCM/a, showing the groundwater infiltration effect caused by the dam. As seen in groundwater head values in Section *'Characterisation of the Study region',* the CHD component recovers 14 MCM during the wet year 2002/2003 and declines then 10 MCM right after the dry hydrological year 2003/2004.

The aquifer drains mainly through the southern border (GHB). The predicted average flow of 41 MCM/a seems a reasonable quantity considering that (1) one part of this volume meets the water requirement of agricultural activities at the south of the model area and (2) the other part serves as recharge in the direction of the Dead Sea, which is connected to the hydrogeological formation of the Jordan Valley group (Al-Weshah 2000b).

An average flow of 12 MCM/a discharges through the western boundary to the Jordan River (DRN), mainly at the north-west of the modelled area. The outflow through the drain component decreases as groundwater level drops since groundwater heads falls under the drain elevation, disconnecting the groundwater from the river.

Positive values for the net storage component show that water mostly comes from the groundwater storage (Anderson et al. 2015). The difference between storage components (net storage) reaches a value close to zero, 0.25 MCM/a, during the wet year 2002/2003, and after that increases reaching its maximum during the dry hydrological year 2007/2008 with 20 MCM/a.

A monthly analysis shows the seasonal variation of the system. Groundwater net flow coming through head boundary conditions (CHD) reacts clearly after rainfall months. A maximum average monthly infiltration of 7.5 MCM occurs in March, while monthly maximum rainfall takes place in January. During the rainy months, the system recovers and the storage component reaches its minimum value in March (-1.8 MCM) (Fig. 3.11b).

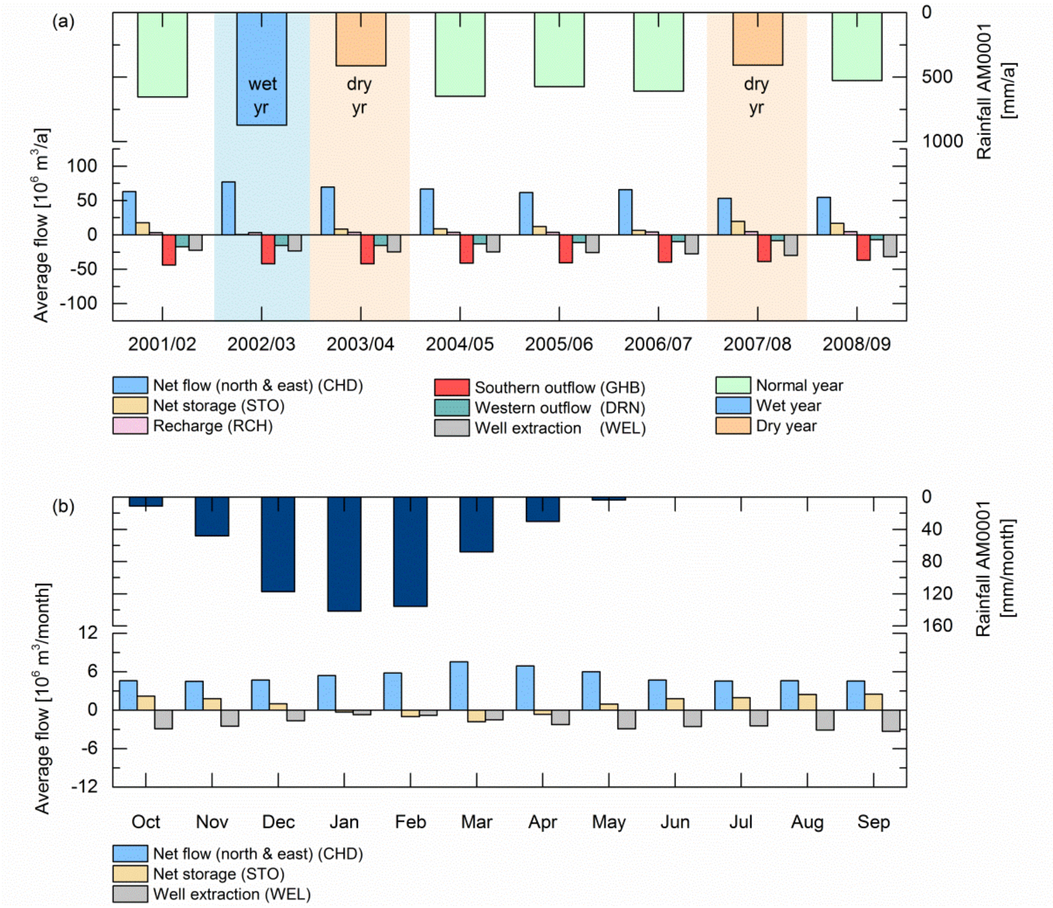


Fig. 3.11 (a) Evolution of sources and sinks during the simulated period, annual average precipitation of climate station in As-Salt (AM0001) and hydrological conditions, (b) monthly average variation of precipitation (AM0001) and water budget components that have a clear seasonal variation: heads (CHD), storage (STO) and extraction (WEL).

3.5.3 *Scenario results*

The six simulated scenarios consider assumptions of climatological conditions, average and dry, and land use extension with the resultant change in groundwater extraction volumes. Regarding hydrological condition, the predicted groundwater heads in scenarios *a* and *b* do not present a significant difference between each other (around 1 m by AB1340); with exception of a stronger seasonal variation in AB3149 for scenarios *a* as a product of higher values in the boundary condition for average hydrological years, where differences fluctuate between 0 and 2 m (Fig. 3.12 a-b). Changes in contour maps between average and dry conditions are therefore minimal and only average (*a*) variants were plotted (Fig. 3.12 c-e).

Supposing that the maximum arable land is reached by 2021 (scenario 1a & 1b), in the period 2001–2025 groundwater level drops by 52 and 40 m in wells AB1340 and AB3149, respectively, with a slightly lower trend from 2021 onward. A less extreme decline can be observed when the water requirement for agriculture remains constant after 2012 (scenario 2), where even under dry hydrological conditions, the water level by 2025 is at least 13 m higher than in Scenario 1a (Fig. 3.12 a-b). Groundwater contour lines of October 2023 for Scenario 1a and 2a (Fig. 3.12 c-d), show how strong groundwater head values drop in the complete modelled area, compared to the contour maps of the calibrated period (Fig. 3.10), for example, the isoline -435 m asl appears at the south-western limit, which is 15 m deeper than in October 2009 at the same location.

Scenarios 3a and 3b show that by reducing 40% the groundwater extraction volume, groundwater levels stabilise and recover from 2014 on. The predicted groundwater heads in scenarios 3a and 3b do not present a significant difference between each other, with exception of a stronger seasonal variation in AB3149 for scenario 3a as a product of higher values in the boundary condition for average hydrological years (Fig. 3.12 a-b). The groundwater contour map shows that in most of the irrigated area, groundwater levels in scenarios 3 and 4 are at least 10 m higher than in the other two, representing the aquifer recovery (Fig. 3.12 e).

In terms of recovery of the groundwater system, the scenarios show that the model responds mainly to two parameters in the model: (1) water extraction by pumping, which depends on the extension of irrigated area or as a consequence of closing illegal wells, and (2) inflow of water from the northern part of the modelled area in the Jordan Valley; both of these points are controlled by the defined groundwater withdrawal. Regardless of the high net contribution of infiltration at the eastern boundary to the water balance, variations in the hydraulic head parameter at the east show no significant influence on the observed values of groundwater heads and thus, on the long term trend.

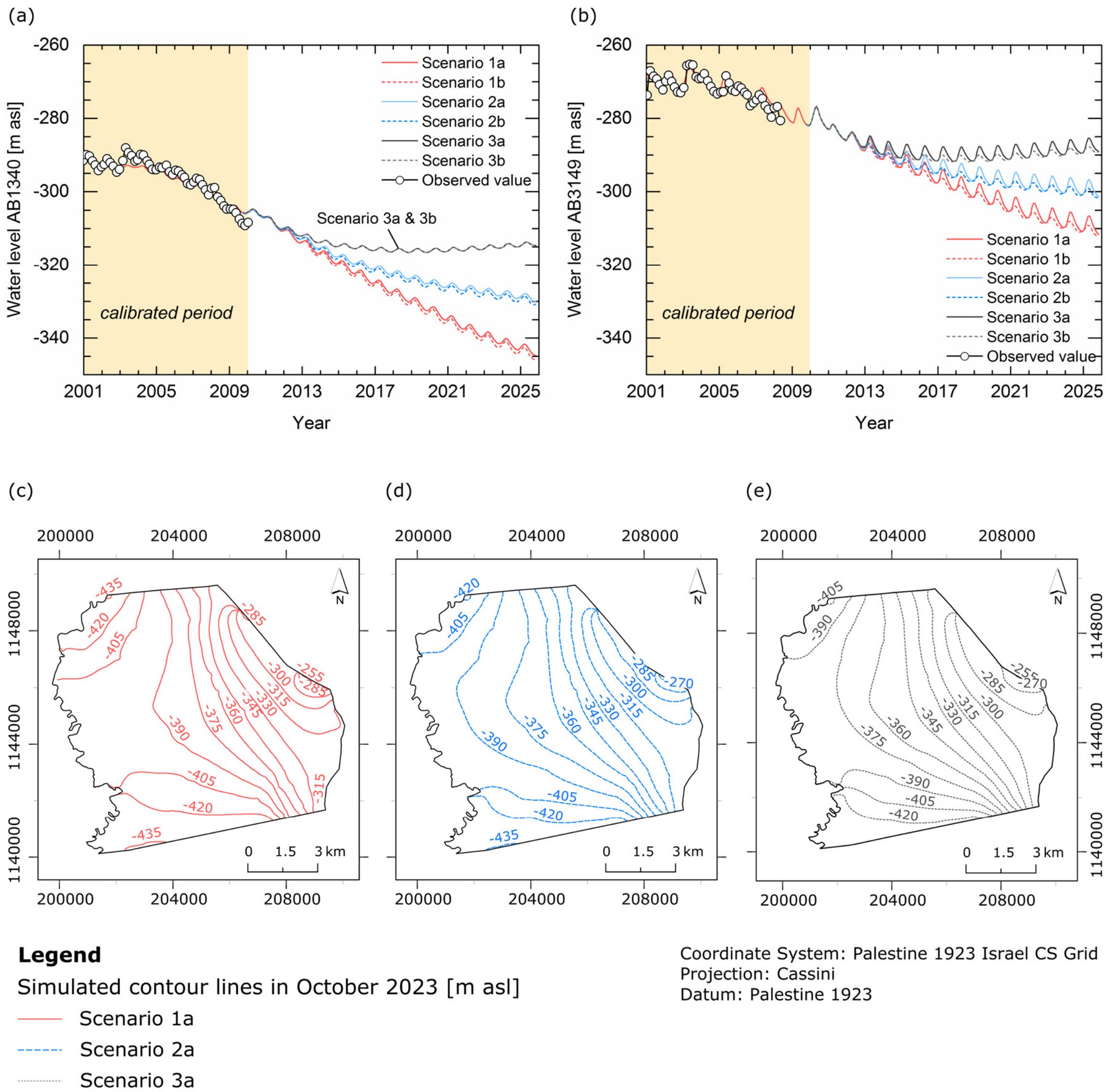


Fig. 3.12 Scenario results for groundwater level in observation wells AB1340 (a) and AB3149 (b) and contour maps of groundwater heads for October 2023 for scenario 1a (c), 2a (d) and 3a (e). Contour maps for dry conditions (scenarios b) present almost no difference to the average conditions (scenarios a).

In terms of water balance (Fig. 3.13), the average water budget for sources and sinks for the period 2001–2025 shows that the main components of the system, regardless of the scenario modelled, are the inflow through the hydraulic head boundary condition and storage, and the outflow through the southern boundary and the groundwater extraction. The minimum total inflow and outflow was achieved during scenarios 3 and 3b, with around 67 MCM/a. The reduction of extraction rates (WEL component) affects the inflow coming from the northern part of the Jordan Valley and therefore, the hydraulic heads (CHD component) increase. Less water is then taken from the storage component and more water can leave the system, particularly, through the general boundary condition in the south (GHB). The scenarios 1a and 1b, followed by Scenario 2a and 2b, present the largest decrease in net storage with an annual average of 14.7 MCM and 10.9 MCM, respectively; that is at least 52% higher than Scenarios 3a and 3b. The flow in the direction of the Jordan River is zero after 2018/2019 for scenarios 1 and 2 and by scenarios 3, it represents only 2% of the average 32 MCM/a for the period 2018-2025 of the outflow through GHB, which emphasizes the relevance of the outflow through the southern boundary.

Changes in storage and southern outflow can be seen for all average (*a*), since differences in components between versions *a* and *b* are not larger than 0.2 MCM (Fig. 3.14): in scenario 1a, the net storage (STO) varies between 17 and 19 MCM before 2020/21 and decreases until 13 MCM, after 2010 when the maximum arable area is achieved, while the outflow through GHB permanently declines reaching 14 MCM in 2024/25, leaving less water to recharge the southern aquifer in the direction of the Dead Sea. In scenario 2a, the net storage and southern outflow component vary and remain almost constant in the last simulated years; compared to Scenario 1a, less water comes from STO and more volume can leave the system in the south (around 23 MCM by 2024/25). In scenario 3a, the reduction of groundwater pumping by 40% leads to negative values in net storage starting in the hydrological year 2019/20. That means that the storage of water in the system increases, and a sustainable development, expected when the rate of water coming from storage is at least zero (Bredehoeft 2002), will be achieved in scenarios 3a and 3b. The outflow through the southern boundary also increases, by 3 MCM between 2019 and 2025, which would result in a higher recharge towards the Dead Sea.

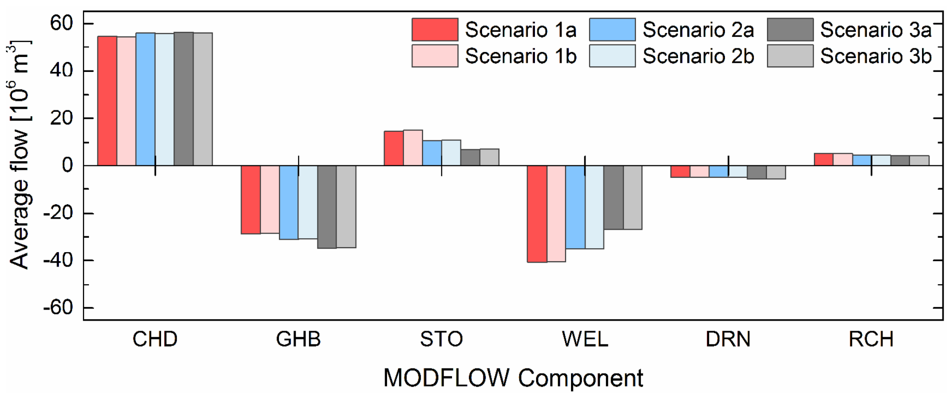


Fig. 3.13 Average water budget for sources and sinks for the period 2001–2025. Negative values indicate that groundwater leaves the modelled area, and positive values are inflows in the system. The MODFLOW components are: hydraulic heads (CHD), general head boundary (GHB), storage (STO), groundwater extraction (WEL), drains (DRN) and return flow (RCH).

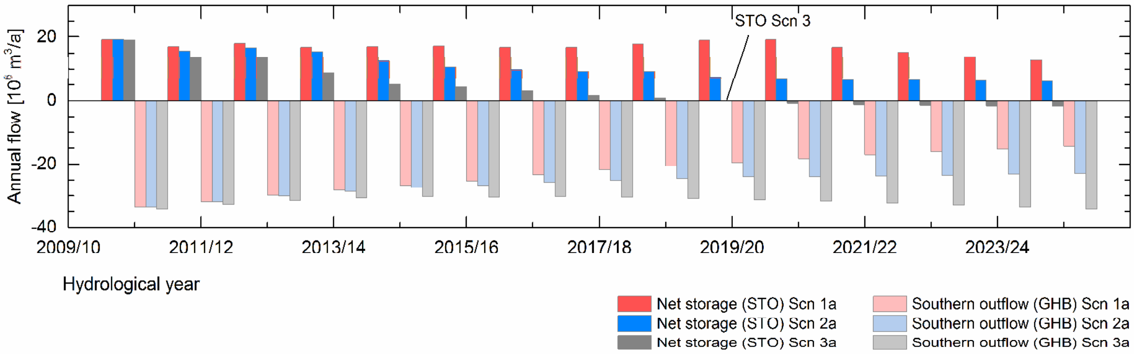


Fig. 3.14 Annual water flow for components of net storage and outflow at the southern boundary (general head boundary) for all scenarios. Negative values mean that the water leaves the system. Flows for dry conditions (scenarios b) present almost no difference to the average conditions (scenarios a).

3.6 MODEL LIMITATIONS

The main objective of this Chapter is to present a local-based numerical groundwater model built on the integration of different data sources to characterise the groundwater system in the Jordan Valley. The overall model calibration and results can be considered as reasonable, since it presents a water balance within reported literature values, it reproduces the seasonal variation and trend of the water table caused by groundwater lateral recharge and groundwater extraction, and groundwater contours are in accordance with the conceptual model and expected flow direction.

However, this model also presents limitations. Given the geological and hydrogeological background, the assumed conceptual model may be non-unique, and geological formations and hydrogeological units had to be simplified due to the lack of detailed borehole information. It was also assumed that the complete model domain was unconfined, which may not be necessarily so.

Regarding extraction rates, illegal groundwater extractions present a severe problem and the applied approach of estimating extraction rates by actual crop distributions and crop water requirements may lead to under- or over estimations, and reliable groundwater extraction rates would be desirable.

The number of monitoring wells is low and their spatial distribution is irregular, which means that calibration against hydraulic heads may be quite acceptable close to these observations points but uncertainty in the predictions in the rest of the model domain cannot be quantified. This also applies to the relevance of the western and southern boundary conditions. Moreover, the scenario simulation is based on extrapolation of time-series. Since the northern and eastern boundary conditions are tied to monitoring wells, the projection of these time-series also depends on assumptions on how groundwater heads develop. The outflow to the north-west of the study area is influenced mainly by the hydraulic heads defined in the boundary conditions, which might overestimate the flow in this direction.

Many of the assumptions made for input in the numerical model are based on previous studies/literature and measurements, which also may involve errors and uncertainty. Though there is a large list of methods for uncertainty analysis for groundwater modelling (for a review of some of them refer to Wu and Zeng 2013), these techniques are dependent on additional data, which are not readily available in the study area. Therefore, under the given scarcity of data in the region, the principle of parsimony was considered, acknowledging the limitations of the model.

3.7 CONCLUSIONS

This chapter shows a groundwater model under limited dataset using a real case study in a semi-arid region, applying alternative methods to field measurements, e.g. determination of unknown pumping values through crop water demands and satellite imagery, on a two-dimensional transient model in a local semi-arid basin in the southern Jordan Valley. Six scenarios are introduced for different climatic and anthropogenic conditions, considering the arable land extension and closure of illegal wells, and therefore, determining water extraction rates.

Applying the principle of parsimony (Hill 1998), the complexity of the system is simplified in one layer, using grid refinement at the most significant part, where groundwater extraction occurs. The local scale requires the use of high resolution data sources, in this case, the combination of analytical methods, field surveys and specific studied reported in the literature. It is also shown that the applied approach achieves a good prediction of groundwater heads (Pearson r for computed versus measured values of 0.91 (AB3149) and 0.96 (AB1340) for the calibration period of 2001–2009).

Water balances given in the literature for the Jordan Valley usually refer to a larger spatial scale, considering at least the southern Jordan Valley or the Jordan Valley in its complete extension. This makes a direct comparison against the results difficult. Nevertheless, the values predicted by the calibrated model are in a plausible range, which supports the overall modelling results.

As discussed by Bredehoeft (2002), if sustainable development is the goal to be achieved, no groundwater should be taken from the storage, obtaining a long term steady state equilibrium or even recovery. The most significant outcome of the computed scenarios is that the marginal difference between the results of average and dry scenarios shows that by decreasing groundwater extraction rates the goal of sustainability can be reached, and this objective is only secondarily influenced by climate.

The current extensive groundwater extraction is unsustainable to meet future water requirements in the modelled area. Options to decrease groundwater extraction rate include reduction of cultivated land area, application of more efficient irrigation techniques and maintenance of the current ones, irrigation with alternative water resources (such as treated wastewater) and reorientation from the widespread cultivation of strongly water-demanding crops, for instance bananas and date palms towards less demanding crops, such as some types of grain legumes. The reduction of crops that consume water during the summer months would imply a reduction in use of the storage component, as seen in seasonal analysis.

As this study presents a groundwater model for the lower Jordan Basin, it will be easier for future studies either to extend the model or to adopt it as a reference for similar research questions. Despite its shortcomings due to the scarce data sources, the presented model can be used to help implement management measures, though more data collected from the study area (groundwater heads, measurements related to geometry, aquifer parameters through an adequate borehole construction and pumping tests, as well as flow measurements associated with the Jordan River) would improve the reliability of the results. Therefore, some essential measures are recommended, which could help to improve the model, and thus, to achieve more precise projections: (1) the drilling of deep wells, to gather more valid information about vertical aquifer geometry, which would allow the definition of more than one layer representing the different aquifers and a more detailed distribution of hydraulic parameters, especially where higher sensitivities for K and Sy are shown (zones ID 1, ID 2 and ID 7); pump test to assess hydraulic aquifer parameters could be also performed in these wells; (2) the quantity and spatial arrangement of groundwater monitoring wells should be improved to ensure better distribution of boundary conditions and better results of model calibration; (3) hydrometric stations in the Jordan River would help to interpret better the hydraulic connection between the river and the aquifer; (4) reliable values regarding extraction rates, requiring the closing of illegal wells and installation of flow meters in registered wells.

This numerical model can be used per se in the situation for which it was calibrated; yet, the approach shown in this paper can be adopted in similar irrigated regions with scarce data for porous aquifers. An understanding of how the groundwater basin reacts according to different stresses is essential to define management strategies to determine sustainable groundwater extraction rates in highly irrigated areas.

CHAPTER 4

4 DECISION SUPPORT SYSTEM FOR WADI SHUEIB AND THE SOUTHERN JORDAN VALLEY

A decision support system (DSS) is formulated for the complete study region, Wadi Shueib and the southern Jordan Valley. Using a DSS numerical model, WEAP, the water system is analysed using future scenarios, indicators and reliabilities, considering different water competitors, particularly municipal and agriculture in both interconnected basins.

4.1 METHODOLOGY

To organise a decision support system, the simulation analysis in Wadi Shueib and the Jordan Valley was formulated using the "XLRM" framework described by Lempert et al. (2003). This method was chosen since it is a concise routine to represent four features that together determine water resources management, such as the uncertainties of the system (X), strategies planned (L), how to assess the system (R) and evaluation of the system and plans (M) (Kalra et al. 2015; Forni et al. 2016). The XLRM elements can be stated in the form of a matrix (Table 4.1) and they represent (Lempert et al. 2003):

X: Exogenous uncertainties or, in this case, external driving forces, on which the decision maker has no influence on, such as climate or population growth (Section 4.1.1)

L: Policy levers, in this study they refer to the water strategies to be analysed (Section 4.1.1)

R: Relationships or potential methods that focus on the attributes of the system. For this study, these methods are the models where the uncertainties (X) and strategies (L) are analysed (Section 4.1.2)

M: Measures or performance metrics, for instance, indicators that show the results from the model applications (R) (Section 4.1.4)

Table 4.1. XLMR matrix.

Uncertainties or external driving forces (X)	Strategies (L)
High resources pressure (HRP)	Business as Usual (BAU)
Low resources pressure (LRP)	Full Implementation (FI)
Models (R)	**Performance metrics or indicators (M)**
MODFLOW WEAP	1 Connection to secondary treatment (%) 2 Water demand satisfaction (coverage) (%) 3 Coverage for external demand (%) 4 Groundwater exploitation index (%) 5 Water harvesting ratio (%)

4.1.1 Definition of external driving forces (X), strategies (L) and scenarios

The evaluation of the water system takes place with the definition of uncertainties, that is, elements that are not controllable by the decision makers, also called external driving forces (X). They refer to hydrological periods and population growth trends, and also to agricultural and industrial production tendencies, if they are not regulated by the water strategy. These uncertainties were categorised within a high and low resources pressure level and are described below and summarised in Table 4.2.

Moreover, considering the geographic differences, the water sources distinctions (surface water and groundwater) and that the water strategy focuses in Wadi Shueib mainly on the domestic demand, and in the Jordan Valley on the agricultural demand, the external driving forces and scenario planning contemplate these two areas separately (see Table 4.2).

High resources pressure (HRP) Dry climate periods and an increasing water demand in the domestic sector for both basins are assumed. Population growth follows the recent trends and remains at very high level for the Wadi Shueib (Riepl 2013), while in South Shunah a low population growth is expected, given the small 0.62% annual population growth rate between 1994 and 2015 (DoS 1994; DoS 2015) and inferring that rural areas will not grow the way larger urban settlements, such as As-Salt, have had. Agricultural production stays on the current level for Wadi Shueib and in the Jordan Valley it is defined within management strategies designated in the Jordanian water strategy, simulated by the BAU and FI scenarios. Water demand from the industry in Wadi Shueib increases after 2009 (Riepl 2013) and it set to zero in 2014, after the cement industry stops operations (Lafarge Cement Jordan 2013).

Low resources pressure (LRP) Average climate periods for the Jordan Valley and Wadi Shueib are adopted. The domestic water demand is assumed with a moderate increment in the Wadi Shueib (Riepl 2013) and constant for the Jordan Valley. Medium population growth rates are considered for Wadi Shueib (Riepl 2013) and in South Shunah, the population growth trend remains low, same as by HRP. Agricultural production decreases 0.5% annually for Wadi Shueib (Riepl 2013) and for the Jordan Valley is simulated within BAU and FI scenarios. Water demand from the industry in Wadi Shueib slightly increases between 2010 and 2013 (Riepl 2013), and then it behaves same as HRP.

The scenarios are based on the selection of strategies (L) for water resources management. In this case, a ***reference scenario*** is defined as the extrapolation of the time-series, without any further analysis and four other future scenarios were constructed based on adopted strategies from MWI, e.g. improvement of infrastructure and use of unconventional water sources. They are sub-classified according to the strategy implementation stage, described as follows and summarized in Table 4.2.

Business as usual (BAU) Projects perform as indicated in the annual reports of MWI and no further implementations are planned. Strategies defined in the BAU scenario for Wadi and the Jordan Valley are the reduction of physical supply network losses, sewer rehabilitation and connection program. Close of illegal wells in the Jordan Valley stops the increase of groundwater extraction after 2012, such as scenarios 2a and 2b in the numerical groundwater modelling.

Full implementation (FI) All strategies of the Jordanian water strategy are fulfilled, including those in the capital investment program (MWI 2016b), where financing is currently uncertain. The strategies contemplate all those for the BAU scenario: reduction of physical supply network losses, sewer rehabilitation and connection program and also, the enlargement of the volume of wastewater treatment plants and the use of household rainwater harvesting for Wadi Shueib. In the Jordan Valley, it is assumed that the gradually reduction of illegal wells reduces the total groundwater extraction by 40%, same as scenarios 3a and 3b in the numerical groundwater model.

Full implementation plus (FI-plus) Considers all strategies of FI scenario and it includes, in the Wadi Shueib and Jordan Valley, wastewater reuse for irrigation through the construction of decentralised wastewater treatment plants (DWWTP), and the increment of height of the Wadi Shueib dam. This scenario was defined separately from FI, to easily identify and evaluate the effects of these strategies on the water system.

Table 4.2. Outline of pressure levels HRP and LRP and scenarios BAU and FI for the Jordan Valley and Wadi Shueib. The assumptions and scenario definitions are based on Lafarge Cement Jordan (2013), Riepl (2013), MWI (2015), MWI (2016) and Alfaro et al. (2017).

	Jordan Valley	Wadi Shueib
High Resource Pressure (HRP)		
• Relatively dry period	✓	✓
• Increasing per capita water demand in the municipal sector	✓	✓
• Population growth follows the recent trends and remains at a very high level		✓
• Population growth trends remain low	✓	
• Agricultural production stays on the current level		✓
• Water demand from the industry increases after 2009, increases between 2010-2012 and stops after 2013		✓
Low Resource Pressure (LRP)		
• Average climatic data	✓	✓
• Domestic water demand follows a moderate increasing		✓
• Domestic water demand remains almost constant after 2009	✓	
• Medium rates of population growth		✓
• Population growth trends remain low	✓	
• Agricultural production is decreasing		✓
• Water demand from the industry slightly decreases after 2009, remains almost constant between 2010-2012 and stops after 2013		✓
Business as Usual (BAU)		
• Reduction of physical supply network losses	✓	✓
• Sewer rehabilitation and connection program	✓	✓
• No further strategies are feasible until 2025	✓	✓
• Close of illegal wells in Jordan Valley	✓	
Full Implementation (FI)		
• Reduction of physical supply network losses	✓	✓
• Sewer rehabilitation and connection program	✓	✓

	Jordan Valley	Wadi Shueib
• Increase volume of wastewater treatment plants		✓
• Household water harvesting starts in 2017		✓
Full Implementation – Plus		
• Decentralised wastewater treatment plants in Ira and Yarka, and South Shunah starts in 2018	✓	✓
• Increase of height of Wadi Shueib dam after 2021	✓	✓
Reference		
• Extrapolation of the time-series, without any further analysis	✓	✓
• Agriculture develops reaching its maximum possible by 2021 (as scenario 1 in the numerical groundwater model)	✓	

The strategies (L) defined in BAU, FI and FI-plus scenarios are then combined with the uncertainties (X), representing seven scenarios, as presented in Table 4.3.

Table 4.3. Summary of analysed scenarios. The number of the scenario will be extensible used in the Section "*Results*".

External driving forces (X)	(Number) Scenario	Sub-Scenario
High Resource Pressure (HRP)	(s1) Business as Usual (HRP-BAU)	-
	(s2) Full Implementation (HRP-FI)	(s5) FI-plus
Low Resource Pressure (LRP)	(s3) Business as Usual (LRP-BAU)	-
	(s4) Full Implementation (LRP-FI)	(s6) FI-plus
	(s7) Reference	

4.1.2 Models (R)

The decision support system model was done using the "Water Evaluation And Planning" system (WEAP), since it is vastly used by MWI, and it was developed on the approach and previous modelling in Wadi Shueib of Riepl (2013), yet, it considers a wider sub-basin level, including the karstic (Wadi Shueib) and porous aquifer (Jordan Valley) into one model boundary, showing a more complete focus under IWRM, integrating two connected basins, which until now have been considered separated. Additionally, a graphical evaluation and representation of the results is presented, simplifying their visualisation and therefore their interpretation.

The boundaries of the existent model were extended to the Jordan Valley and the new water strategy of MWI, introduced on 2015, was implemented in the simulated scenarios. Moreover, the results of the numerical groundwater model in the Jordan Valley of Chapter 3 were successfully incorporated to WEAP. The results were visualised and post-processed using Visual Basic, Matlab and R.

The model boundaries coincide with the Wadi Shueib catchment and the lower Jordan Valley, directly downstream of the Wadi, where the numerical groundwater model was set up (see Chapter 3). The model from Wadi Shueib connects with the Jordan Valley through its main outlet, the Wadi Shueib dam, which supplies irrigation with direct surface water and groundwater from infiltration into the porous aquifer in the Jordan Valley.

The calibrated model was run in monthly time steps during the years 2001-2009, whereas for scenario planning, the period was extended until 2025, considering the new water strategy of Jordan of 2015.

4.1.3 Input data

The data structure used in WEAP is defined through nodes, which represent for instance supply sources, withdrawal and wastewater treatment plants, and links that connect the different elements of the system (Sieber and Purkey 2015). The conceptual model of Fig. 2.7 was implemented in WEAP as shown in Fig. 4.2.

Where applicable, the parameters and values previously assigned by Riepl (2013) were used, such as the projections regarding population growth and future rainfall and trends in Wadi Shueib, which define in this area the HRP and LRP external driving forces or uncertainties (X). Population trends were projected using the information from the Higher Population Council of Jordan. Regarding future time-series of precipitation, for the HRP uncertainty (dry), and annual rainfall volumes from 1994-2009 were applied to the years 2010-2025 at random and for LPR driving force, the values assigned for HRP were set up 25% higher (Riepl 2013) (Fig. 4.1). The consumption goals of 120, 100 and 80 l/cap/day for major urban centres, small town and rural areas, respectively, were also updated.

The new nodes considered in the water allocation model describe the water system downstream of the Wadi Shueib dam, where irrigation represents the main water user in the Jordan Valley. The new nodes, during 2001-2009, are mainly demand sites, which stand for elements with water requirement and a groundwater node as a new water source (Table 4.4). Additional nodes were also implemented for the scenario simulations.

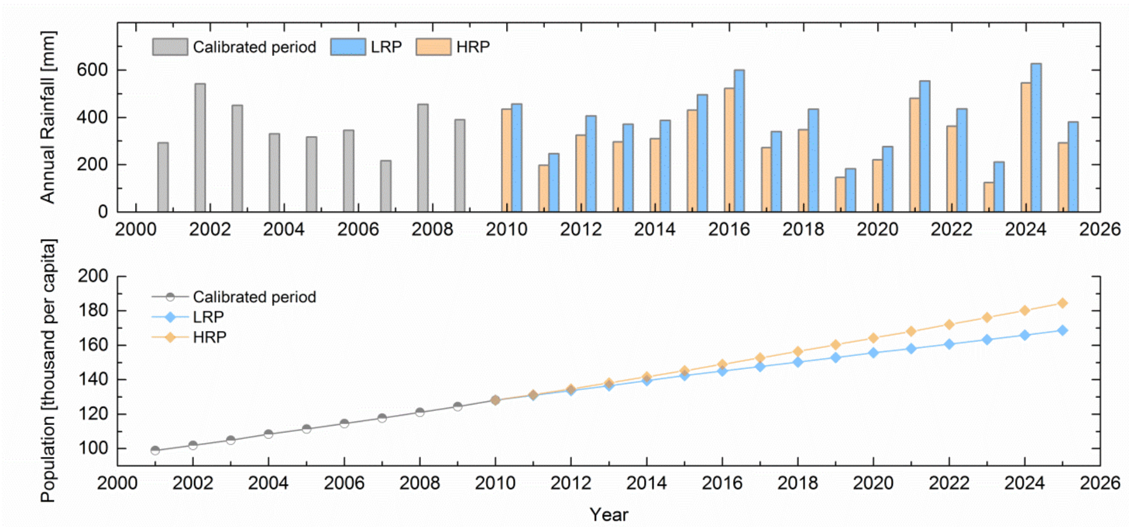


Fig. 4.1 Annual rainfall (above) and population (below) for Wadi Shueib, showing the calibrated period of 2001-2009 and future projections for 2010-2025. Based on Riepl (2013).

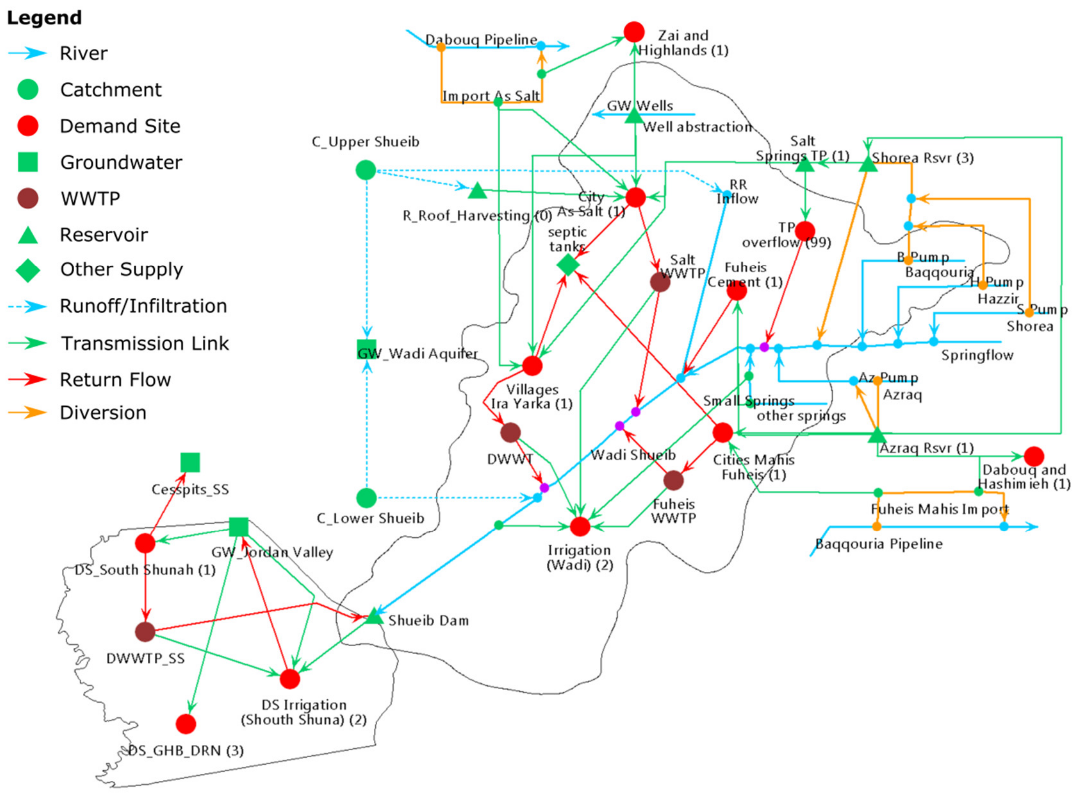


Fig. 4.2 WEAP schematic of the Wadi Shueib and Jordan Valley system through nodes and links definition.

Table 4.4. Nodes and short description added in the Jordan Valley extension within the simulation time 2001-2009.

Name New Node	Type	Major Input Parameters	Description
DS_South Shunah	Demand site	Population Annual water use rate	Represents the rural settlement of South Shunah
DS_Irrigation	Demand Site	Monthly water use rate	Represents irrigation water
GW_Jordan Valley	Groundwater	Natural recharge	Represents the porous aquifer in the Jordan Valley. The natural recharge represents the infiltration from the adjacent aquifer through the northern and water limit, calculated with MODFLOW.
DS_GHB_DRN	Demand Site	Monthly water use rate	Represents the outflow from the groundwater system in the Jordan Valley, previously modelled with MODFLOW

New nodes and updated information are described in the following points:

i. Demand Site South Shunah (DS_South Shunah)

The demand site of South Shunah represents the municipal requirement and therefore, it was assigned as first priority, as stated in the water strategy.

The population of the rural settlement of South Shunah grew from 6630 inhabitants in 1994 to 7553 inhabitants in 2015, which represents an annual population growth rate of 0.62%, calculated with Equation 4.1. Values from the Jordan census in 2004 were only collected on complete district level, which includes other localities than South Shunah, and therefore could not be used.

$$Population_{Future} = Population_{Present} \cdot (1 + i)^{n} \quad (4.1)$$

Where i is the growth rate and n the number of periods.

It was assumed that by the year 2025 the municipal water demand, without losses, will grow reaching 80 l/c/d. Considering the ranges of administrative and physical losses for the national average and the Balqa Governorate (MWI 2009; MWI 2015a), losses were assumed to be around 20 and 40% for the low and high resources pressure scenarios, respectively; achieving consumptions for LRP of 98 l/d/cap and for HRP of 112 l/d/cap (Fig. 4.3).

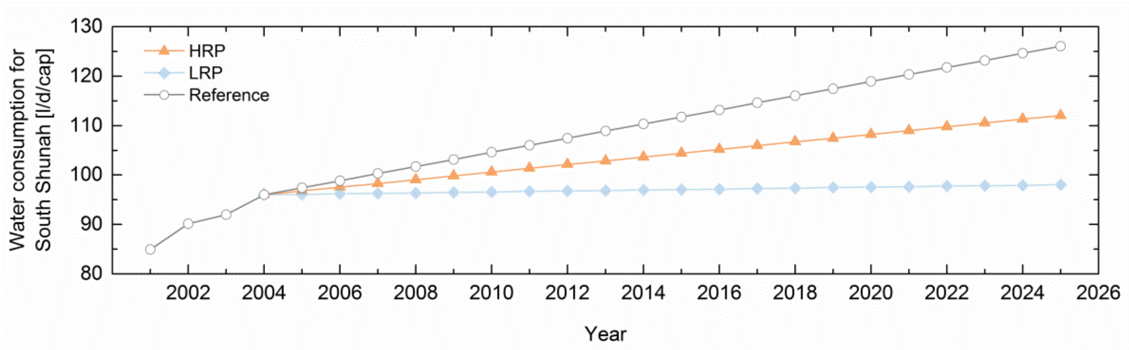


Fig. 4.3 Municipal demand projections for the rural settlement of South Shunah. The values consider administrative and physical losses.

ii. Demand Site Irrigation (DS_irrigation)

Agriculture is the main activity in the Jordan Valley. It was represented through a demand node. The alluvium aquifer is the main source for irrigation water, followed by superficial water from the Wadi Shueib dam.

The estimated water demand corresponds to the calculated crop water requirement from Chapter 3.2.3 and their assignation in the WEAP model in the BAU, FI and Reference scenarios are shown in Fig. 4.4. A decentralised wastewater treatment plant was added as irrigation water source after 2018, as part of the FI-Plus scenarios (s5 and s6).

Moreover, following the same assumptions as in Alfaro et al. (2017), the consumption of this demand site was set as 90%, which means that 10% of the flow returns to the groundwater aquifer.

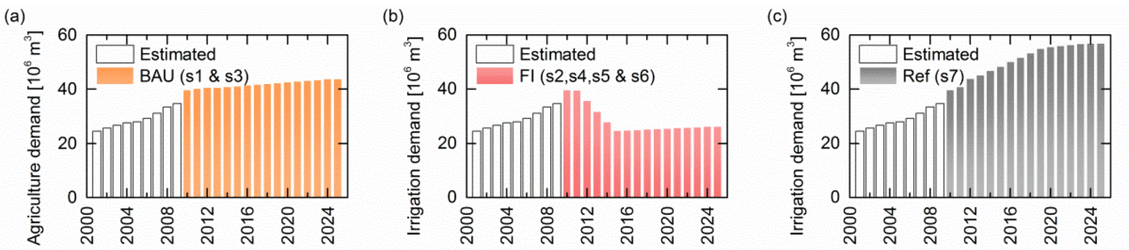


Fig. 4.4 Annual agriculture water demand for the (a) BAU scenarios, (b) FI scenarios and (c) reference scenario.

iii. Groundwater Jordan Valley (GW_Jordan Valley)

The porous alluvium aquifer was represented by a groundwater node, which provides water for municipal demand (1st priority), agriculture (2nd priority) and, to the recharge in the north-west direction and especially, to the south in the direction of the Dead Sea (3th priority). The priorities were assigned in accordance to the preferences dictated in the new water strategy (MWI 2015a).

The estimated flows coming from the northern and eastern boundaries of the Jordan Valley, as computed in the numerical groundwater model, determined by the CHD components in MODFLOW (around 50 MCM/a) (Fig. 3.11a and Fig. 3.13), were assigned in WEAP as natural recharge.

Infiltration from the Wadi Shueib dam into the groundwater aquifer was also defined in WEAP; therefore, to avoid double volumes, this infiltrated flow was subtracted to the recharge simulated by MODFLOW.

iv. Recharge of external users (DS_GHB_DRN)

As defined in the conceptual model, groundwater flows towards the north-west direction and through the southern boundary. The numerical groundwater model simulated these water volumes through the drain and general head boundary component (see Chapter 3). The computed fluxes were assigned to WEAP as the water requirement of the demand node DS_GHB_DRN.

v. Rainwater Roof Harvesting (R_Roof_Harvesting)

A reservoir node is created in the Wadi Shueib area to share the runoff of the Upper Shueib catchment from 2017 on. The roof rainwater harvesting supplies the drinking water demand of the City of As Salt, with a constant storage capacity of 0.1 MCM, which is around 7% of the total volume of harvested rainfall in Balqa Governorate reported in Abdulla and Al-Shareef (2009).

vi. Modification in the industrial water demand (Fuheis Cement)

The cement factory in Fuheis represented the industrial user in Wadi Shueib. However, the cement plant stopped its operation at the beginning of 2013 (Lafarge Cement Jordan 2013). Thus, the water consumption of 266 l/year/ton cement, according to the water footprint of Lafarge (2011) was reduced in 2013 and then set to zero from the year 2014 on.

vii. Increase in the volume capacity of the WWTP (Salt WWTP & Fuheis WWTP)

The expansion of the wastewater treatment plants Fuheis and As-Salt to a total capacity of 3500 and 12000 m^3/day, respectively, is part of the capital investment plan (MWI 2016b). Since their financing is not yet available, these measures have been included in the FI scenarios.

The distribution of the flow from the urban and rural demand sites through return flow links to their respective sewer system, WWTP or septic tanks, was varied considering the restriction that the total capacity of the centralised wastewater treatment plants should not be exceeded, since an overflow in the WWTP produces untreated wastewater.

viii. Nodes implemented and updated for the FI-plus scenarios (5 & 6)

Scenarios 5 and 6 include all the assumptions of the FI scenarios, s2 and s4, and two main new elements were added or updated:

a. Decentralised Wastewater Treatment in the Jordan Valley (DWWTP_SS)

In FI-plus scenarios (s5 and s6), the construction of decentralised wastewater treatment plants (DWWTP) up the year 2018 was assumed for the rural settlements of South Shunah and, Ira and Yarka. They were based on the new water strategy that (1) in the highlands, agriculture will only expand if treated wastewater is available, and (2) in the Jordan Valley, irrigation can increase if new water sources are developed and treated wastewater is added (MWI 2016b). The plant in South Shunah was implemented in these scenarios as part of the construction of a new sewer network system, with uncertain financing, mentioned in the capital investment plan (MWI 2016b), and to visualise the potential of a new water source for irrigation in the area of the Jordan Valley. However, the flat nature of the terrain makes the transportation of the treated wastewater from the plant to the agricultural units through gravity rather unfeasible and new associated costs, which are not studied here, should be considered.

The design of the plants were based on Afferden et al. (2015), who presented a case study in Ira and Yarka with a cost-effective local wastewater management solution. The design of one plant for a population equivalent (PE) of 5000 was done assuming a wastewater production of 74 l/d/c, which represents around 80 to 90% of the drinking water consumption.

To avoid untreated overflow, the capacity of the plant should not exceed 100%. Once this capacity is exceeded one or more new plants can be constructed in parallel. Therefore, the monthly plant capacity was assigned using Equation 4.2, which results in a monthly capacity of 740 m^3/d for South Shunah, and for Ira and Yarka, 740 and 1480 m^3/d for the periods 2018-2019 and 2020-2025, respectively.

$$Daily\ plant\ capacity\ \left[\frac{m^3}{d}\right] = WW_{production}\left[\frac{l}{c\cdot d}\right]\cdot\frac{1}{1000}\cdot n\cdot 5000 \qquad (4.2)$$

Where, n is the number of plants for 5000 PE constructed to treat the generated wastewater.

b. *Wadi Shueib dam - change in operational capacity (Shueib dam)*

The operational capacity of the Wadi Shueib dam has been 1.43 MCM (Riepl 2013). The maximum operational volume in the reservoir was then assumed to increase 10% yearly after 2021, reaching a maximum operational capacity of 2.1 MCM by the year 2025, which coincides with the additional 0.8 MCM capacity estimated in the capital investment plan (MWI 2016b).

4.1.4 Performance metrics or indicators (M)

An indicator (M) is a parameter that gives information about the condition of what is being studied, e.g. environment (OECD 1997). The indicators chosen to evaluate the results of the allocation model are descriptive and aim to answer the question: will targets be reached in the scenario planning*?* (Smeets and Weterings 1999).

They were based on the necessity to show different environmental aspects of the study area, such as wastewater treatment ratio, groundwater flow and coverage of municipal demand, where measures to improve the system have been included in the water strategy, as mentioned in the scenario definition, and are therefore, in-line with the objectives of the water sector in Jordan. Each indicator is individually described to avoid possible ambiguity in the definition or interpretation done by different stakeholders (Mazzi et al. 2012).

i. *Indicator 1: ratio of treated wastewater with secondary treatment to generated wastewater*

The treatment of wastewater in the water strategy of Jordan has three main purposes: (1) the necessity of connection to a safe sanitation system, (2) protection of groundwater (e.g. from leakage through septic systems) and (3) the use of treated wastewater as an additional source for irrigation (MWI 2015a).

Measures to achieve these objectives are reparation and maintenance of the sewage network (scenarios BAU and FI), expansion of current centralised wastewater treatment plants (scenarios FI), consideration of decentralised solutions for rural and sub-urbans areas (scenarios FI-plus).

This indicator considers domestic wastewater generated by urban and rural settlements ($WW_{generated}$) and at least a secondary treatment to remove most of the organic matter (Tchobanoglous et al. 2003). It is calculated using Equation 4.3. Secondary treatment and disinfection are the minimum treatment expectancy to tolerate at least the irrigation of non-food crop plants (EPA 2012) (Table S3 of the SM). The treated wastewater ($WW_{treated}$)

originates from demand sites that feed wastewater treatment facilities, namely As Salt, Mahis-Fuheis, Ira-Yarka in Wadi Shueib, and South Shunah in the Jordan Valley.

$$Indicator\ 1 = \frac{WW_{treated}}{WW_{generated}} \cdot 100 \tag{4.3}$$

ii. *Indicator 2: covered supply*

The coverage of the water requirement is defined as the ratio in percentage of the supply delivered to the supply requirement (Equation 4.4), where 100% is the ideal objective according to the water strategy. For this indicator all demand sites in each zone are considered, that is, municipal, industrial and irrigation.

$$Indicator\ 2 = \frac{Supply\ delivered}{Supply\ requirement} \cdot 100 \tag{4.4}$$

iii. *Indicator 3: covered supply for external demand site*

Indicators for sustainability should be applied consistently and universally (Dahl 2012). The water strategy focuses, with the adoption of the Sustainable Development Goals, in the sustainability of groundwater resources extraction (MWI 2015a). Moreover, the explicit declaration to use IWRM as the approach to manage water resources endorses the need to define indicators that display the achievement (or not) of a sustainable basin.

The demand site DS_GHB_DRN considers the estimated groundwater volume that flows to the Jordan River and through the southern boundary of the groundwater model domain to the south towards the Dead Sea. The groundwater storage component compensates the water balance and an increase of the net storage component leads to a sustainable system (see Chapter 3).

In WEAP, unmet demand of this node is calculated and indicator 3 is defined as the ratio of the supply delivered by the system to the supply requirement of the node (Equation 4.5), in other words, the covered supply. The closer to 100%, the closer to achieve sustainability, taking into account that all other users (domestic and agriculture) in the basin have higher distribution priorities, and thus, they are first covered.

$$Indicator\ 3 = \frac{Supply\ delivered\ to\ DS\_GHB\_DRN}{Supply\ requirement\ of\ DS\_GHB\_DRN} \cdot 100 \tag{4.5}$$

iv. *Indicator 4: groundwater exploitation index (GWI)*

The groundwater exploitation index (GWI) is determined only for the Jordan Valley, where groundwater is the most relevant water source. Calculated with Equation 4.6, it is the ratio of water supplied by groundwater (GW) for irrigation and domestic use to the total recharge of groundwater, considering (1) natural recharge of groundwater, (2) return flow and (3) inflow from Wadi Shueib dam. It gives information on the level of pressure on the groundwater resource. It is based on a similar indicator, the water exploitation index (WEI), which accounts for total freshwater resources. Same as for WEI, a GWI above 20% indicates that the groundwater resource is under stress and above 40% the system is in acute stress (Raskin et al. 1997). As seen by the estimation of the crop requirement in Section 3.2.3, bananas and date palms have to be irrigated in summer and therefore, the seasonality effect for this indicator due to irrigation practices is not large and a yearly analysis is performed.

$$Indicator\ 4\ (GWI) = \frac{(Irrigation + Domestic)\ water\ from\ GW}{Total\ GW\ recharge} \cdot 100 \tag{4.6}$$

v. Indicator 5: water harvesting ratio

The water harvesting ratio provides information on the potential additional water that it can be achieved through roof water harvesting. It is estimated as the proportion between the inflow from roof water harvesting and the total water sources for the urban settlement of As-Salt (Equation 4.7).

$$Indicator\ 5 = \frac{Inflow\ to\ As\text{-}Salt_{from\ roof\ water\ warvesting}}{Inflow\ to\ As\text{-}Salt_{from\ all\ water\ sources}} \cdot 100 \tag{4.7}$$

4.1.5 Framework for representation and visualisation of results

The results of the DSS model are represented using the methodology described in Forni et al. (2016), which considers three steps to illustrate the results generated under the XLMR framework (see Fig. 4.5).

First step: indicators are defined and results are shown as time-series

Second step: reliability of indicators for each scenario is estimated regarding various thresholds and different periods of analysis

Third step: the results for all scenarios, indicators and variation of thresholds, defined by decision makers, are plot together to visualise the results and the impact of strategies

While the first step is rather straightforward, the second step involves actually the criteria and preferences of the decision makers. Each indicator can be evaluated depending on the compromise of the stakeholders to achieve a determined goal. This can be done defining thresholds that represent standards such as (1) high, if the stakeholders seek for ambitious results (2) medium, if results are good enough to "live with" and (3) low, if that minimum to accomplish is, for example, the regulatory laws.

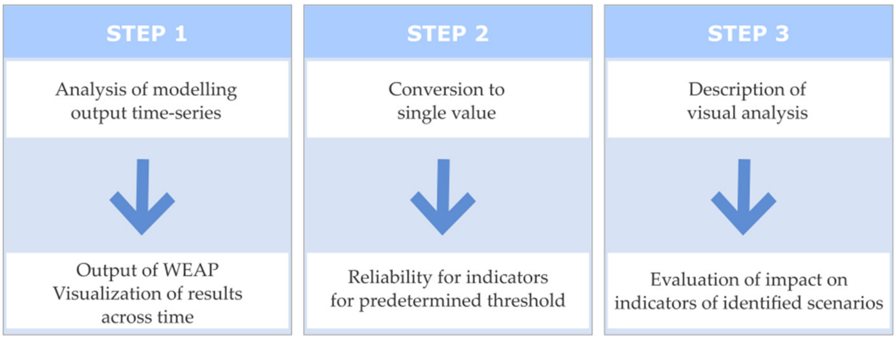


Fig. 4.5 Steps for visualisation of scenario planning and indicators adapted from Forni et al. (2016).

The definition of a threshold or criterion (*C*) for each indicator can result in a single value derived from the reliability (R_I) of indicators (M). This reliability measures the frequency of success to achieve any threshold (Fowler et al. 2003) for the evaluation period *T* and time step *t*, and it is determined as

$$R_M = \frac{\sum_{t=1}^{T} z_t}{T} \tag{4.8}$$

Where,

$$Z_t(M_t) = \begin{cases} 1, & M_t \geq C \\ 0, & M_t < C \end{cases} \tag{4.9}$$

In the third step, a grid plot for each evaluated period is generated; it includes the reliability value for each indicator and scenario. Decision makers can then audit the model results by comparing strategies visually.

4.2 RESULTS

4.2.1 Calibration

Two parameters of the original model were adjusted during calibration: (1) transmission losses of surface runoff regarding flow volume, determined as 7.7% for the dry year, 14.2% for the average year and 32.6% for the wet year; and (2) the reservoir seepage estimated as 9.8% of the stored volume (Riepl 2013). This calibration was verified for the upgraded model for the period 2001-2009, obtaining a good agreement between the observed and simulated values, with a Pearson coefficient of 0.95 and a standard deviation of 0.5 MCM, which represents the seasonal variability of the time-series (Fig. 4.6).

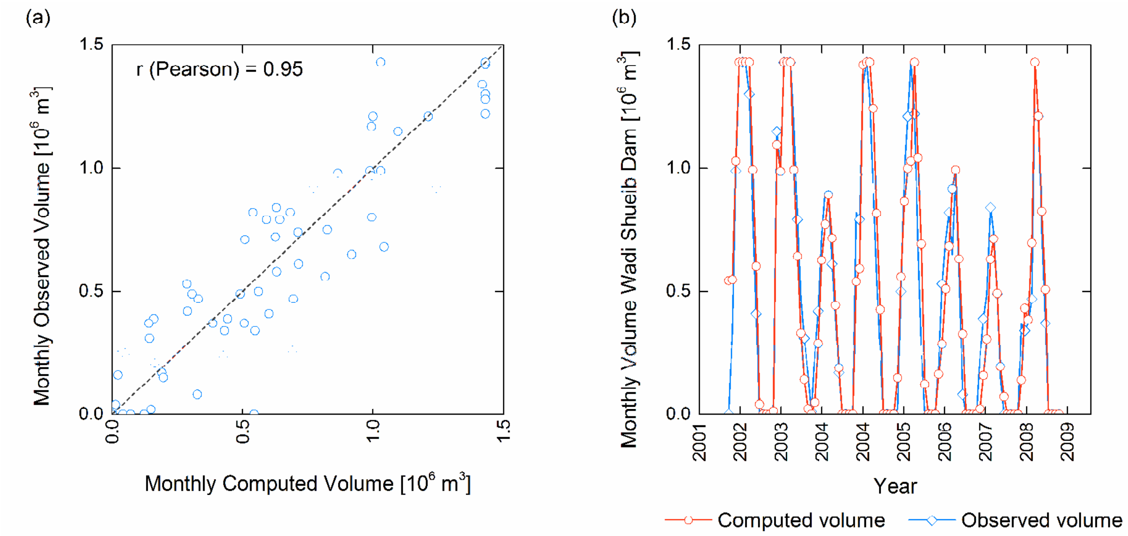


Fig. 4.6 (a) Computed versus observed volumes in Wadi Shueib dam, (b) observed and simulated monthly volume values.

4.2.2 *Time-series of indicators (step 1)*

i. *Indicator 1: ratio of treated wastewater with secondary treatment to generated wastewater*

In South Shunah and Wadi Shueib, after 2018, there is a clear improvement of this indicator due to the influence of the construction of a decentralised wastewater treatment plant in the FI plus scenarios. The indicator increases in the Jordan Valley from zero to 80% in 2018 and 92% in 2025, while in Wadi Shueib it increases from 59 to 62% in 2018 and 68% in 2025 (scenarios 5 and 6) (Fig. 4.7a-b).

In Wadi Shueib, the inflow in centralised WWTP after 2010 for the BAU scenarios remains almost constant around 3 MCM/a, since (1) the total capacity of the plants does not change and (2) the inflow should not exceed the maximum capacity of the plant (see, for example, Fig. 4.8); therefore, as the total generated wastewater increases for each scenario, the ratio of treated wastewater with secondary treatment decreases to 36% and the outflow to septic tanks increases, reaching in Scenario 1 (HRP-BAU) 5.5 MCM/a in 2025. The FI scenarios show an improved result, the extension in the capacity of WWTP allows an increasingly inflow entering 4.5 MCM/a of wastewater in 2025 in scenario 2 (HRP FI), that is

1.5 MCM/a more than in scenario 1 (Fig. 4.8), helping to maintain the ratio of treated WW to around 60%, similar to the period 2001-2009 (Fig. 4.7b).

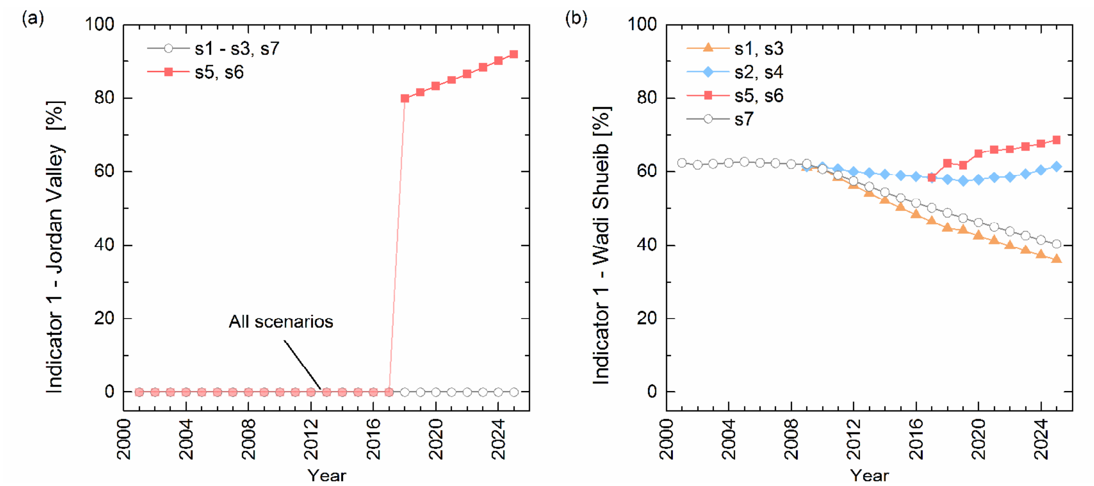


Fig. 4.7 Ratio of treated wastewater with at least secondary treatment to generated municipal wastewater by (a) South Shunah in the Jordan Valley and (b) in Wadi Shueib. Scenario 7 represents the "Reference".

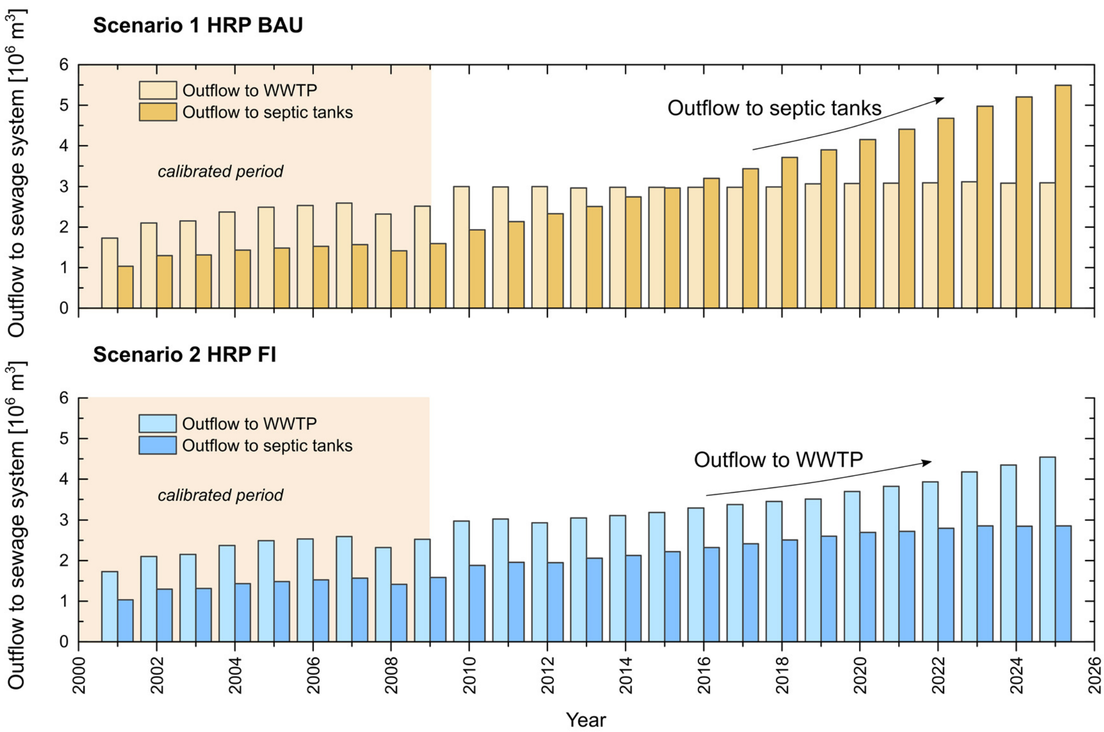


Fig. 4.8 Outflow from urban and rural demand sites in Wadi Shueib to WWTP As-Salt and Fuheis, and to septic tanks for HRP scenarios (top) BAU (s1), and (bottom) FI (s2).

ii. Indicator 2: covered supply

The result for all scenarios regarding the covered supply in the Jordan Valley, accounting the rural settlement of South Shunah and irrigation, is 100%. New water sources provide with additional water for agriculture within the FI-plus scenarios: (1) surface water from the Wadi Shueib dam, after the increment of operational volume, increases 0.2 MCM/a, and (2) DWWTP contributes with another additional 0.2 MCM/a (Fig. 4.9). However, an important part of the water source comes from groundwater storage of the aquifer, therefore, despite the full coverage of the water demands in the Jordan Valley, the water system is not necessarily sustainable and further analysis must be done (see indicator 3).

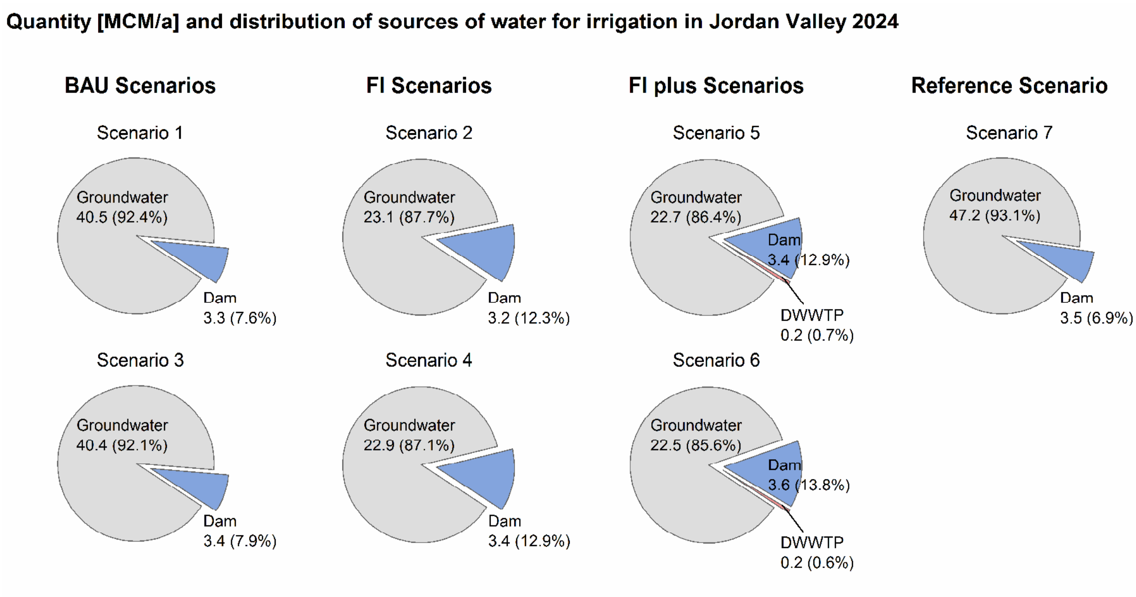


Fig. 4.9 Distribution of sources of water for irrigation in the Jordan Valley for all scenarios for the year 2024.

The analysis for Wadi Shueib was divided in the different users: (a) irrigation, (b) domestic and (c) industrial. This was done to differentiate the behaviour of the water sources for each user.

Indicator 2a: The irrigation water requirement is not completely covered, especially during the summer months of July and August, where the average monthly unmet demand can reach 0.4 MCM. The fluctuations of the irrigation sources in Wadi Shueib, namely, the runoff and discharge from small springs, explain the variations of indicator 2a. In this case, the presence of wet years increases the supply covered, whereas dry years increase the unmet demand. At the end of the simulation period, the low resources pressure (LRP) scenarios have greater covered supply than those with high resources pressure (HRP), they differ around 7% between maximum (s6) and minimum (s2) (see Fig. 4.10).

Implementation strategies have small impact, since no measures, regarding agriculture practices, were specified in the Wadi Shueib and the supply requirement only varies in HRP and LRP scenarios (Fig. 4.10b). This coincides with the results presented in Riepl (2013), which shows that the unmet demand of agriculture decreases by the end of the simulated years.

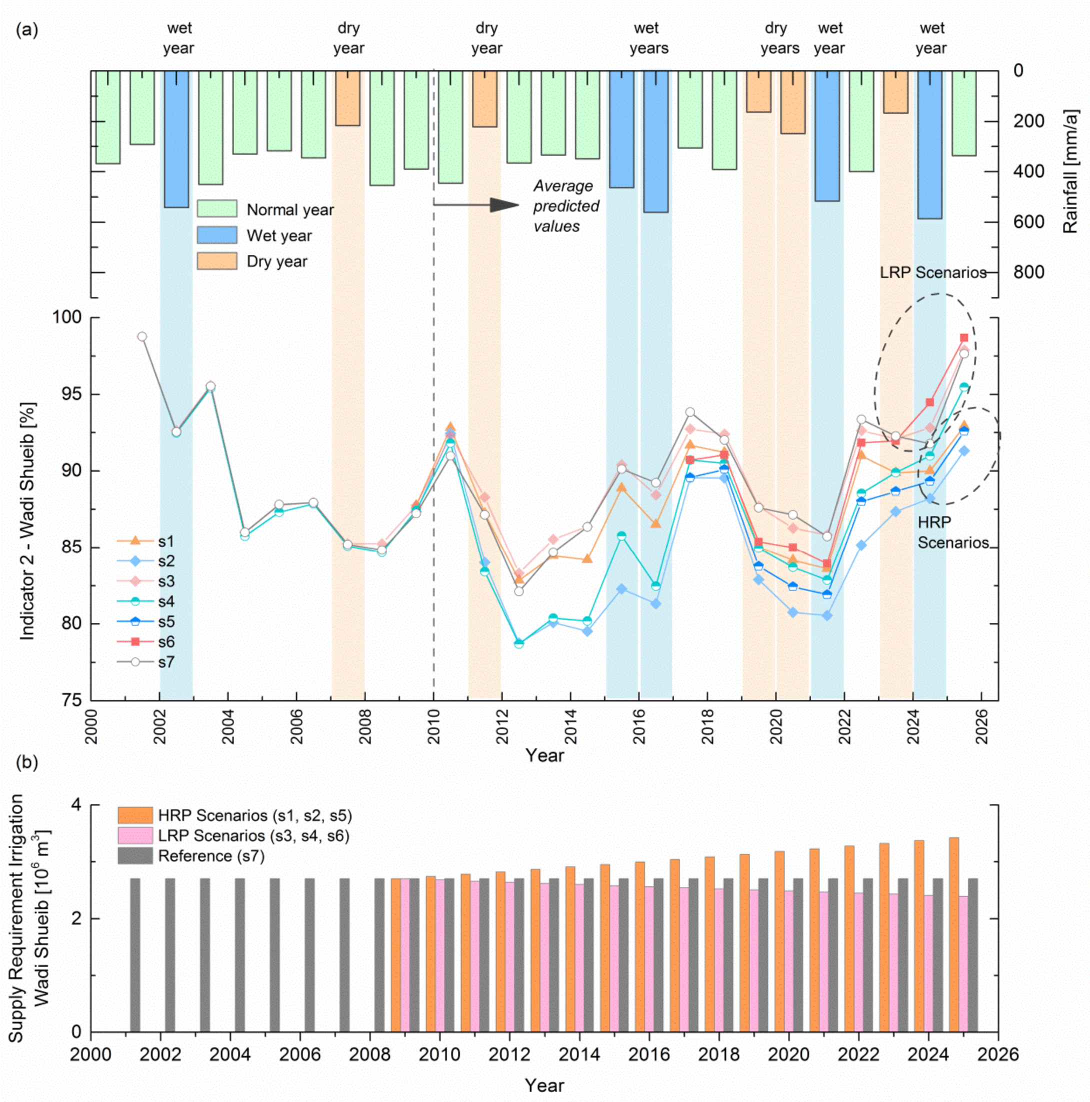


Fig. 4.10 (a) Annual rainfall for the calibrated period and average predicted rainfall from HRP and LRP scenarios (Riepl 2013) and (b) covered supply in Wadi Shueib for irrigation, representing results of indicator 2a.

Indicator 2b: Considering only the internal water resources of Wadi Shueib (and not water import), the covered supply for the BAU scenarios (s1, s3) stays stable around 40%. Only the implementation of measures in the FI Scenarios leads to a coverage of around 70%. These results coincide with the volumes of imported water, which vary from 3 MCM/a

(LRP FI scenarios) to 10 MCM/a (HRP BAU scenario), the more the imported water, the less is the water demand covered through internal water sources. The decrease around the year 2019 (Fig. 4.11) is tied to the dry hydrological years defined in the projected climatological data, shown in Fig. 4.10a.

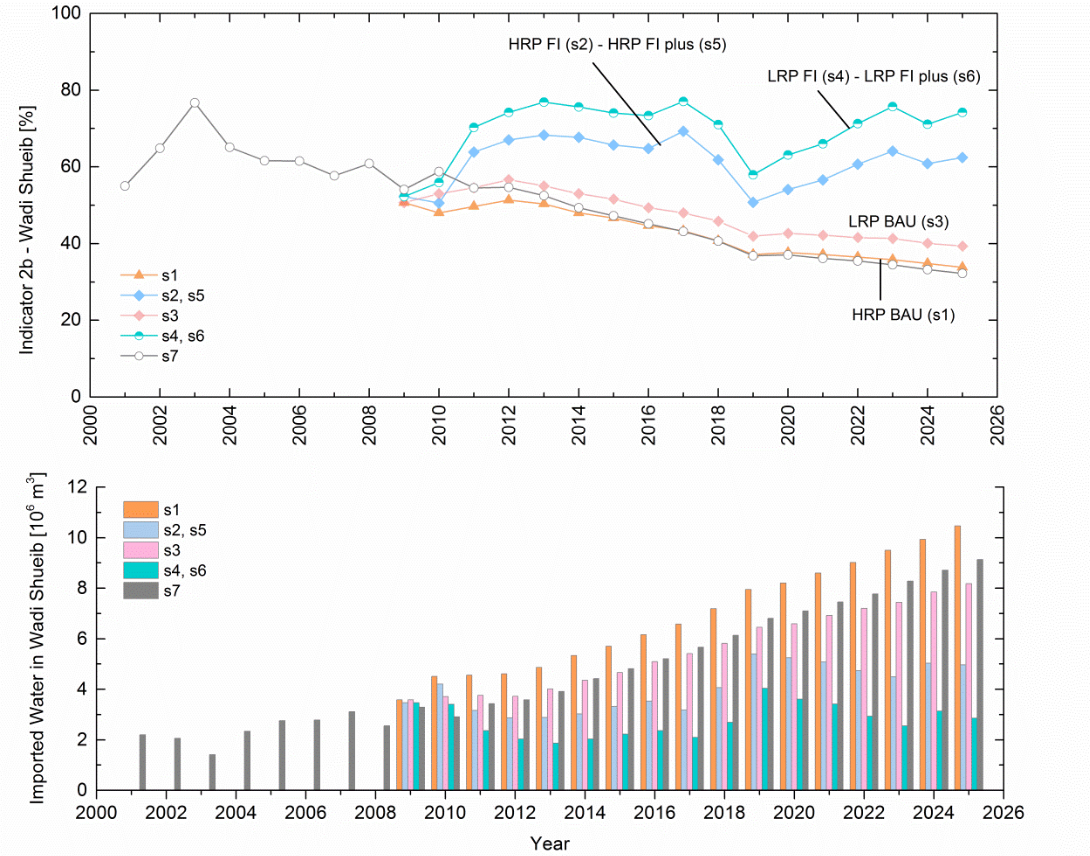


Fig. 4.11 Covered supply in Wadi Shueib for domestic use representing results of indicator 2b (top) and annual imported water for domestic consumption in the Wadi Shueib (bottom).

Indicator 2c: the industrial demand is fully met in all scenarios, especially, since the water consumption for this user is set to zero after 2014, when operations of the cement industry were stopped.

iii. Indicator 3: covered supply for external demand site

This indicator shows that even if the arable area remains constant after 2012 (BAU scenarios), the covered supply for the external groundwater demand is only covered around 60% and only a substantial reduction of irrigated land (FI scenarios), no matter the level of resources pressures, achieves a 100% after 2021, which agrees with the results of the numerical groundwater modelling (see Fig. 4.12).

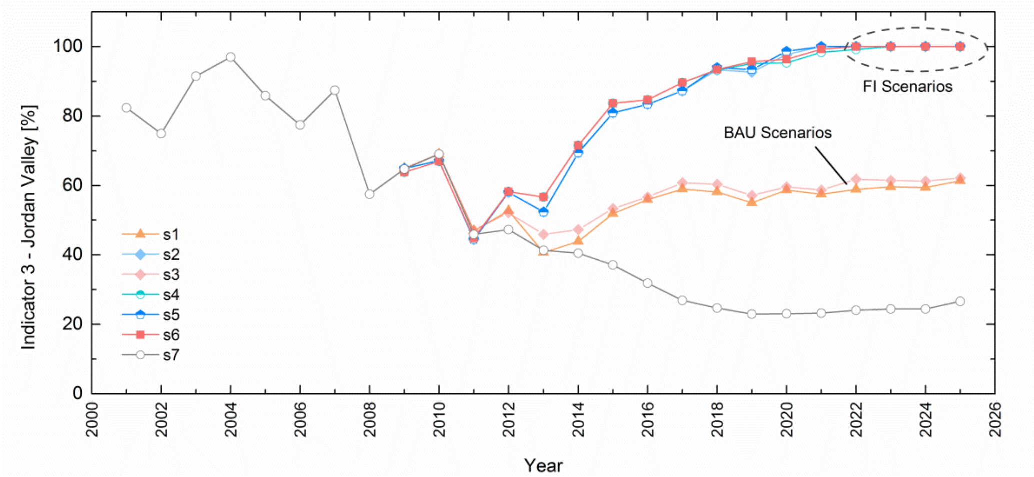


Fig. 4.12 Covered supply for external demand site representing groundwater flows that leave the model domain in the Jordan Valley through the western and southern boundaries.

iv. Indicator 4: groundwater exploitation index (GWI)

The results describe a groundwater resource that is 100% of the analysed time under stress. As indicator 3 showed, the GWI improves and it falls under the *severe stress* line only after 2022 as a product of the reduction of groundwater withdrawals, simulated in FI scenarios. The FI plus scenarios do not influence these results since the additional irrigation water from treated wastewater, with a yearly average of 0.2 MCM, represents less than 1% of the total sources volumes (see Fig. 4.13).

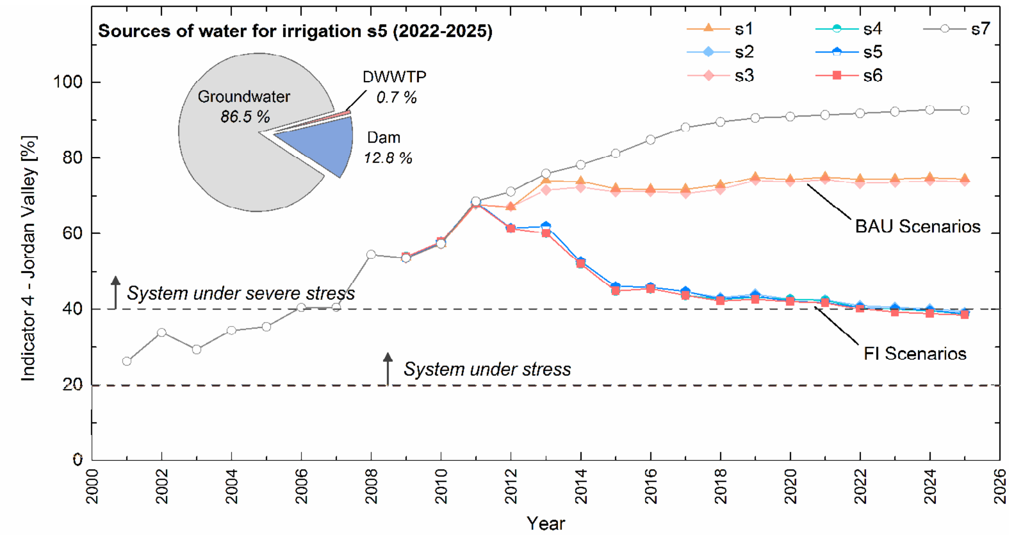


Fig. 4.13 Groundwater exploitations index (GWI) or indicator 4. The pie chart shows the distribution of sources of water for irrigation in the Jordan Valley for scenario 5 (HRP-FI plus) as an average for the period 2022-2025. Return flows are considered within the groundwater component of the chart.

v. Indicator 5: water harvesting ratio

The water harvesting ratio provides information on the potential additional water that can be allocated through roof rainwater harvesting. Defined in the FI scenarios, annual roof rainwater volume calculated reaches 0.3 MCM, representing around 5% of the total inflow in As-Salt by the year 2025, which lessens the demand for imported water (see Fig. 4.14).

This unconventional water source contributes proportionally more water than DWWTP. Its implementation should consider chlorination and the flushing of first rainwater to eliminate the dirt, since faecal coliform have been found by water analysis performed on rainwater harvested samples in Jordan (Abdulla and Al-Shareef 2009). Other physical and chemical parameters analysed were in accordance with the World Health Organization (WHO) guidelines, as reported by Abdulla and Al-Shareef (2009).

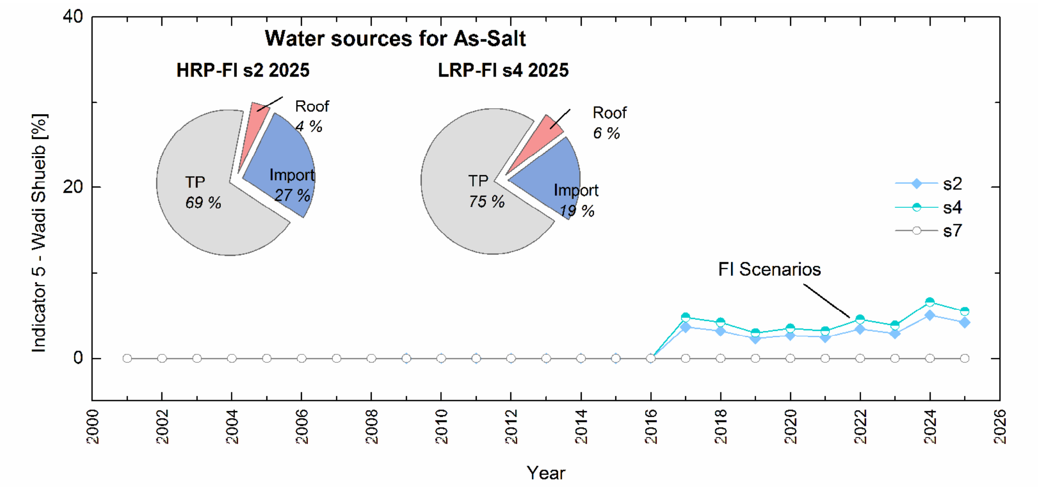


Fig. 4.14 Water harvesting ratio for FI scenarios, where water roof harvesting was simulated. The pie charts show the proportions of the different sources of water for the city of As-Salt for the HRP (s2) and LRP (s4) scenarios. *TP* stands for the Salt Springs treatment plant, *Roof* for roof rainwater harvesting and *Import* for imported water.

4.2.3 Reliability of indicators (steps 2 & 3)

Following Step 2 and using Equation (4.8), the reliability for each indicator and threshold was determined for three different periods of analysis 2010-2015, 2015-2020 and 2020-2025 (refer to Table S6 in SM for an example of the determination of reliability values for one indicator). The defined thresholds and the respective graphic representation of the results (Step 3) for Jordan Valley and Wadi Shueib are shown in Fig. 4.15 and Fig. 4.16, respectively.

The outcome shows three main results for both, the Jordan Valley and Wadi Shueib: (1) the lower the standard, the greater the success of the strategies; (2) as time passes, the possibility to meet a threshold or standard is also higher, since some strategies start in the last years of the scenario modelling, for instance, the construction of decentralised wastewater plants; (3) the best performance is mostly achieved during the FI scenarios, specially, FI-plus.

In general, the reference scenario has the worst performance, followed by the BAU scenarios, which means that despite the progress towards water availability and sustainability, the strategies currently under execution (BAU) alone are not sufficient to achieve reliabilities higher than zero, even for the low standards defined, for example, indicators 1 and 4 for the Jordan Valley and 1, 2b and 5 for the Wadi Shueib (Fig. 4.15 and Fig. 4.16).

In the Jordan Valley, indicator 1 is only successful in scenarios 5 and 6 (FI plus), where the construction of a new sewage system is incorporated in the strategy, since this was simulated after 2018, and therefore, only during the analysis period 2020-2025 a 100% reliability is achieved for all standards. The supply coverage for demand sites, domestic and irrigation, represented with indicator 2, is always covered and has 100% reliability in all periods and for all standards. Indicator 3, which denotes a sustainability indicator, presents better reliability for medium and high standards for FI scenarios (s2, s4, s5, s6) and for low standards, specified as 50%, after 2015 each scenario achieves a complete reliability. However, 50% is a very low standard and it still indicates that groundwater from the storage is being used. The groundwater exploitation index (indicator 4) never falls under the high standard of 20% and reliability is zero for every scenario, meaning that the groundwater system is always under stress. In fact, this high standard limit shows the real issue: the studied basin in the Jordan Valley is certainly under water stress; decision makers can chose a lower standard, such as 40% (medium standard), to avoid falling in the category "under severe stress", which is accomplished with the FI scenarios after 2020 (see Fig. 4.15).

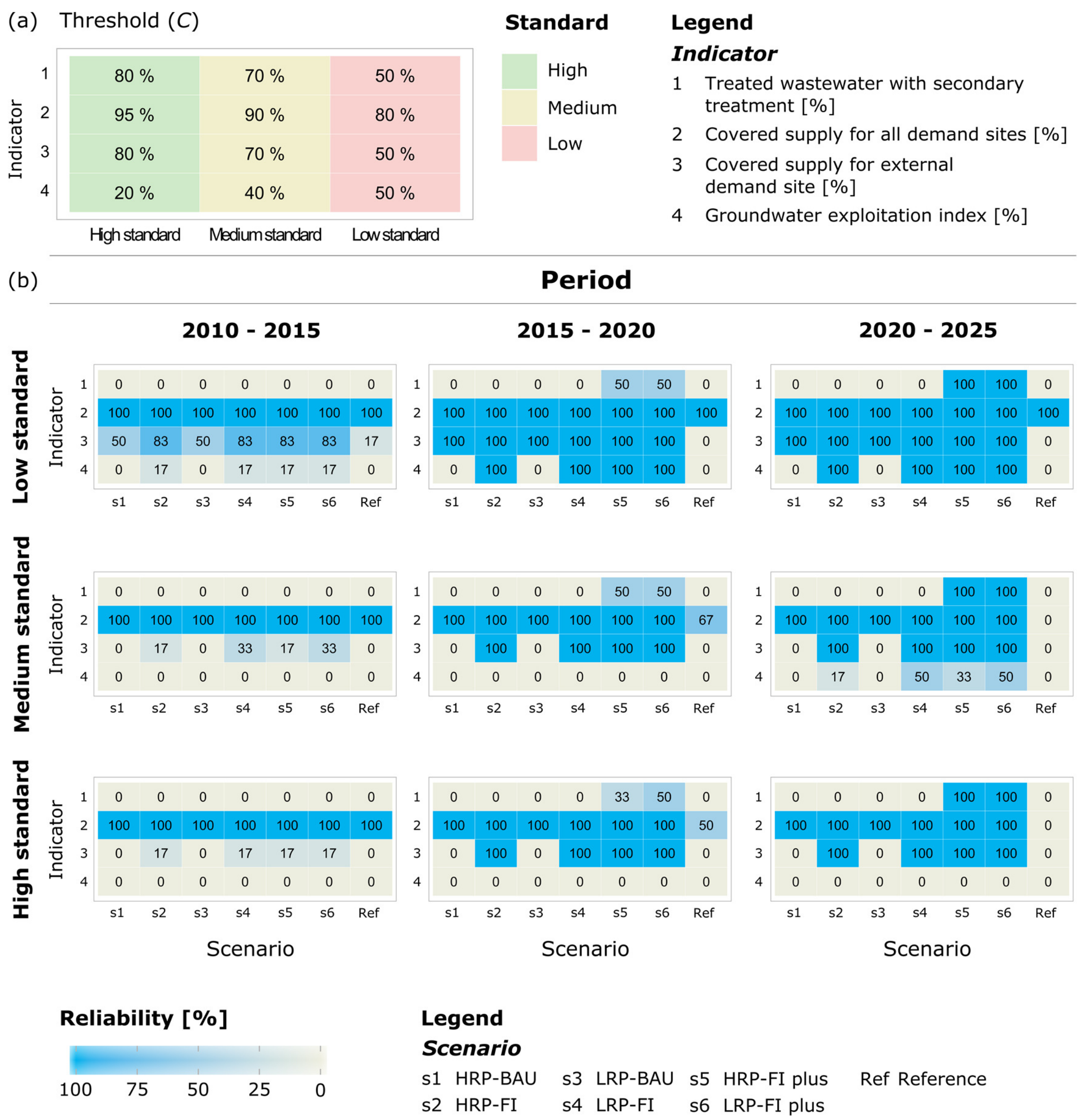


Fig. 4.15 (a) Threshold and (b) reliability values for all four indicators evaluated for high, medium and low standards in the Jordan Valley for periods 2010-2015, 2015-2020 and 2020-2025. Note that indicator 4 has an inverse interpretation to the other indicators, the lower the value, the higher the standard.

In Wadi Shueib, the standard for indicator 1 is varied in 5% among standards, and the results do not vary linearly with the time. The best outcome for the medium standard, when all scenarios show reliability larger than zero, is seen during the period 2010-2015, since the capacity of the plants is working the most efficiently to treat the generated wastewater. After the plants are expanded, the reliability of the FI scenarios increases and with the construction of DWWTP, it achieves even 100% reliability. Indicator 2 in Wadi Shueib was divided for the water users: (a) domestic, (b) agriculture and (c) industry; since the industry demand ceased after 2014, only 2a and 2b are analysed. By 2020-2025 the irrigation achieves 80% of coverage and in general, the BAU and FI scenarios do not present a significant difference. The indicator 2b, which represents the coverage supply coming only from internal water resources, shows that Wadi Shueib can only supply itself successfully at a proportion of at least 40% of internal resources and 60% imported water (low standard), if full implementation strategies are carried out; Wadi Shueib alone cannot be self-sufficient for their domestic water requirements. Measures, such as water harvesting (indicator 5), help to reduce this deficit providing with alternative water sources, which for the city of As-Salt is around 5% of the water sources for domestic use.

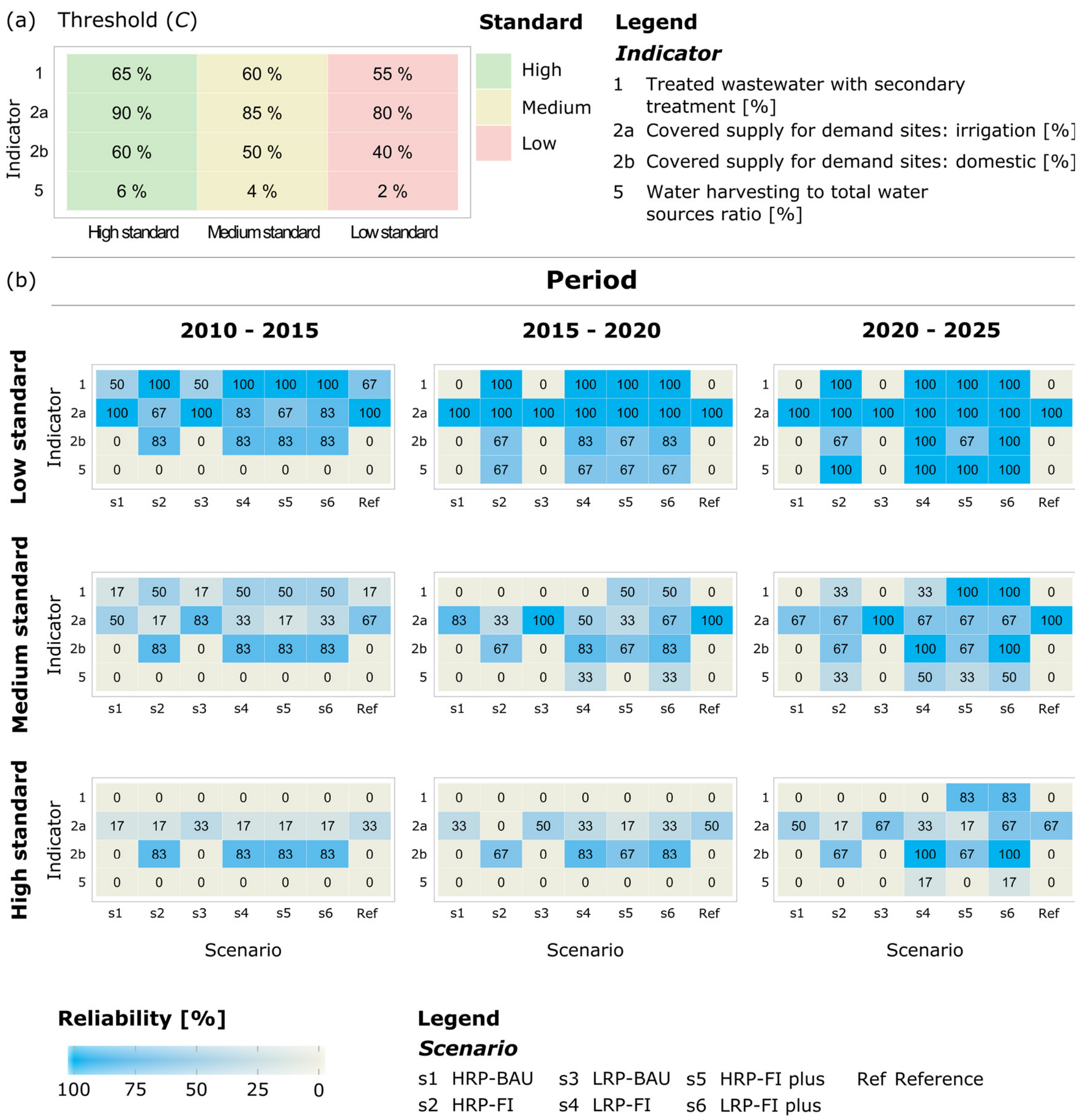


Fig. 4.16 (a) Threshold and (b) reliability values for all four indicators evaluated for high, medium and low standards in Wadi Shueib for periods 2010-2015, 2015-2020 and 2020-2025.

4.3 MODEL LIMITATIONS

The objective of the decision support system modelling framework is to simulate the effect of water resources management strategies on the water system, reflected on the distribution of water among the different users, the achievement (or not) of water related goals, such as resilience of the water sector, adequate water supply and sanitation, protection of groundwater, and sustainability (MWI 2015a). The modelling results are evaluated using indicators that describe the system and are presented in terms of reliability of the system, namely, the degree of successful performance.

The model calibration was verified, and with a Pearson coefficient of 0.96 can be considered as acceptable. The model also reproduces the changes in the system according to simulated strategies. The results regarding groundwater in the Jordan Valley are consistent with those obtained with the numerical groundwater modelling.

However, this model also presents limitations. Given the amount of elements representing the complete basin, from spring volumes to transmission losses in the runoff, the uncertainty associated to each parametrisation was not considered during the modelling set-up. Nevertheless, a data quality control to ensure acceptable results was done previously in the original model (Riepl 2013) and in the current update.

This water allocation model also considers the results of a prior numerical groundwater model, which added further associated errors to the analysed system. The complexity associated to the definition of boundary conditions within the numerical groundwater model made a direct WEAP-MODFLOW coupling impractical. To obtain similar, not yet the same, results of MODFLOW in WEAP, more than 10 new auxiliary nodes per boundary would have to be created, generating an over-parametrised model with an unclear structure.

During the modelling process the influence of refugees on the population statistics were not included, considering that only 3% of them are going to the state of Aqaba (MOPIC 2016a). Immigrants and refugees not only bring to the region a demographic growth, but they also bring different water-consumption customs. Syrians have always had 24 hours of drinking water access, while Jordanians are used to the regime of receiving water once per week. Syrians have to adapt to the water saving plans of the Jordanian government. The increase in demand from Syrian refugees has lowered the quantity and frequency of water available for Jordanians (MOPIC 2016b).

The analysis of the results given by WEAP has to be done carefully. A superficial evaluation of volumes can give the impression that water demands are mostly fully covered, however, water sources have to be separated to identify internal and external sources (imported water). The definition of a storage capacity of the aquifer or the use of groundwater storage as an infinite source of water has to be also applied cautiously. In this case, the previous numerical groundwater modelling provided this information.

4.4 CONCLUSIONS

The analysis for the decision support system was organised following the XLMR framework (Lempert et al. 2003), evaluating the system performance using the concept of reliability, as described in Fowler et al. (2003). The final assessment of the system was done adopting a dynamic approach, where thresholds or criteria for selected indicators can be defined and adjusted by decision makers, visualising the outputs of the model in one frame. Strategies planned in the new water strategy were included in the form of seven scenarios, considering also external pressures, such as hydrology and population growth trends.

The decision support system, modelled with WEAP, applying nodes and links that connect and interconnect the different users of the Wadi Shueib basin and downstream in the Jordan Valley, allows the integral analysis and evaluation of these two interconnected basins. The water balance obtained by the numerical groundwater model was included in the Jordan Valley, creating a complete system that considers surface water and groundwater as sources of water for domestic and irrigation use. Other water sources were also incorporated: (1) the simulation of decentralised wastewater plants generates an additional water source for irrigation and (2) roof water harvesting provides extra water for domestic consumption.

The model calibration was revised for the period 2001-2009, achieving a good agreement between observed and calculated values of the storage volume in the Wadi Shueib dam (Pearson coefficient of 0.96). Since the water demand in both local basins concentrates in different water users, domestic for Wadi Shueib and irrigation for the Jordan Valley, the results were separated for the evaluation, in order to identify the particular strengths and weakness of the each part of the water system.

The overall results, seen in the reliability grids, showed that the implementation of those not yet financed strategies is crucial, especially if decision makers aim to achieve the medium or high standards designated in this study. As expected, the lower the standard, the higher the reliability of the scenarios. The period of analysis also influences the reliability, since some strategies are implemented at the end of the simulated period.

The ratio of connection to wastewater treatment with secondary treatment (indicator 1) increases above 80% in the Jordan Valley and remains by 60% in the Wadi Shueib with the construction of decentralised plants (scenarios 5 and 6), getting closer to achieve the national goals of improving the connection for safe sanitation system and protecting the groundwater, reducing the leakages from septic tanks and cesspits. Although the construction of decentralised plants does not contribute with a large volume of water for irrigation, it provides at least a small fraction (0.7% in the Jordan Valley) reducing the stress of other water sources. The water quality of the effluent from DWWTP (Table S4 in SM) does not meet the Jordanian water regulations for use of treated wastewater in artificial recharge (Table S5 in SM), making the adoption of this water in agriculture reasonable.

The coverage supply in the Jordan Valley for domestic and irrigation use (indicator 2) reaches always 100%. The increase of operational capacity of the Wadi Shueib dam (FI-plus scenarios) adds 0.2 MCM/a to the water balance, which is only available, if the Wadi Shueib runoff rises, for instance, as more effluent from WWTP is discharged.

Groundwater for irrigation is taken from the storage of the aquifer in the BAU scenarios, and only in the FI scenarios; the objective of the water strategy for a sustainable management of water is accomplished. Moreover, only the reduction of arable land can help to achieve a sustainable groundwater extraction level and to define the groundwater resources system below the “severe stress” level (indicator 4). The demand for external users, representing the groundwater flow in the direction of the Dead Sea and the north-west by Jordan River (indicator 3), is also only met by FI scenarios.

The domestic water demand in Wadi Shueib relays not only on the natural water resources generated by recharge of the superficial and groundwater catchment, but also on imported water from other basins (indicator 2). Full implementation measures, like reduction of water losses in FI scenarios, contribute to close the gap between internal and external water resources in Wadi Shueib, with supply coverage through internal sources of around 70%. The IWRM strategy considers the development of new water sources such as roof water harvesting, which can alleviate the stressed system providing between 4 and 6% of the total water sources in As-Salt (indicator 5).

Decision makers were involved as they confirmed that scenarios and indicators used in this dissertation are in accordance with the goals set by the Ministry of Water and Irrigation, giving extra value to this modelling set-up. Including stakeholders during the modelling process can give an extra awareness and confidence on the latter modelling outputs and it is part of how IWRM contributes to solving the key issues of water management, in this case specifically, incorporating the participation of different groups like modellers and decision makers.

The evaluation of the decision support system model, using reliability values and grids, is adaptable to different thresholds and other indicators can be added. Decision makers can benefit from the simplicity of a visual structure of a complex system, such as the interactions between different water sources (surface water –groundwater) and users.

The presented model can be updated and more information can be included, for example, in terms of more detailed volumes or population growth trends. The focus of this study is mainly on water quantity, an extensive water quality and financial analysis would be also recommendable to evaluate the strategies already simulated.

CHAPTER 5

5 RESEARCH SUMMARY

5.1 SUMMARY AND CONCLUSIONS

The area of the Jordan Valley and Wadi Shueib represents the interconnection of two local basins, both suffering high water pressure, mainly due to high population growth rates and over-extraction of groundwater. The challenge resided in merging these two local basins for an integrated water resources management analysis, which water resources differentiate in their main source: surface and groundwater, in their geological and hydrogeological characteristics, and in the different competitors for the water demand: domestic (Wadi Shueib) and agriculture (Jordan Valley).

To understand the decrease of groundwater levels in the Jordan Valley a conceptual model of the study area was generated and used as a basis for the model set-up of a two-dimensional numerical groundwater model. The results of the groundwater model were then included in a decision support system, as part of the IWRM analysis, in Wadi Shueib and Jordan Valley.

The numerical groundwater model in the Jordan Valley had to be constructed under data scarcity. Field surveys, an extensive literature review and the adoption of analytical methods, such as water crop requirement method, were used to determine the unknown groundwater abstraction, validated by realistic values obtained in the water balance. Therefore, the principle of parsimony was applied, simplifying the complexity of the groundwater system in one layer. On the basis of the available information, the results of the model calibration show a good agreement with the conceptual model and the model is able to reproduce the observed groundwater levels.

The calibrated model was used to simulate scenarios that consider climatic conditions and the Jordanian water strategy, regarding anthropogenic actions, modifying the arable land extension and implementing the closure of illegal wells by reducing the estimated extraction rates.

The most significant outcome of the groundwater model is that the decrease in groundwater levels is mostly associated to pumping rates while the climatic variation of groundwater recharge from the adjacent aquifer plays a secondary role. This can be deduced by the equivalent outcomes of scenario simulations of average and dry hydrological conditions (scenarios *a* and *b*) and is also confirmed by the effect on the water balance of reducing groundwater extraction volumes: a sustainable system, namely when groundwater is not taken from the storage, can be achieved only if groundwater extraction is reduced at least 40% (scenarios 3a & 3b). On the contrary, if future water requirement increases until all possible arable land is irrigated (scenario 1a & 1b), the system not only consumes storage water, but also the outflow to the South diminishes over time.

Possible measures to decrease the agricultural water demand are: the reduction of cultivated land area, the application of more efficient irrigation techniques and maintenance of the current ones, the irrigation with alternative water resources (such as treated wastewater). The reorientation from the widespread cultivation of strongly water-demanding crops towards less demanding crops that tolerate brackish water, characteristic of the Jordan Valley, should be also considered, since despite the good adaptation of date palms to heat and high levels of soil salinity, their irrigation with brackish water also reduces the productivity of the fruits palms (Yaish and Kumar 2015).

The numerical groundwater model could be improved in terms of more reliable results, if (1) new monitoring wells and boreholes with detailed drill-logs are constructed and pumping tests are conducted, especially where the parameters hydraulic conductivities and storage coefficient have high sensitivities (zones ID 1, ID 2 and ID 7); (2) the hydraulic connection between the Jordan River and the aquifer could be better defined, e.g. by the installation of hydrometric stations and (3) groundwater extraction could be monitored reliably and in a higher temporal resolution, by installing flowmeters and closing illegal wells.

To meet the requirements of an IWRM context, the numerical groundwater model was supplemented by a successful integration of two upstream-downstream local basins into a decision support system, applying a modelling application, to understand the influence of water management strategies on the entire water resource as well as the interaction of both basins. The numerical groundwater model in the Jordan Valley provided relevant information for an existing water allocation WEAP model, which was updated and extended, such as groundwater recharge and storage. Yet, since the water demand in both basins concentrates in different water users, a separate evaluation of the results was done to identify the particular effect of measures in each part.

The DSS analysis was done following the XLMR framework (Lempert et al. 2003), defining the uncertainties of the system or external driving sources (X) as high and low resources pressures regarding mainly hydraulic conditions and population growth, strategies planned (L) considering the water strategy of MWI, the assessment of the system (R) through a WEAP model, and assessment of the system and plans (M) defining indicators, evaluating them over time and using reliability grids for assumed standards to complement the results of time series.

Scenario simulation included not only surface water and groundwater as sources to supply the demand, but also the reuse of treated wastewater and roof rainwater harvesting were included as unconventional water sources, as stipulated by the Jordanian water strategy. An acceptable calibration with a Pearson coefficient of 0.96 was obtained.

Defining environmental indicators, the WEAP model results were analysed and evaluated using the concept of reliability, measuring the frequency of success to achieve pre-defined standards or desired limits for the indicators. Largest reliabilities were found by low standards in the last analysed period 2020-2025. The overall results showed that especially strategies without secured financing are the key to achieve medium or high standards. The final results are presented in a reliability grid format to facilitate the evaluation of the strategies represented in the WEAP modelling, offering a method to reduce possible misinterpretation of outcomes, to help reducing the gap between the scientific community and decision makers.

The presented study of the complex water system of Wadi Shueib and Jordan Valley supports the IWRM implementation in the study region by considering part of the following key issues of water management to tackle:

(1) securing water for people: understanding the complex nature of the water balance and the interaction of the single elements of the water basin, for instance the use of alternative water sources to provide more drinking water, as well as the influence of climate,

(2) securing water for food production: explaining the effect of actual practices in agriculture, which is the first step to protect the natural groundwater resources from over-exploitation, and to achieve sustainable production yields also in the future,

(3) governance through stakeholders' participation validating the scenario and indicators definitions,

(4) protecting vital ecosystems: recognising environmental water demand, such as groundwater recharge to the southern aquifer in the direction of the Dead Sea. Moreover, considering the maintenance of the infrastructure to decrease pipe leakages and reduce sewage losses through septic tanks helps protecting also groundwater quality from undesired infiltrations.

5.2 PERSPECTIVES AND OUTLOOK

Following the idea that a resource can be managed only if we can measure it and its development is published (Hammond and World Resources Institute 1995), the water research and management strategy in Jordan should focus on generating a larger network of monitoring systems (e.g. for groundwater level and surface flows), updating the metering instrumentation of the water usage, including groundwater abstraction values, and continue to close illegal water abstraction wells. This monitoring and its reporting would reduce the amount of assumptions and uncertainties related to water modelling, and it would allow the improvement of studies of water systems at basin-scale, to achieve a better understanding of the connection among the different hydraulic elements (runoff-infiltration processes, flow within consolidated and unconsolidated aquifers), and water users (municipal, agriculture, etc.).

However, the installation of instrumentation and the gathering of more reliable data to be used for long term modelling will take time. Therefore, the presented methodology is valuable, despite the discussed shortcomings and uncertainties, for the time being with prevailing data scarcity. Moreover, the models are constructed in order that available data can be incorporated at any stage, and the methodology can be transferred to other basins in arid and semi-arid regions, with similar surface-groundwater systems.

Though the scenario modelling showed that groundwater abstraction is the crucial factor affecting groundwater levels and the climate plays only a minor role at the current stage, climate change should not be neglected in further studies. In Jordan, mean temperatures are projected to rise by 2085 up to 3.1°C and median precipitation should decrease by 20% by 2055 (MOENV and UNDP 2014). Climate change affects agriculture, in terms of quantity and quality of crops, water and fertilizers uses, soil drainage, soil erosion, reduction of crop diversity and land use, regarding land degradation and speculation (MOENV 2013). Climate change is considered as another relevant aspect to work on by the national water strategy (MWI 2016b) and its study at local scale should therefore also be contemplated in scenario modelling involving at least the Ministry of Water and Irrigation, Ministry of Environment, Ministry of Agriculture, etc. including the large uncertainties in future projections, and considering the long term analysis, which is outside the scope of IWRM (Ludwig et al. 2014).

On decision support system modelling, it would be interesting to see a real-time evaluation platform, where results can be discussed within a participatory process of all stakeholders involved, including farmers groups, institutions and ministries. Examples of this kind of processes have already proved to be fructiferous in two basins, in Bolivia and California in the U.S (Forni et al. 2016).

Though water quantity is the basis for all further studies in water management, the inclusion of not only water quality and financial aspects, but also of the influence of other sectors such as energy, climate security and food on the water strategy should be analysed in the future. That implies moving from an IWRM to a nexus approach, where the perspective of analysis is based on the equality of all sectors, and not only studied under the water management perspective (Benson et al. 2015).

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REPORT

Modelling groundwater over-extraction in the southern Jordan Valley with scarce data

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Abstract To deal with the challenge of groundwater over-extraction in arid and semi-arid environments, it is necessary to establish management strategies based on the knowledge of hydrogeological conditions, which can be difficult in places where hydrogeological data are dispersed, scarce or present potential misinformation. Groundwater levels in the southern Jordan Valley (Jordan) have decreased drastically in the last three decades, caused by over-extraction of groundwater for irrigation purposes. This study presents a local, two-dimensional and transient numerical groundwater model, using MODFLOW, to characterise the groundwater system and the water balance in the southern Jordan Valley. Furthermore, scenarios are simulated regarding hydrological conditions and management options, like extension of arable land and closure of illegal wells, influencing the projection of groundwater extraction. A limited dataset, literature values, field surveys, and the 'crop water-requirement method' are combined to determine boundary conditions, aquifer parameters, and sources and sinks. The model results show good agreement between predicted and observed values; groundwater-level contours agree with the conceptual model and expected flow direction, and, in terms of water balance, flow volumes are in accordance with literature values. Average annual water consumption for irrigation is estimated to be 29 million m^3 and simulation results show that a reduction of groundwater pumping by 40% could recover groundwater heads, reducing the water taken from storage. This study presents an example of how to develop a local numerical groundwater model to support management strategies under the condition of data scarcity.

Keywords Numerical modeling · MODFLOW · Irrigation · Over-extraction · Jordan

Introduction

Water needs per capita in the Middle East are not met and this situation is worsening; projections estimate that by 2050 water availability per person will decrease by half, and considering also West Africa, it is expected to reach only 550 m^3/cap/a (Seckler et al. 1999; Bucknall and World Bank 2007; Droogers et al. 2012). One of the impacts of water scarcity is the inability to meet water demands for different sectors such as domestic, industrial and environmental. Even water for irrigation for food production is insufficient (Seckler et al. 1999; Zhou et al. 2010). In Middle East countries, agriculture and livestock water-use percentage (compared with the total), to name some examples, is 60% in Lebanon, 87% in Syria, 86% in Egypt and 65% in Jordan (FAO 2016).

Good water management is the key to deal with scarce water resources and their allocation. Management strategies should address water scarcity based on a holistic comprehension of the water balance, understanding each element of the basin and their interactions (Steduto et al. 2012). However, while surface-water flow dominates a river basin, the storage and lower flow rates of groundwater dominate the subsurface environment (Garduño et al. 2006) and therefore, the application of management strategies should be adjusted according to

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SUPPLEMENTARY MATERIAL

S1 CROP COEFFICIENTS (KC) AND CROP WATER REQUIREMENT (ETC)

Table S1. Crop coefficients (Kc) and duration of each growth stage for crops found during field surveys in November 2012. Kc values sources are: Wittwer and Honma 1979, Allen et al. 1998, GTZ 2002, Israeli et al. 2002, Zaid et al. 2002, Orloff and Putnam 2007 and Díaz-Méndez et al. 2014.

Crop \ Growth stage	Initial		Development		Mid-season		Late season		Total Duration [days]
	Kc1	D [days]	Kc2	D [days]	Kc3	D [days]	Kc4	D [days]	
Sweet corn*	0.40	20	0.90	30	1.15	30	1.05	10	90
Eggplant*	0.60	30	0.85	40	1.10	40	0.90	20	130
Tomato*	0.60	30	0.93	40	1.25	40	0.65	25	135
Squash/Zucchini*	0.60	10	0.80	20	1.00	20	0.80	15	65
Banana 1st Year	0.50	120	0.83	90	1.15	120	1.10	60	390
Banana 2nd year	0.70	120	0.95	60	1.20	180	1.10	5	365
Olives	0.40	30	0.55	90	0.70	60	0.70	90	270
Wine grapes	0.30	30	0.50	60	0.70	40	0.45	80	210
Date palm	0.90	150	0.95	35	0.95	150	0.80	30	365
Herb	0.60	10	0.85	20	1.10	20	1.10	10	60
General crop	0.60	23	0.90	33	1.10	33	0.90	18	105
General – green houses	0.60	20	1.00	30	0.75	40	0.70	15	105

Table S2. Crop water requirement (ETc) for different crops found in the study area in mm/day for 2000, with the associated duration of each growth stage, as well as the respective crop factor (Kc); the duration in each month is considered in the row of Kc value. *In parentheses the growth stage: Initial (Ini), Development (Dev), Mid-Season (Mid), Late Season (Late).*

Sweet corn	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Growth stages		Ini (20)	Dev (30)	Mid (30)	Late (10)							
Kc		0.3	0.9	1.15	0.3							
ETcrop [mm/day]		0.5	3.1	5.2	1.9							

Eggplant	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Growth stages								Initial (30)	Dev (30)	Dev (10) / Mid(20)	Mid (20) / Late(10)	Late(10)
Kc								0.6	0.9	1.0	1.0	0.3
ETcrop [mm/day]								3.4	4.3	4.3	3.0	0.5

Tomato	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Growth stages	Mid(5) / Late (25)	Ini (15 d)	Ini (15) / Dev (15)	Dev(25) / Mid (5)	Mid (30)	Mid(5) / Late (25)			Ini (15 d)	Ini (15) / Dev (15)	Dev(25) / Mid (5)	Mid (30)
Kc	0.8	0.30	1.0	1.0	1.3	0.8			0.30	0.8	1.0	1.3
ETcrop [mm/day]	1.2	0.6	3.3	4.5	7.0	4.8			1.5	3.2	2.8	2.1

Squash/Zucchini	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Growth stages								Ini (10) / Dev (20)	Med (20)/ Late (10)	Late (5)		
Kc								0.7	1.1	0.1		
ETcrop [mm/day]								4.1	5.7	0.5		

Banana 1st year												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Growth stages	Dev (30)	Dev (30)	Mid (30)	Mid (30)	Mid (30)	Mid (30)	Late (30)	Ini (30)	Ini (30)	Ini (30)	Ini (30)	Dev (30)
Kc	0.83	0.83	1.2	1.2	1.2	1.2	1.1	0.5	0.5	0.5	0.5	0.83
ETcrop [mm/day]	1.3	1.7	3.9	5.2	6.4	7.3	6.9	2.9	2.5	2.1	1.4	1.4

Banana 2st year												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Growth stages	Dev (27) / Mid (4)	Mid (28)	Mid (31)	Mid (30)	Mid (31)	Mid (30)	Mid (26) / Late (5)	Ini (31)	Ini (30)	Ini (31)	Ini (28) / Dev(2)	Dev (31)
Kc	0.98	1.20	1.20	1.20	1.20	1.20	1.18	0.7	0.7	0.7	0.7	0.95
ETcrop [mm/day]	1.60	2.50	4.10	5.40	6.70	7.70	7.50	4.0	3.5	3.0	2.1	1.60

Olives												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Growth stages			Ini (30)	Dev (30)	Dev (30)	Dev (30)	Mid (30)	Mid (30)	Late (30)	Late (30)	Late (30)	
Kc			0.4	0.4	0.4	0.6	0.7	0.7	0.7	0.7	0.7	
ETcrop [mm/day]			1.4	1.8	2.2	3.5	4.4	4.0	3.5	3.0	2.0	

Wine grapes												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Growth stages			Ini (10)	Ini (20) / Dev (10)	Dev (30)	Dev(10) / Mid (20)	Mid (30)	Mid (30)	Mid (30)	Late (7)		
Kc			0.1	0.4	0.5	0.6	0.7	0.7	0.7	0.1		
ETcrop [mm/day]			0.3	1.7	2.8	4.0	4.4	4.0	3.5	0.4		

Date palm												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Growth stages	Mid (31)	Mid (28)	Mid(1) / Late (30)	Ini (30)	Ini (31)	Ini (30)	Ini (31)	Ini (28) / Dev (3)	Dev (30)	Dev (2) / Mid(29)	Mid (30)	Mid (31)
Kc	1.0	1.0	0.8	0.9	0.9	0.9	0.9	0.9	1.0	1.0	1.0	1.0
ETcrop [mm/day]	1.6	2.0	2.7	4.1	5.0	5.8	5.7	5.2	4.8	4.0	2.7	1.6

Herb	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Growth stages			Ini (10)	Dev (20) / Mid (10)	Mid (20) / Late (10)				Ini (10)	Dev (20) / Mid (10)	Mid (20) / Late (10)	
Kc			0.2	1.3	1.1				0.2	1.3	1.1	
ETcrop [mm/day]			0.7	5.9	6.1				1.0	5.5	3.2	

General crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Growth stages		Ini (23) / Dev (5)	Dev (28)/ Mid (3)	Mid (30)	Late (18)				Ini (23) / Dev (7)	Dev (26) / Mid (5)	Mid (28)/ Late (2)	Late (16)
Kc		0.6	0.9	1.1	0.5				0.6	0.9	1.1	0.4
ETcrop [mm/day]		1.3	3.0	5.1	2.8				3.1	3.8	3.2	0.7

General - green houses	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Growth stages	Ini (20) / Dev (10)	Dev (20) / Mid (10)	Mid (30)	Late (15)					Ini (20) / Dev (10)	Dev (20) / Mid (10)	Mid (30)	Late (15)
Kc	0.7	0.9	0.8	0.4					0.7	0.9	0.8	0.4
ETcrop [mm/day]	1.2	1.9	2.5	1.9					3.7	3.9	2.2	0.7

S2 QUALITY STANDARDS FOR THE REUSE OF WATER IN AGRICULTURE

Table S3. Suggested guidelines for water reuse. Extraction from EPA (2012).

Reuse Category and Description	Treatment	Reclaimed Water Quality (12)
AGRICULTURAL REUSE		
Food Crops (11) The use of reclaimed water for surface or spray irrigation of food crops which are intended for human consumption, consumption raw.	Secondary (1) Filtration (2) Disinfection (3)	pH = 6.0-9.0 ≤ 10 mg/l BOD (4) ≤ 2 NTU (5) No detectable faecal coliform/100ml (6, 7) 1 mg/l CL_2 residual (min.) (8)
Processed Food Crops (11) The use of reclaimed water for surface irrigation of food crops which are intended for human consumption, commercially processed. **Non-Food Crops** The use of reclaimed water for irrigation of crops which are not consumed by humans, including fodder, fibre, and seed crops, or to irrigate pasture land, commercial nurseries, and sod farms.	Secondary (1) Disinfection (3)	pH = 6.0-9.0 ≤ 30 mg/l BOD (4) ≤ 30 mg/l TSS ≤ 200 faecal coli/100 ml (6, 9, 10) 1 mg/l CL_2 residual (min.) (8)
GROUNDWATER RECHARGE – NON-POTABLE REUSE		
The use of reclaimed water to recharge aquifers which are not used as a potable drinking water source.	Site specific and use dependent Primary (min.) for spreading Secondary (1) (min.) for injection	Site specific and use dependent

(1) Secondary treatment process includes activated sludge processes, trickling filters, rotating biological contractors, and may stabilization pond systems. Secondary treatment should produce effluent in which both the BOD and SS do not exceed 30 mg/l.

(2) Filtration means; the passing of wastewater through natural undisturbed soils or filter media such as sand and/or anthracite; or the passing of wastewater through microfilters or other membrane processes.

(3) Disinfection means the destruction, inactivation, or removal of pathogenic microorganisms by chemical, physical, or biological means. Disinfection may be accomplished by chlorination, ozonation, other chemical disinfectants, UV, membrane processes, or other processes.

(4) As determined from the 5-day BOD test.

(5) The recommended turbidity should be met prior to disinfection. The average turbidity should be based on a 24-hour time period. The turbidity should not exceed 5 NTU at any time. If SS is used in lieu of turbidity, the average SS should not exceed 5 mg/l. If membranes are used as the filtration process, the turbidity should not exceed 0.2 NTU and the average SS should not exceed 0.5 mg/l.

(6) Unless otherwise noted, recommended coliform limits are median values determined from the bacteriological results of the last 7 days for which analyses have been completed. Either the membrane filter or fermentation tube technique may be used.

(7) The number of total or faecal coliform organisms (whichever one is recommended for monitoring in the table) should not exceed 14/100 ml in any sample.

(8) (This recommendation applies only when chlorine is used as the primary disinfectant. The total chlorine residual should be met after a minimum actual modal contact time of at least 90 minutes unless a lesser contact time has been demonstrated to provide indicator organism and pathogen reduction equivalent to those suggested in these guidelines. In no case should the actual contact time be less than 30 minutes.
(9) The number of faecal coliform organisms should not exceed 800/100 ml in any sample.
(10) Some stabilization pond systems may be able to meet this coliform limit without disinfection.
(11) Commercially processed food crops are those that, prior to sale to the public or others, have undergone chemical or physical processing sufficient to destroy pathogens.
(12) Unless otherwise noted, recommended quality limits apply to the reclaimed water at the point of discharge from the treatment facility.

Table S4 Design inflow and effluent parameters from Cardona et al., (2012).

Inflow			Effluent quality		
Parameter	*Unit*	*Value*	*Parameter*	*Unit*	*Value*
Inflow	l/d/cap	74	COD	mg/l	< 90
COD	mg/l	1820	BOD	mg/l	< 20
BOD	g/m^3	910	Suspended solids	mg/l	< 30
Ammonium (NH_4-N)	g/m^3	100	NH_4-N	mg/l	< 10
Ph	[ ]	6.5 – max 8.0	N inorganic	mg/l	< 25
Temperature	° C	12 – max 30			

Table S5 Standards for irrigation water in Jordan (JS 893/2006).

Parameter	Unit	Irrigation			GW recharge	Discharge to wadis, streams or water bodies
		Water class A *cooked vegetables, parks, playgrounds and side of roads within city boundaries*	Water class B *fruit trees, side of roads outside of city limits and landscape*	Water class C *Field crops and forest trees*		
BOD	mg/l	30	200	300	15	60*
COD	mg/l	100	500	500	50	150**
DO	mg/l	> 2	-	-	> 2	> 1
Total suspended solids	mg/l	50	150	150	50	60**
pH	[ ]	6-9	6-9	6-9	6-9	6-9
Turbidity	NTU	10	-	-	2	-
Nitrate	mg/l	30	45	45	30	45
Ammonium	mg/l	-	-	-	5	-
Total Nitrogen	mg/l	45	70	70	45	70
E. *Coli*	MPN or cfu/100 ml	100	1000	-	< 2.2	1000
Intestinal Helminth eggs	Egg/l	≤ 1	≤ 1	≤ 1	≤ 1	≤ 1
Fats oils grease	mg/l	-	-	-	8	8

* For biological WWTP or WWTP with polishing ponds BOD_5 is considered filtered BOD

** For biological WWTP or WWTP with polishing ponds the limit is twice this value

S3 ESTIMATION OF RELIABILITY

Table S6. Example of determination of reliability for period 2020-2025 for Indicator 1 in Wadi Shueib, using Equation 4.3. The grid representation is shown for the threshold 60% (medium standard). For each scenario, a value is defined as "success" (S) (in *blue*) if the result is larger than 60%, otherwise "failure" (F) (in *shades of red*) is designated.

Years \ Scenarios	**s1**	**s2**	**s3**	**s4**	**s5**	**s6**	**s7**
2020	F	F	F	F	S	S	F
2021	F	F	F	F	S	S	F
2022	F	F	F	F	S	S	F
2023	F	F	F	F	S	S	F
2024	F	S	F	S	S	S	F
2025	F	S	F	S	S	S	F
Reliability [%]	0	33	0	33	100	100	0