WATER INNOVATION TECHNOLOGIES

SIMULATION OF THE PROJECT IMPACT ON GROUNDWATER RESOURCES UNDER SCENARIOS OF ADOPTION OF WATER SAVING TECHNOLOGIES AND PRACTICES IN AZRAQ AND MAFRAQ, JORDAN

WATER INNOVATION TECHNOLOGIES

The Water Innovation Technologies (WIT) Project is a five-year initiative funded by the U.S Agency for International Development (USAID) and implemented by Mercy Corps (MC). The purpose of the project is to increase water conservation in Jordan by focusing on water efficiency in the agricultural sector, community and household levels.

The Project brings together various international and local research and development partners to work with market actors across the public, private and civil society sectors to market and promote evidence-based water saving practices and innovative technologies in agriculture and households in Jordan. The Project's mission is to support and catalyze the efforts of various market actors to provide improved knowledge, skills, practices and access to affordable innovative technologies that will help save 18.5 million cubic meters of water in agriculture and households in Jordan by 2022.

MERCY CORPS

Mercy Corps is a global humanitarian aid agency that has been working hand-in-hand in Jordan with local communities and partners since 2002 to implement US, UN, EU, UK, and private donor funded projects.

WATER INNOVATION TECHNOLOGIES PROJECT

Mercy Corps
Seventh Circle, 3 Tabasheer Street, Building No. 8,
P.O. Box 830684, Amman 11183 Jordan.
Phone: (+962) 6 554 8570/1/2, Fax: (+962) 6 554 8573.
Email: jo-info-wit@mercycorps.org
www.mercycorps.org

THIS STUDY WAS PREPARED BY

The International Center for Biosaline Agriculture (ICBA)
Authors: Marwan Al-Raggad and Makram Belhaj Fraj
ICBA Project Manager: Diletta Ciolina
1, ICBA, International Center for Biosaline Agriculture, Academic City, Dubai, UAE; partner of WIT Project USAID-MC; FYR3: May 10th, 2019
2, Mercy Corps Jordan;
3, USAID-Jordan

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1. Introduction

The USAID/Jordan Water Innovations Technologies (WIT) is implemented by Mercy Corps and partners including ICBA and it is designed to increase water conserved in Jordan by driving the adoption of new water saving technologies and practices in agriculture and at the household level.

WIT is adopting a market system development (MSD) approach to achieve the following three outcomes:

- Increase the adoption of water saving technologies and practices by farmers, households, and communities;
- Improve access to finance for water saving technology adoption;
- Strengthen institutions to further support water conservation.

WIT facilitates the uptake of advisory services and financing while using social marketing to overcome individual and institutional behavioral change barriers. WIT has committed to a market-based approach with the end goal of promoting sustainable and scaled adoption of technologies and greater conservation of water. WIT targets agriculture users in Azraq and Mafraq, as well as communities and households in the North who are hosting large numbers of Syrians refugees.

In this context, it is important to study and understand how groundwater pumping for agricultural use is impacting groundwater aquifer (quantity and quality of water) to guide the project's interventions accordingly.

The purposes of this study are to (1) provide WIT Team with a baseline dashboard on crop types, water use, over-irrigation and groundwater aquifers availability and salinity in Azraq and Mafraq, and (2) simulate changes in groundwater level in response to adoption of irrigation water saving technologies in Azraq and Mafraq during the period 2019-2023, under an assumption of no change in crop type patterns. Scenarios are developed to answer a series of "What if" questions: what the response of groundwater level is if:

A. Irrigation practices do not change (baseline scenario)?
B. Water innovation technologies are introduced in 20% of the orchard's farms covering more than 200 dunams, with savings of 50% on average?
C. Water innovation technologies are introduced in all orchard's farms covering more than 200 dunams, with savings of 50% on average?
D. Irrigation amounts are increased by 20% under 2-3-degree projections of climate change (2050)?

This scenario analyses will support ICBA and WIT team in defining sub-localities of priority intervention that the project should target in order to achieve the highest impact on saving water while sustaining crop productivity.

The targets of this study are:

- Mapping crop type, water application, maximum water requirements and over-irrigation/losses
- Determining the baseline situation of the aquifer systems to define current water availability and develop simulations
- Determining of the baseline situation of the aquifers salinity to define current salinity hot spots and to develop simulations.

2. Executive Summary

The climate of Northern Jordan is marked by sharp seasonal variations in both temperature and precipitation with hot dry summers and cool wet winters. Potential evaporation is high and together with the precipitation amounts characterize the area as arid to hyper-arid.

WIT project intervention area includes Azraq and Mafraq that are in Northern Jordan within Zarqa and Mafraq governorates and over two groundwater basins, Azraq and Amman-Zarqa basins. Azraq includes the basaltic uplands (*plateau*), Azraq *Qaa* (Arabic name of depression) and the wetland, whereas Mafraq shares with Azraq the Basaltic *plateau* in the East and Western parts where Mafraq city is located and includes limestone aquifer.

Azraq includes three major aquifer systems consisting in upper aquifer (shallow unconfined which is the main aquifer), middle aquifer (confined) and deep aquifer system (confined). These three aquifers vary in groundwater quality and quantity. The upper aquifer consists of four members: Alluvium (Quaternary Sediments), Basalt, Um Rijham and Wadi Shahala. Basalt and B4/B5 units are the most abundant units composing the upper aquifer. The middle aquifer known as Amman-Wadi Sir (B2/A7) is unconfined due to the presence of low permeable bituminous marl (B3 Formation). The deeper aquifer (400-3,000 meters depth) Kurnub composed of stratified sandstone (marl-limestone) with high concentration of quartzite was formed in lower Cretaceous between B2 and A7 and is acting as a semi-permeable layer which makes the aquifer confined. This aquifer is brackish to saline but still not utilized yet.

Mafraq basin is mainly covered by basaltic rocks underlain by Tertiary and Cretaceous calcareous or basaltic rocks inter-fingering with recent lacustrine sediments. The main formations are Wadi Sir (A7), Um Ghudran (B1), Amman (B2) and Basalts. Wadi Sir (A7) is the oldest relevant rock formations of Upper Cretaceous age, mainly composed of 220 m thick massive limestone strongly jointed and karstified, that makes it an excellent aquifer. Um Ghudran (B1) overlies Wadi Sir, with up to 30m in thickness that consists of marls and chalks in lenses (discontinuous formation) and is in turn overlain by Amman formation. Amman (B2) consists in a 130 m thick sequences of chert, limestone and phosphate beds with some marl and chalk intercalations very strongly jointed and fractured and builds an excellent aquifer with very high yields. Mafraq's main aquifer is the B2/A7 composite aquifer generally overlain by basaltic rocks of significant thicknesses considered as the upper aquifer. The basalt aquifer covers about 78% of Za'atri area and builds the major aquifer in NE part of Badia area, with a total thickness of up to 550 m mainly consisting of limestone and some marl intercalations belonging to the most Upper Cretaceous rock sequences.

The Ministry for Water and Irrigation (MWI) crop type map of 2013 was updated using cloud-free Landsat 8, 30-m resolution images covering Azraq District and Mafraq governorate in Northern Jordan for the 2017-2018 season. The results showed that the total irrigated area equals 4,738 and 10,617 ha in Azraq and Mafraq, respectively. Azraq is mainly cultivating olive trees (1,750 ha), mixed alfalfa-Olives and alfalfa in pure stand. In Mafraq, the results showed that stone fruits are the major crops with 4,635 ha (37% of the total irrigated area). The second largest crop in Mafraq is olives with 3,968 ha, then vegetables are grown over 1,383 ha. Cropping pattern mapping in Azraq showed an intense pattern in the central part of the basin East of Azraq city, where medium and large size and new farms are dominating the landscape. Agricultural practices in Mafraq are taking place along the main road where the B2/A7 Basalt aquifer complex has high pumping yield and good water quality. The B2/A7 Basalt aquifer supports irrigation and drilling municipal wells that supply cities with fresh drinking water.

Daily weather data acquired from MWI were used to estimate reference ET and to calculate actual evapotranspiration for the studied crops according to FAO56 formalism using average crop coefficient (Kc standard stable). Net crop water requirements were higher in Azraq area as weather conditions are characterized by a higher air temperature than Mafraq by 1-2 degrees in average and lesser precipitations and air relative humidity. ETo values were found to be 1,619 mm/yr in Azraq and only 1,317 mm/yr in Mafraq. The highest ET_C values were recorded for Alfalfa (1,518 mm/yr) that is grown only in Azraq district.

The groundwater modeling was conducted using the MODFLOW (USGS modular three-dimensional finite-difference groundwater flow code, McDonald and Harbaugh, 1988, and Harbaugh and McDonald, 1996) and the graphical interface Model-Muse (Winston, 2009) that runs at daily basis with horizontal grid block dimensions of 30 m x 30 m and vertical discretization for one layer of variable thickness (ranges from 50 m to 700 m).

Simulations in Azraq showed that the average drawdown will be 4.33 m for the period. The maximum drawdown of 8.79 m is expected in the central part of the basin due to excessive agricultural uses. Simulations in Mafraq showed an average drawdown of 9.12 m for the period. The maximum drawdown of 14.21 m is expected along Baghdad road which is the area of highest agricultural and domestic pumping.

Basic chemical analyses performed on 70 groundwater samples showed significant dominancy of $MgCl_2$ hydrate in brines, KCl salt, Halite (NaCl) in the aquifer systems. Azraq and Mafraq water types are earth alkaline to alkaline water with prevailing bicarbonates, sulfate and chloride. This clarifies the origin of Sulphur in the waters to be associated with Gypsum dissolution caused by irrigation return flows, indicating the high impact of agriculture on the groundwater system in irrigated areas. Saturation Index estimated as the logarithm of the ratio between ionic activity product and mineral equilibrium constant at a given temperature was measured using laboratory and field analyses and was modelled using PHREEQC interactive software (USGS 2003). The most common mineral phases of Azraq and Mafraq aquifer are calcite, aragonite, gypsum, anhydrite and dolomite. Results indicated an oversaturation in Aragonite (CaCO3), Calcite (CaCO3) and Dolomite (CaMg(CO3)2), while Anhydrite (CaSO4) and Gypsum (CaSO.2H2O) are generally under-saturated. This composition is justified by the over irrigation process. Irrigation water dissolves carbonates from the soil profile to the groundwater body leading to a case of over saturation. As halite is one of the last minerals that crystallized in the soil after irrigation, it is rarely formed due to excessive irrigation.

Timeseries salinity measurements in monitoring wells were used to identify trends during 1984-2015 period for Azraq and 2010-17 period for Mafraq. Annual increase in salinity was considered in the projection period. Interpolation was achieved using natural neighbourhood model. There is a clear increasing trend in salinity starting from the eastern part of the basin and moving towards the west during 1990-2017 period. Salinity expansion is due to irrigated agriculture expansion. This leads to a drop in wells levels that has been accompanied by increasing groundwater salinity, exceeding, in some wells, 3,500 µS/cm, which is the upper limit for irrigating vegetables in Leptosols. In Mafraq, TDS maximum value increased from ~1750 in the year 1990 to 1998 mg/l in 2017. Overtime degradation in water quality resulted from over-exploitation, which has led to disturbances in the groundwater flow regimes and mobilization of neighbouring and underlying salty bodies. This has allowed the salty groundwater to irreversibly reach the production wells. Simulated salinity for the year 2050 provided an alert for a rapid increase in the GW salinity which will affect the whole GW system.

MWI and the actual modeling estimated groundwater abstraction for agricultural use to be 204 to 276 MCM, 67% in Mafraq. This number is higher than estimates of groundwater abstraction using net crop water requirements averages for main crop types (129 MCM) and even 20% higher than estimates using an average irrigation efficiency coefficient. This means that irrigation efficiency is lower and can be obtained from on-farm water audit. The consultancy team suggests here using outputs from agronomic studies as an additional source of data. This consists in crop type map and average crop water use determined from on-farm water audits. Water audit data interpolated over a crop type map showed a total groundwater abstraction of 359 MCM. Water audit-based estimate of groundwater abstraction is an unusually high number that need to be verified. Several sources of uncertainty include crop classification, model boundary condition and abstraction data.

To reduce these uncertainties, the development in the future of a dynamical estimation of actual ET and soil water balance for every hectare and daily, which allows an accurate, near-real time, near-continuous estimation of water use, is strongly recommended.

3. Description of the WIT project intervention areas

3.1. Climate conditions

The climate of Northern Jordan is marked by sharp seasonal variations in both temperature and precipitation with hot dry summers and cool wet winters. Summer starts around mid-May and winter starts around mid-November, with two short transitional periods to autumn and spring (Table 1, JMD, 2017). Precipitation consists mainly in rain and rarely snow and is characterized by its irregularity, duration and high spatial variability. Potential evaporation is high and together with the precipitation amounts characterize the area as arid to hyper-arid (Figure 1).

The weighted average method (Thiessen polygons, Chow, 1988) and IDW method (Inverse Distance Method) on 1970–2017 data set (MWI stations) were applied to build precipitation isohyets and to estimate statistical certainty with elevation corrections. The resulting average precipitation was 112 mm/year in the central parts of the study area.

Observed precipitations of the four JMD stations in Azraq and Mafraq ranged from 113 mm in Deir El-Kahf to 144 mm in Um El-Quttein.

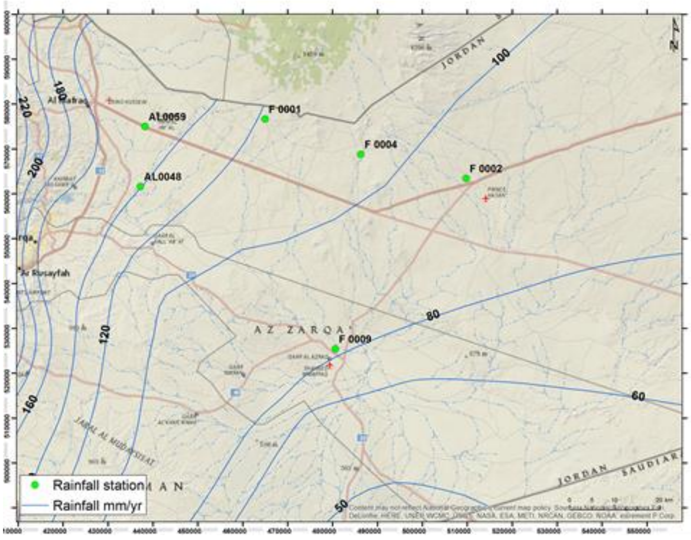


Figure 1. Precipitation isohyets for 1970-2017 period.

Table 1. Average weather parameters in the project intervention area (1980-2017).

Variable	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept
T_{min} (°C)	13.3	8.9	6.1	4.1	4.7	6.7	9.7	13.1	16.0	18.0	17.8	16.3
T_{max} (°C)	27.5	20.4	16.3	13.6	15.9	18.3	3.9	28.4	31.5	33.1	32.5	31.4
T_{mean} (°C)	20.4	14.7	11.2	8.8	10.3	12.5	16.8	20.7	23.7	25.6	25.2	23.9
Sunshine (hr/day)	8.3	6.8	5.4	5.3	6.2	7.2	8.2	10.1	11.1	11.4	10.8	9.3
Wind speed m/s	1.6	1.9	1.9	1.9	2.2	2.2	2.3	2.3	2.4	2.1	2.1	1.7
Wind direction 1	W	W	W	W	W	W	W	W	W	W	W	W
Wind direction 2	SW	SW	SW	SW	SW	NW	NW	NW/NE	NW/NE	SW	SW	SW
Relative humidity (%)	71.0	73.4	81.1	82.6	81.1	73.5	65.2	59.2	59.8	63.7	68.0	69.3
Rainfall (mm)	7.3	18.2	36.4	41.6	39.2	31.5	6.4	1.9	0	0	0	2.3
Class-A pan (mm/d)	7.6	5.2	3.2	2.8	3.8	5.2	8.1	11.0	12.5	13.4	11.8	10.4
Potential ET (mm/d)	4.2	2.5	2.3	2.1	2.6	3.9	5.7	6.8	7.6	8.1	7.2	5.6

Evapotranspiration was calculated using the J2000 ETP module based on Jensen and Allen (1990) and Penman-Monteith equation (1948), combining energy balance with the mass transfer method to correct resistance factors as suggested by FAO (1989). Model outputs were validated using actual ET from SEBAL.

3.2. Topography

WIT project intervention area includes Azraq and Mafraq that are in Northern Jordan within Zarqa and Mafraq governorates and over two groundwater basins, Azraq and Amman-Zarqa basins. Azraq includes the basaltic uplands (*plateau*), Azraq *Qaa* (Arabic name of depression) and the wetland, whereas Mafraq shares with Azraq the Basaltic *plateau* in the East and Western parts where Mafraq city is located and includes limestone aquifer (Figure 2).

Slopes were extracted from the DEM map with three classes discriminating Jebel Druz, Mafraq and Azraq depression with low slope resulting in higher recharge rates and groundwater contamination. Azraq basin is a depression surrounded by hilly relief where all the water flows from all directions towards the center of basin (*Mudflat*) *Qa'a Al-Azraq,* which is the lowest elevation within the basin.

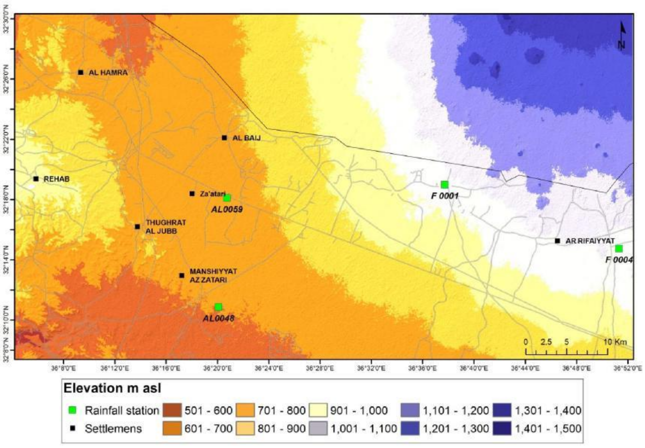


Figure 2. Digital elevation model (DEM) of Northern Jordan showing main settlements and rainfall stations.

The topography of Azraq basin varies from around 500 to 1,750 m above sea level (m asl). Elevation at the basin's center is about 500 m asl and it rises to 900 m asl in the Southern, Eastern and Western parts of the basin, where it increases sharply and reaches the maximum elevation around 1,750 m asl in North part of the basin in Syria at Jebel Druze area (maximum elevation in Jordan is about 1,230 m asl).

3.3. Geology and aquifer systems

3.3.1. Azraq basin

As described by Bender (1963), Azraq basin is a part of limestone plateau in E Jordan (NW part of limestone *plateau*). In NE *plateau,* half of the basin is covered with basalt which is originated from volcanic activity in *Miocene* and *Oligocene* geological ages. Thickness of basalt varies from N to S. In N-area at Mount Arab of Syria, it reaches the thickness of 1,500 m where it progressively declines towards S. Both igneous and sedimentary rock types are exposed within the basin which is formed between late *Cretaceous* to *Quaternary* geological age (Bajjali, 1997). Sedimentary rocks within the basin includes mainly limestone, chert, clay, marl, sandstone and evaporites. Outcrop formations of sedimentary rock exposed in the Azraq basin are *Rijham* and *Wadi shalalla* in the Eastern and Central parts of the basin, whereas the Northern part is dominated by basalt and S and W by *Muwaqqar* and *Rijham* formations of late *Cretaceous*. The origin of the sedimentary rock is marine, and it is about 3.5 km thick layers of sediment. However, in N and NE basalts cover an area about 11,000 km^2 (Ibrahim, 1993). Azraq basin geology is controlled by movement of Arabian plate towards NE with respect to the African plate. The basin is tectonically active with several structural faults and lineaments. The most dominant one is the *Sirhan* fault zone in SE Azraq basin with vertical displacement of 325 km and a very thick sediment sequence (Al-Hammoud, 1996). Further, a dominant structure consisting in *Graben* is trending NW-SE. Another major fault is trending EW and the second one is *Fuluk* fault that stretches from basalt extending NW to SE and it forms the Eastern flank of *Hamza Graben*. Some faults are also extending NW-SE parallel to *Graben* and the remaining of them have NW-W-S-SE strike. The basin has several structures which controlled the geology of Azraq including the *Sirhan-Fuluk*, *Siwaqa*, *Baqal-Wisad* and *Zarqa* main fault systems (NRA, 2008).

Azraq includes **three major aquifer systems** consisting in upper aquifer (shallow unconfined which is the main aquifer, Table 2), middle aquifer (confined) and deep aquifer system (confined). These three aquifers vary in groundwater quality and quantity.

Upper aquifer is the most important for our study and consists of multilayers which are responsible to make major differences in the chemical and physical properties of groundwater in Azraq basin. The major recharge of the upper aquifer complex is at N, NE, NW and minor recharge at W of the basin (Al-Raggad et al, 2010 ; El-Naqa, 2007). The shallow aquifer consists of four members: *Alluvium* (Quaternary Sediments), *Basalt*, *Um Rijham* and *Wadi Shahala* and *B4/B5* units are the most abundant units composing the upper aquifer (Table 2, Figure 2). *Basalt* extended from C and ends at N Azraq basin in Syria highland and covers the Northern part of Azraq basin. However, *B4/B5* formation is composed of chert and limestone and covers W and S part of the basin. According to Al-Raggad and Jasem (2010) and El-Naqa (2007), the basalt aquifer is hydraulically connected to the *B4/B5* formation. This shallow freshwater aquifer is the highest yielding but overexploited since last three decades with a significant depletion and salinization.

The middle aquifer known as *Amman-Wadi Sir* (*B2/A7*) is unconfined due to the presence of low permeable bituminous marl (*B3 Formation*). This layer act as *Aquiclode* between the upper and middle aquifers. This formation is a combination of *B2* (limestone, chert and chalk) and *A7* (marly-limestone and marl and occasionally sandstone). This middle aquifer is karstic limestone and chert overlain by *B3* aquitard formation. Formation *B2/A7* is below the upper aquifer and is exposed in W and SW part of Azraq. However, it is recharged from the N highland at Jebal Druze area (BGR-WAJ, 1994). According to Mesnil and Habjoka (2012), *B2/A7* aquifer is most important throughout Jordan due to its high productivity and high drinkable quality. In C-Azraq, *B2/A7* water is mineralized and rich in Sulphur which affects water quality with total dissolved solid particles of 800 to 2,500 mg/l, however in the W and NW part water is of good quality with total dissolved concentration from 200 to 500 mg/l. Irrigation and drinking waters are currently pumped from the middle aquifer (Kharabshah, 1991).

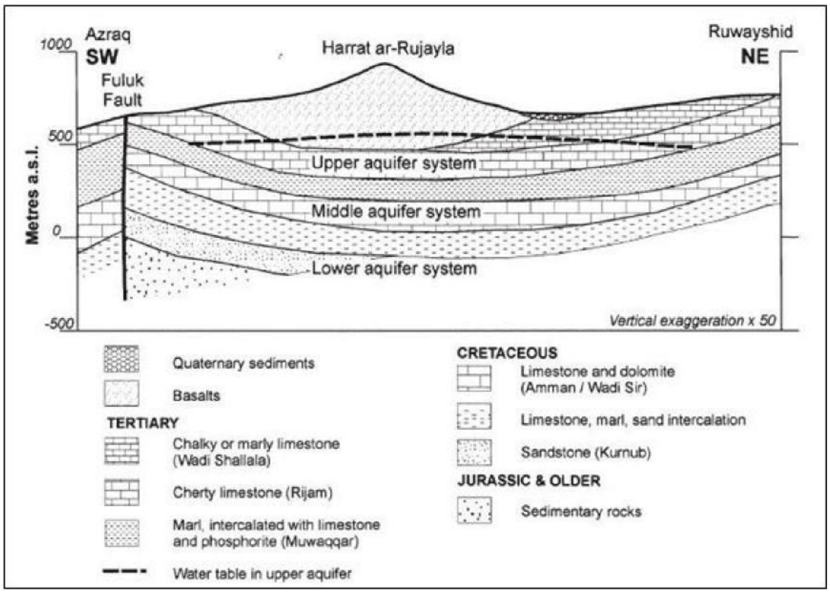


Figure 3 Hydrogeological cross section in Azraq basin

The deeper aquifer (400-3,000 meters depth) *Kurnub* composed of stratified sandstone (marly-limestone) with high concentration of quartzite was formed in *lower Cretaceous* between *B2* and *A7* and is acting as a semi-permeable layer which makes the aquifer confined. This aquifer is brackish to saline but still not utilized yet.

Groundwater flow in Azraq was updated from BGR (2011) in the current work based on 2017 water level in observation wells operated by MWI. Groundwater flow is taking place from higher elevation (with higher rainfall) in N and W to the lowest point known as *Qaa Azraq* (Sabkha area, Figure 4).

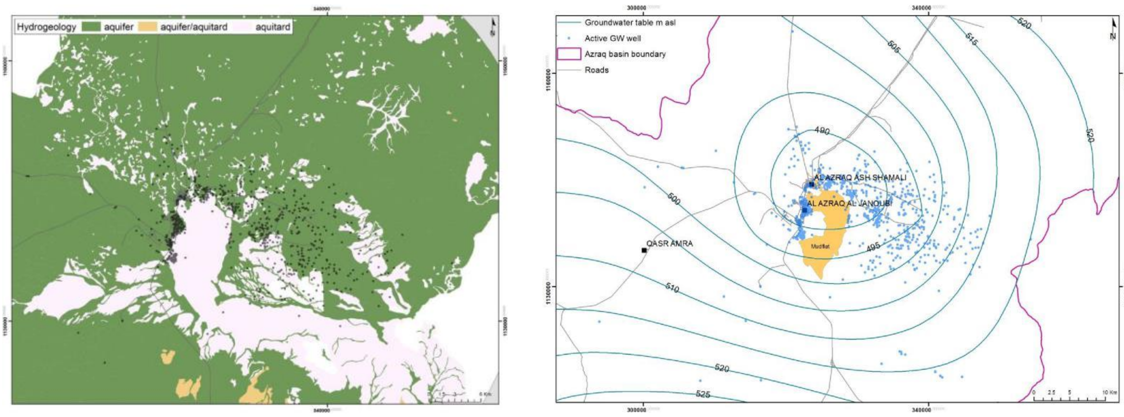


Figure 4. Hydrological units (left caption) and Groundwater flow pattern (right caption) in the shallow aquifer of Azraq basin

Table 2. Major units of shallow aquifer in Azraq basin area (adapted from El-Napa, 2010)

Formation	Code	Systems	Extend	Permeability	Quality	Yield	Use	Age	Lithology	Thickness (m)	Hydraulic Character
Um Qirma	B5	Water table	Unknown	unconfined	Fresh	Low	Low	L. Eocene	Limestone	0-15	Aquifer
Alluvium		Upper	C-Azraq E-Azraq Qa'a to NE-Azraq Druze (connected to B5)	unconfined	Brackish	Low	Low	Recent Quaternary	Sands, gravel, limestone, marl and lacustrine	0-35	Aquifer
Basalt	B4/B5	Upper	Half N-Azraq Jabel Druz to C-Azraq connected to B4-5	unconfined	fresh	High	High	L. Tertiary	Basalt	0-400 (max 1,500 at Jabel druz)	Aquifer
Urn Rijham	B4	Upper	SW- C-Azraq	unconfined	fresh	High	High	Mid-Eocene	Silicified limestone	170-300	Aquifer
Wadi Shallala	B5	Upper	NW Azraq	unconfined	fresh	High	High	L. Eocene	Marl, Chalky-limestone, and black and brown nodules chert	160-430	Aquiclude
Muwaqar	B3	Shallow	W-S	unconfined	fresh	High	High	E. Eocene	Marly-limestone	>100	Aquiclude
Amman Wadi Sir	B2/A7	Middle	W-SW	Unconfined (Jabel Druz)	Fresh to Sulphur in	High	High	*U. Cretaceous*	karstic limestone and chert	100 - 230	Aquifer
Kurnub	B2/A7	Deep	Not exposed	confined	Brackish/saline	Low	Low	*L Cretaceous*	Sand stone	400-3,000	Aquifer

Basalt aquifer is highly fractured and originated from alkali lava flows which are intercalated with red layer of clay (tertiary to quaternary).

Shallala acts as an aquitard between two groundwater bodies basalt and B4 in the northern part of the basin (WAJ, 1989). In southeast of the well field this B5 aquifer acts as an aquifer because it contains sandy layer in this area. According to Gibbs (1993) Shallala thickness increases from 160 to around 430 meter eastward towards the Fuluk fault.

Rijham aquifer is composed of white chalky limestone, black and brown nodules chert which is underlain by the green marls and contains gypsum occasionally. Rijham aquifer underlies the Shallala formation (B5) except at Q'a Azraq at the center of the basin where it is replaced by Sirhan sandstone and marl. Average thickness is around 60 meter. More importantly Rijham (B4) is connected to the basalt aquifer through Shallala (B5) aquifer (El-Naqa, 2010).

3.4. Mafraq Basin

Mafraq area is mainly covered by basaltic rocks underlain by Tertiary and Cretaceous calcareous or basaltic rocks inter-fingering with recent lacustrine sediments. The main formations are *Wadi Sir* (*A7*), *Um Ghudran* (*B1*), *Amman* (*B2*) and *Basalts*.

Wadi Sir (A7) is the oldest relevant rock formations of Upper Cretaceous age, mainly composed of 220 m thick massive limestone strongly jointed and karstified which makes it an excellent aquifer.

***Um Ghudran* (B1)** overlies *Wadi Sir*, with up to 30 m in thickness that consists of marls and chalks in lenses (discontinuous formation) and is in turn overlain by *Amman* formation. *Um Ghudran* is an aquiclude that is hydraulically interconnected with other formations.

***Amman* (B2)** consists in a 130 m thick sequences of chert, limestone and phosphate beds with some marl and chalk intercalations very strongly jointed and fractured and builds an excellent aquifer with very high yields.

Wadi Sir* and *Amman formations build together one interconnected composite aquifer, where *Um Ghudran* is present in the two formations.

Basalts formation consists in volcanic rocks that cover vast areas in C and N Jordan, CS Syria and NE Saudi-Arabia. These basalts are called *Jabal Druz* (JD) basalts and form a continuous basaltic cover extending in length on a NW-SE direction over 500 km and NE-SW direction for 200 to 300 km in width, thus covering a total area of about 45,000 km^2 (Bender 1968). The trend of basalt covered area coincides with the trend of *Sirhan* depression and indicates that the extension of *Sirhan* depression is to be found under JD basalts.

Mafraq's main aquifer is the B2/A7 composite aquifer generally overlain by basaltic rocks of significant thicknesses considered as the upper aquifer (Figure 5). *Basalts* play an excellent role as aquifers and as filter media for water that infiltrates and percolates through them down into the B2/A7 aquifer, through joints and fractures. The basalt aquifer covers about 78% of *Za'atri* area and builds the major aquifer in NE part of *Badia* area with a total thickness of up to 550 m mainly consisting of limestone and some marl intercalations belonging to the most *Upper Cretaceous* rock sequences. High thicknesses of basalts occur in areas close to the northern borders of Jordan, especially in the area extending from *Um al Jemal* and eastwards. Basalts overlie the B2/A7 aquifer and possess much higher permeability of the B2/A7. Unfortunately, its salinity and nitrate content have increased over the past two decades due to overexploitation and intensive irrigation in the *Badia* region.

Porosity of the basaltic rocks varies very strongly from one place to another and from one type of basaltic rock to another and ranges from 5-50% but the effective porosity is around 1% (BGR 1996). Permeability exceeds in some places 10^{-2} m/s (WAJ files, Gibbs 1993) depending on type of basaltic rock such as solid basalt, scoria, tuff etc. Wells yields are generally very high where the basaltic aquifer is saturated. Basaltic rocks are generally not saturated with water and lie in the phreatic zone of the composite aquifer consisting of *Basalts*, *Amman and Wadi Sir* formations.

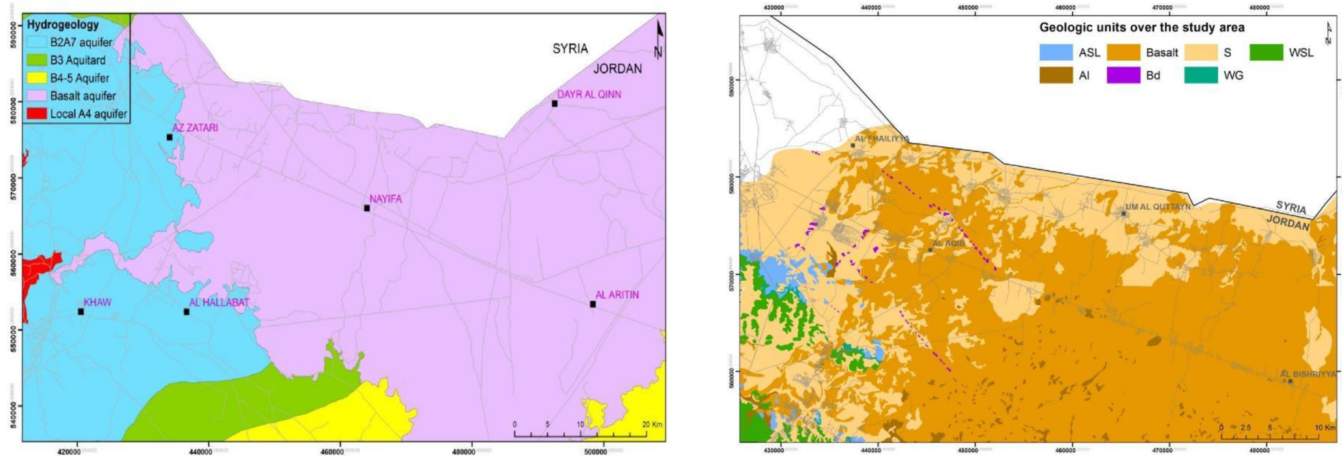


Figure 5. Hydrogeological settings (left caption) and geological map (right caption) for Mafraq (NRA 1:50000)

Only in the eastern and northern parts are the lower parts of the basaltic rocks which directly overlie older aquifers saturated with water. Therefore, the permeability and porosity of the basalts cannot directly be correlated with well productivities. But the porosity and permeability serve as a factor enhancing and speeding up of infiltrating recharge water to reach the groundwater table.

The thickness of the *B2/A7* composite aquifer increases from S to N. The base of the *B2/A7* is low in E (-100 m asl near *Um al Quttein*) and in the area along the NW border, where rocks dip steeply towards north. The *A1* to *A6* (*Na'ur*; *A1*, *Fuheis*; *A2&3*, *Hummar*; *A4* and *Shueib*; *A5&6*) formations consist of marl, limestone shale and dolomite, and form a poorly developed aquifer complex with very limited porosities and permeabilities, hence their very low potential as aquifers. The underlying Lower Cretaceous sandstone (*Kurnub*) consists mainly of sandstone beds intercalated by thin layers of marl and limestone and forms a good aquifer, but its great depth of more than 1,000 m and its very low water replenishment potentials make it practically an irrelevant source for water supply. The thickness of the *Kurnub* aquifer in the area is around 600 m with a general groundwater movement towards the west (the discharge area).

As a conclusion, it can be stated that the *Amman-Wadi Sir* composite aquifer is the main groundwater aquifer in Mafraq. Before the eruption, this aquifer overlying basaltic rocks was exposed to strong erosion and karstification processes, which is reflected in its high porosity and permeability. Erosion of the top of the *Amman-Wadi Sir* aquifer before the volcanic eruptions reduced its thickness by different degrees in its different outcrop areas.

The area served since the 1980s as agricultural development area where agriculture has rapidly spread during the past 30 years. The high precipitation rates over the highlands of *Jebel Druze* area result in high local recharge mound due to the highly fissured basalts covering the area. This recharged water flows then radially towards all the surrounding areas. One main groundwater flow is directed towards the Azraq depression and another one is directed towards the Yarmouk Valley, where the B2/A7 aquifer discharges through springs such as *Hammeh*. Another local recharge mound is found in the north-eastern part of the *Amman-Zarqa* area, southwest of the study area from where a groundwater flow is directed towards the south of the study area, from where the groundwater flows towards *Zarqa river*. A groundwater flow map was prepared by the BGR (2013) for the major aquifers in the study area. It shows that the groundwater flows from *Jabal Druz* basaltic area radially towards the surrounding areas. This map was updated for the year 2017 to show similar trends but with 5 to 15 m lowered head (Figure 6).

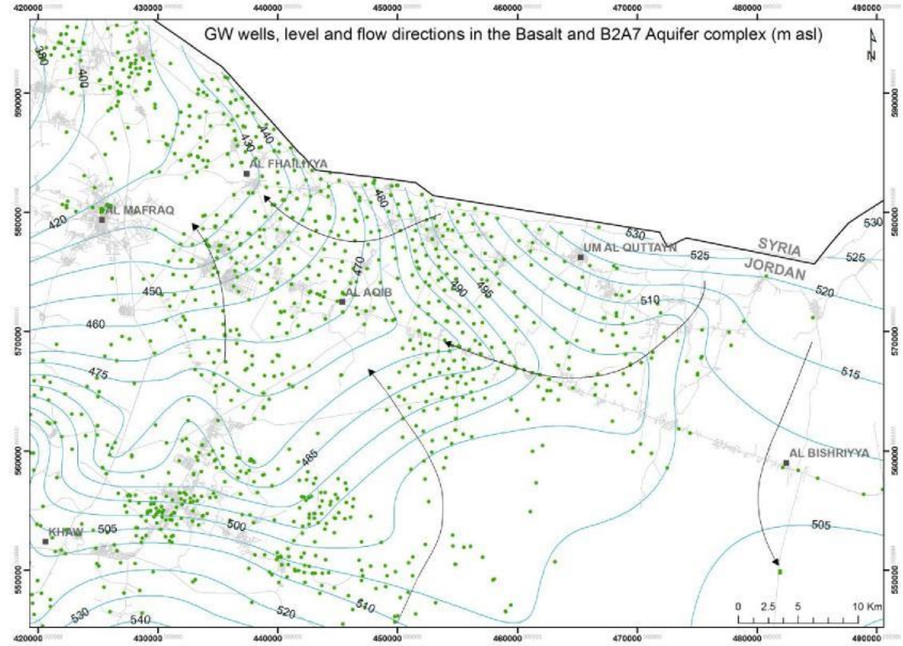


Figure 6. Groundwater flow pattern in the upper aquifer in Mafraq area

4. Agricultural baseline

4.1. Crop type mapping

The Ministry for Water and Irrigation (MWI) crop type map of 2013 (Bakri et al., 2013; WISP Project of GEF-WB-NASA Earth Science Lab.) was updated using Landsat 8 Operational Land Imager (OLI)/Terra 30-m resolution images (acquired from USGS, http://earthexplorer.usgs.gov/) covering Azraq District and Mafraq governorate in Northern Jordan for the 2017-2018 season. Cloud-free images were selected using F mask algorithm of Zhu and Woodcock (2012) in ESRI ArcGIS 10.3 software. Landsat 8 visible and near infrared bands were staked and geometrically corrected using a third order transformation model to clip borders of the studied areas based on Ground Control Points (GCPs) data collected from handheld 3-m accurate GPS devices at road crosses locations. NDVI values were calculated from the atmospherically corrected B4 and B5 bands using Spectro-radiometers. Crop types were ground-truthed using handheld GPS and NDVI timeseries were produced.

The results showed that the total irrigated area equals 4,738 and 10,617 ha in Azraq and Mafraq, respectively (Table 3). Grown area equals irrigated area as no possible rainfed production is achievable based on low precipitations recorded of about 115-140 mm/yr). Azraq is mainly grown in olive trees (1,750 ha), mixed alfalfa-Olives and alfalfa standing alone. In Mafraq, results showed that stone fruits are the major crops with 4,635 ha (37% of the total irrigated area). The second largest crop in Mafraq is olives with 3,968 ha, then vegetables are grown over 1,383 ha. It was noticed that Alfalfa farming is not practiced in Mafraq and that stone fruits are limited to Mafraq with no records in Azraq (Figure 7).

Table 3. Area of irrigated crops in Azraq district and Mafraq governorate.

	Area grown per intervention zone (ha)	
Crop	**Azraq**	**Mafraq**
Olives	1,750.422	3,967.836
Stone Fruits	0	4,634.964
Mixed	1,362.672	444.420
Alfalfa	990.014	0
Vegetables	218.630	1,383.585
Date palm	186.361	0
Grapes	125.484	132.260
Pomegranate	104.392	53.628
Total	**4,737.975**	**10,616.694**

Cropping pattern mapping in Azraq showed an intense pattern in the central part of the basin East of Azraq city where medium and large size and new farms are dominating the landscape. Within this area, depth to groundwater is low and pumping cost is accordingly less, making the area more suitable for irrigation and growing profitable agribusinesses with prevailing olive trees and alfalfa. Both crops are practiced at different scales from subsistence smallholders farming system in Azraq to profitable large agribusiness in Eastern Azraq.

Agricultural practices in Mafraq take place along the main road where the B2/A7 Basalt aquifer complex has high pumping yield and good water quality. The B2/A7 Basalt aquifer supports irrigation and drilling municipal wells that supply cities with fresh drinking water. Stone fruits and olives are grown in both smallholder farms in Northern Mafraq on the Syrian border and in medium to large size farms spread all around the governorate showing a possible agricultural expansion during fruit and olive oil market demanding period of the early 2000s.

4.2. Net crop water requirements estimating minimum groundwater abstraction

Daily weather data acquired from MWI were used to estimate reference ET (http://www.fao.org/land-water/databases-and-software/eto-calculator/en/) and to calculate actual evapotranspiration for the studied crops according to FAO56 formalism using average crop coefficient (Kc from standard stable). Start of season and end-of season for individual crops were obtained from MWI field data. Crop water requirements were calculated using ETc values corrected by irrigation efficiency coefficient.

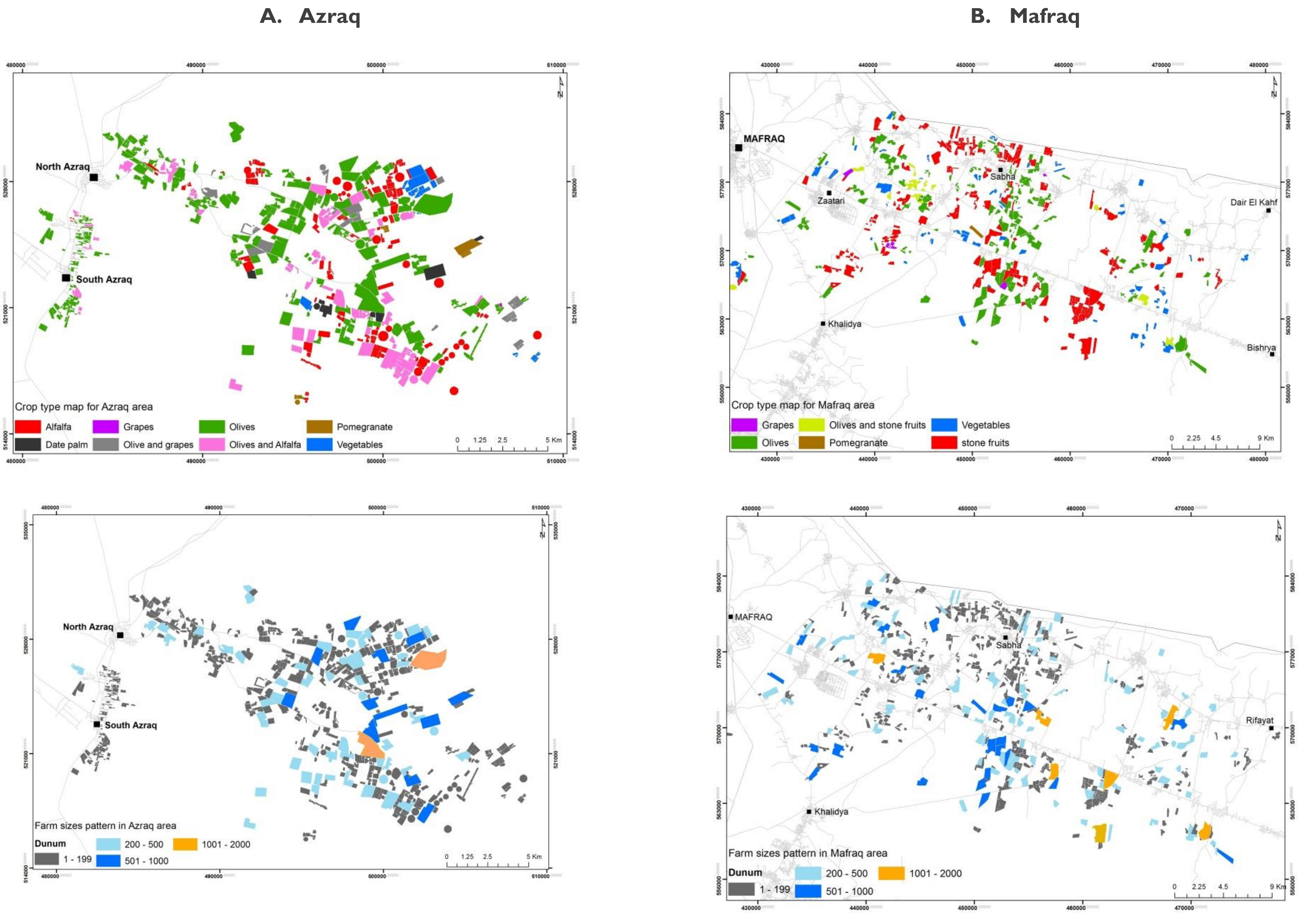


Figure 7. Updated crop type (above) and farm size (below) maps: A. in Azraq district; B. in Mafraq governorate, using Landsat 8 images for 2017-2018 season.

Net crop water requirements were higher in Azraq area as weather conditions are characterized by a higher air temperature than Mafraq by 1-2 degrees in average and lesser precipitations and air relative humidity (Table 4). ETo values were found to be 1,619 mm/yr in Azraq and only 1,317 mm/yr in Mafraq. The highest ETc values were recorded for Alfalfa (1,518 mm/yr) that is grown only in Azraq district. ETo and ETc values of the present study were close to MWI values. Annual cumulative evapotranspiration was similar for seasons 2012-13 and 2017-18, assessed by MWI and the present study, respectively. Actual ET values for fruit trees were 180 mm/yr higher in Azraq than Mafraq, however ET values displayed no significant difference for the remaining crops. For MWI data all ETc values, except for vegetables, were 250-330 mm higher in Azraq compared to Mafraq. This could mean that the sensitivity of the model used by MWI is higher than ours. However, when comparing these findings to Wim Bastiaanssen data on the year of record drought of 2013-14, ETo is 30% higher, while ETc data is 20% lower which can be due to different crop type mapping results.

Table 4. Monthly reference evapotranspiration (ETo in mm, from MWI weather station data) and actual evapotranspiration (ETc in mm, using average Kc from FAO56) for main olives, fruit trees (stone fruits, grapes, pomegranate and palm dates), alfalfa and vegetables in Azraq and Mafraq, Jordan.

	ETo		**ETc Olives**		**ETc Fruit trees**		**ETc Alfalfa**		**ETc Vegetables**	
Month	**Azraq**	**Mafraq**	**Azraq**	**Mafraq**	**Azraq**	**Mafraq**	**Azraq**	**Mafraq**	**Azraq**	**Mafraq**
Oct	116	94	43	67	68	61	108	-	86	93
Nov	66	64	29	35	22	10	59	-	0	0
Dec	31	51	8	3	0	0	36	-	0	0
Jan	48	71	11	25	0	0	46	-	0	0
Feb	71	72	16	38	0	0	82	-	28	0
Mar	95	122	32	46	46	49	82	-	36	35
Apr	156	128	64	68	104	90	145	-	87	134
May	171	166	97	73	102	77	153	-	105	103
Jun	197	145	114	91	156	130	184	-	108	92
Jul	266	154	126	95	193	139	248	-	123	86
Aug	238	142	92	81	143	114	222	-	120	78
Sept	164	108	68	67	81	76	152	-	76	60
Total	**1,619**	**1,317**	**700**	**689**	**915**	**744**	**1,518**	**-**	**769**	**681**
MWI	1,586	1,311	915	673	1,076	742	1,484	-	494	494
Wim	2095		472	669	648	758	988	-	360	336
MB.	2,095		975	830	1,350	1,125	1538		-	-

Note that other crop type classes CWR were provided by ICBA.
MWI, Ministry of Water and Irrigation data of 2013.
Wim, Data of 2014 using SEBAL runs outputs;
MB, average Azraq-Mafraq potential ET estimated by Makram Belhaj Fraj under no limiting conditions with Kc estimated based on average crop phenology, fraction ground cover (35-40%) and wetting fronts (2.6 to 7 m^2 per tree for stone fruits and olives, respectively) of prevailing irrigation systems efficiency (60-70%) and water salinity (15% leaching fraction) for the dry year of record 2014: Belhaj Fraj and Bergaoui (2019).

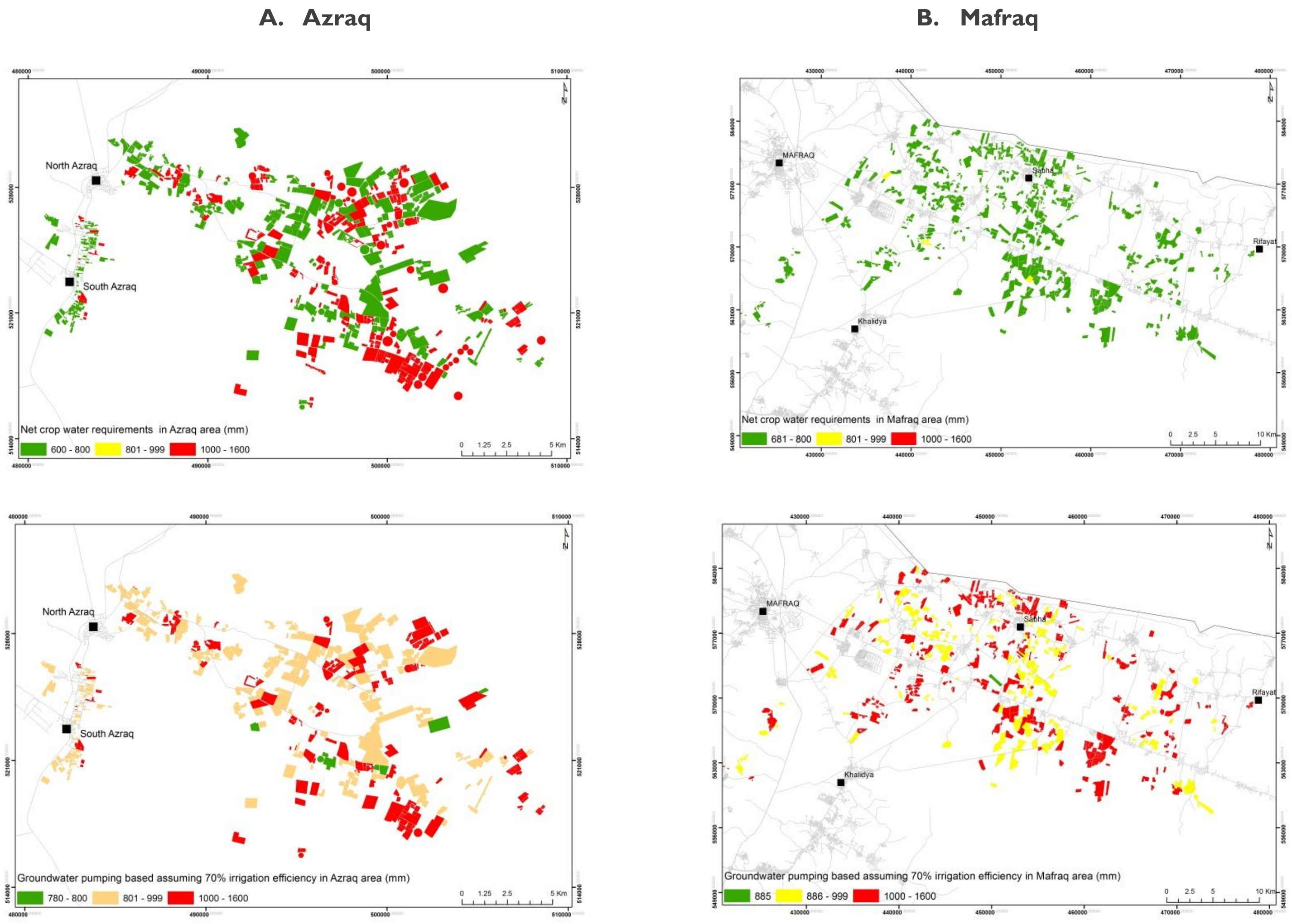


Figure 8. Net crop water requirements (estimated using MWI weather station data and average Kc from FAO56 standard table) and estimation of groundwater pumping based assuming 70% irrigation efficiency: A. in Azraq district; B. in Mafraq governorate, using Landsat 8 images for 2017-2018 season.

Makram Belhaj Fraj et al. (2018) assessed data from Wim Bastiaanssen (2015) in relation of crop phenology and used potential ET data under no-limiting conditions in geo-localized fields to reduce errors due to crop type classification and found ETc values to be 100-150 mm higher in Azraq than Mafraq despite the highest planting densities in Mafraq than Azraq. Potential ET data was used to provide irrigation hardware suppliers with maximum crop type requirements for designing their irrigation systems to face peak water demand in case of dry season. However, in the present, data represents average condition of evapotranspiration for estimating average groundwater abstraction in Azraq and Mafraq areas (Figure 8).

4.3. Empirical estimation of groundwater abstraction using estimates of over-irrigation: irrigation efficiency and water audit data

Estimating groundwater abstraction for irrigation purposes is the task of Water Authority of Jordan (WAJ-ROs Office). Over the last 30 years, groundwater abstraction was estimated using water meter readings. In case of lack of monitoring wells or low meters reliability, WAJ staff estimates abstraction based on their field experience and crop requirements. MWI observed massive decline in water level that depends on irrigation and municipals wells pumping for drinking purposes (unknown data). Using statistics of grown area in prevailing crop types and net crop water requirements, the estimated groundwater abstraction is at minimum about 49 and 80 MCM/yr for Azraq and Mafraq, respectively (Table 5).

The total CWR (under 70% irrigation efficiency) was estimated to be 64 MCM/yr in Azraq (against 24 MCM/yr in Wim study showing similar area grown) and 104 MCM/yr in Mafraq (against 92 MCM/yr in Wim study, with 6,726 ha higher area grown) distributed as shown in Figure 7. We are not yet showing net groundwater use in this section. Note that Wim Bastiaanssen estimated groundwater recharge of 30% while it was estimated by MWI to be 8-12% only.

Water audits performed in 100 farms in both areas showed that total groundwater abstraction reaches 358.3 MCM with abstractions of 107.6 and 250.74 MCM/yr in Azraq and Mafraq, respectively. This means that irrigation efficiency does not exceed 36%, while it was generally assumed to be 70% in most of the previous studies. The water audit report of Belhaj Fraj et al (2018) reporting results of 200 farms shows that the existing open tube and super jet irrigation systems have efficiencies varying from 30 to 60%.

Table 5. Estimation of crop water requirements, water use and irrigation-based groundwater abstraction using net crop water requirements, irrigation efficiency factor and water audit results in Azraq and Mafraq.

		Crop water requirements and use (in mm/ha/yr)			Groundwater abstraction (MCM/yr) based on:		
Crop	**Area grown (ha)**	**Net CWR**	**IE-CWR**	**Actual water uses from water audit**	**CWR**	**IE**	**WA**
Mixed	1,362.672	1,225.00	1592.50	2,300.00	16.69	21.70	31.34
Olives	1,750.422	700.00	910.00	1,574.00	12.25	15.93	27.55
Alfalfa	990.014	1,518.00	1973.40	4,000.00	15.03	19.54	39.60
Grapes	125.484	1,100.00	1430.00	1,676.00	1.38	1.79	2.10
Pomegranate	104.392	800.00	1040.00	1,200.00	0.84	1.09	1.25
Vegetables	218.630	769.00	999.70	800.00	1.68	2.19	1.75
Date palm	186.361	600.00	780.00	2,133.00	1.12	1.45	3.98
Total Azraq	**4,737.975**	**-**	**-**	**-**	**48.99**	**63.69**	**107.57**
stone fruits	4,634.964	794.32	1032.62	3,300.00	36.82	47.86	152.95
Olives	3,967.836	689.35	896.15	1,880.00	27.35	35.56	74.60
Vegetables	1,383.585	769.57	1000.44	1,000.00	10.65	13.84	13.84
Mixed	444.420	815.00	1059.50	1,200.00	3.62	4.71	5.33
Grapes	132.260	823.51	1070.56	2,715.00	1.09	1.42	3.59
Pomegranate	53.628	681.04	885.35	800.00	0.37	0.47	0.43
Total Mafraq	**10,616.694**	**-**	**-**	**-**	**79.89**	**103.86**	**250.74**

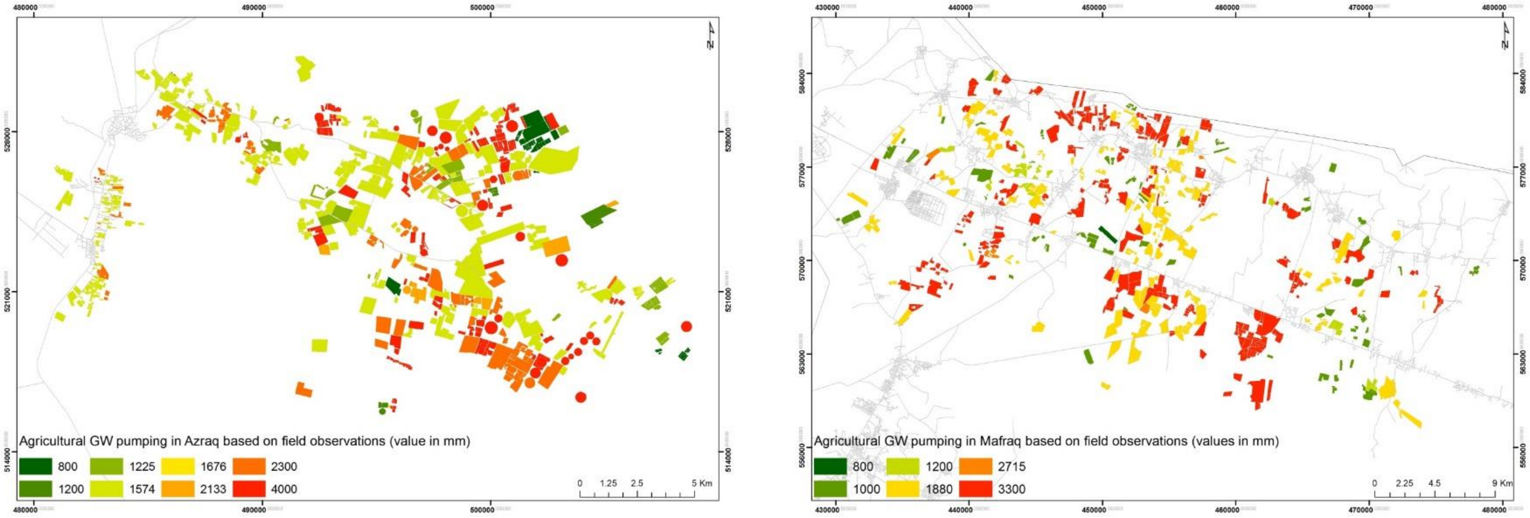
CWR, crop water requirement estimated using MWI weather station data for calculating ETo and average Kc from FAO-56 standard table.; Net CWR, net crop water requirements; IE, 70% irrigation efficiency; WA, water audit conducted in 100 farms in 2018.; WA, water audit achieved in 100 farms in 2018.; IE-CWR, Crop water requirements calculated using an irrigation efficiency factor.

4.4. Groundwater abstraction under various scenarios of adoption of water saving technologies

Total number of medium size farms were identified to be 648 out of 1,100 licenses for farming in both areas. These farms were targeted by WIT project as the profitable ones, according to the Ministry of Agriculture (MoA). These farms accounts for 365 farms in Azraq (mainly olives plantations, mixed systems and alfalfa) with average size of 22.9 ha, and 283 in Mafraq (mainly stone fruits, olives and vegetables) with average size of 34.2 ha. This information needs to be verified using proper cadaster data from MoA. Total groundwater abstraction by profitable farms is about 42 and 87 MCM/yr out of 64 and 104 MCM/yr all crops included, in Azraq and Mafraq, respectively. As the water audit data used covers only 100 farms and the used over-irrigation rate is accounted as average, at this first phase of the study the final figures of groundwater abstraction are based on crop water requirements corrected using an irrigation efficiency factor of 70%. Simulating changes in groundwater abstraction in response to the adoption of irrigation water saving technologies in Azraq and Mafraq (under an assumption of no change in crop type patterns) showed that for the scenario where water innovation technologies are introduced in 20% of the orchard farms covering more than 200 dunams, with savings of 50% on average, groundwater abstraction will be reduced in total by 12.9 MCM/yr (4.2 and 8.7 MCM/yr saved in Azraq and Mafraq, respectively, Figure 9).

Groundwater abstraction in Azraq (mm/yr)

Groundwater abstraction in Mafraq (mm/yr)



Percent over-irrigation in Azraq

Percent over-irrigation in Mafraq

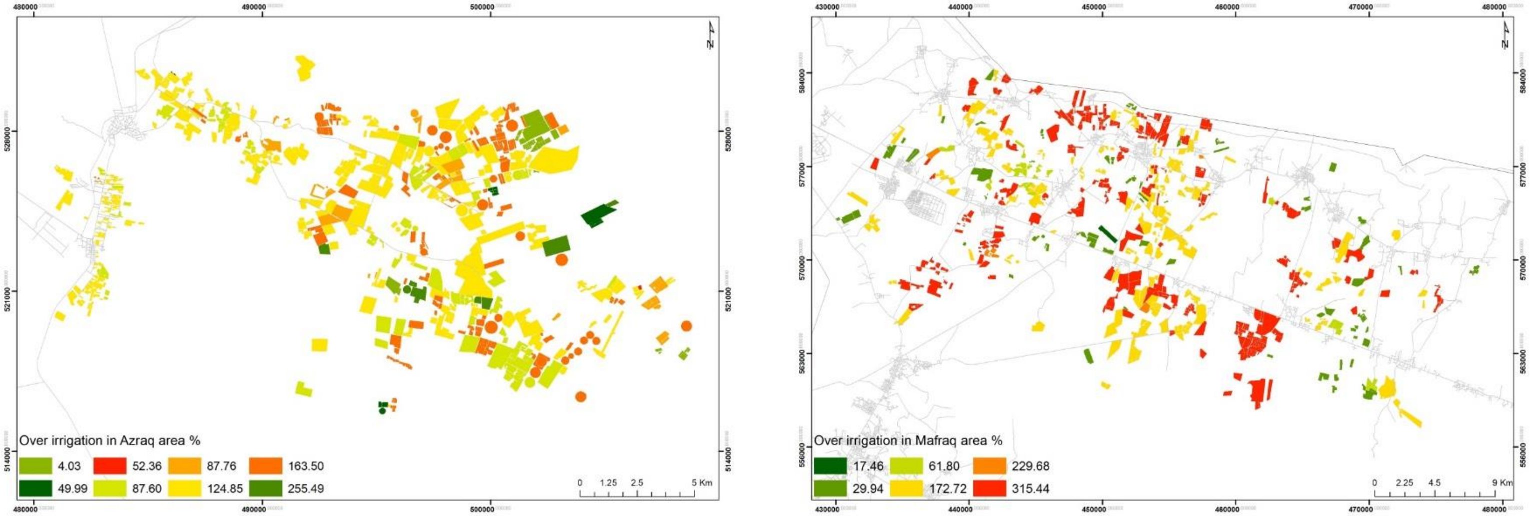


Figure 9. Maximum agricultural groundwater abstraction estimated using average water use per crop type from the water audit study (Belhaj Fraj and Hammami, 2018), and consequent over-irrigation maps showing hotspots of over-irrigation in Azraq district and Mafraq governorate, respectively.

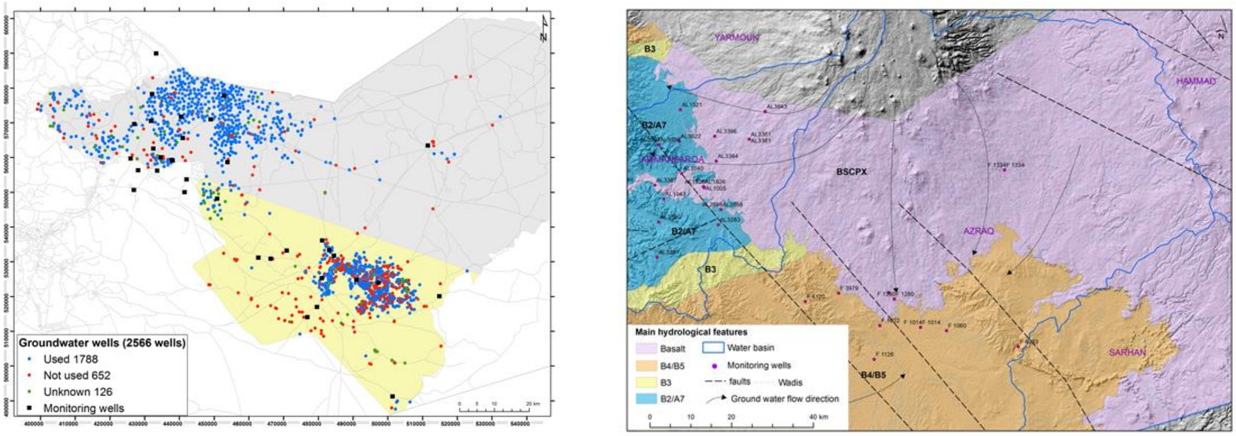
Whereas, scenario C of adoption in all orchards targeted by the project, with water use reduction by 50% due to irrigation hardware (optimized irrigation scheduling practices not accounted), on average saves 32.25 MCM/yr (10.5 and 21.75 MCM/yr saved in Azraq and Mafraq, respectively). Under climate change scenario and if we continue the business as usual, groundwater would reach 200 MCM/yr which constitutes a real threat on the aquifer and farming sustainability.

5. Groundwater Modeling

5.1. Model setup

Due to the limited number of pumping tests, only few transmissivity (T) values of wells are found in the Drilling Department of WAJ. However, pumping water levels are taken by WAJ for most wells at the time of completion. *Amman-Zarqa* area contains about a quarter of all wells in Jordan since there are 1,872 wells in this basin (3,080 km^2, i.e. 3.4% of Jordan's land surface), and more than half of these wells exist in the studied area.

We generated a mosaic of the existing geological maps at scale 1:50,000 based on surface geology and corresponding hydrogeological units (first model layer, Figure 10) with major faults (structural offsets of much more than 200 m) in the modelled area (according to the BGR reports, Margane and Hobler, 1994). The faults include *Aljun dome* North of the *Zarqa river* bounded by flexures, *Sirhan* as the most important fault zone in Azraq, the *Hamza Graben* that is bounded in the East by the *Fuluq fault* and a parallel counterpart west of the graben, in addition to several small faults over distances of some kilometers but with small offsets.



Governorates partition and wells

Hydrogeological units

Figure 10. Project intervention area: administrative divisions, hydrological units and groundwater wells.

Factors affecting recharge include precipitation, topography, and soil cover. As there are no site-specific recharge studies, we used J2000 water balance model (connected to GIS environment) for recharge calculation over macro-catchment areas (Healy, 2010). Within J2000 system, simulation of hydrological processes is carried out in an environment where parameters of water balance are independent of each other and are calculated separately, then simulated to calculate recharge (Figure 11).

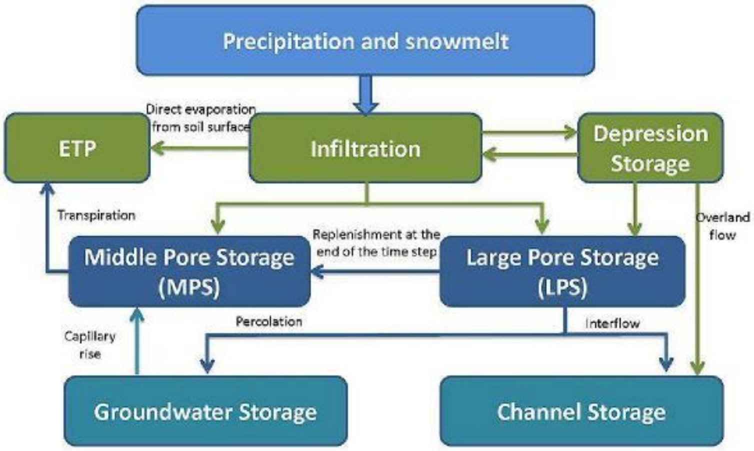


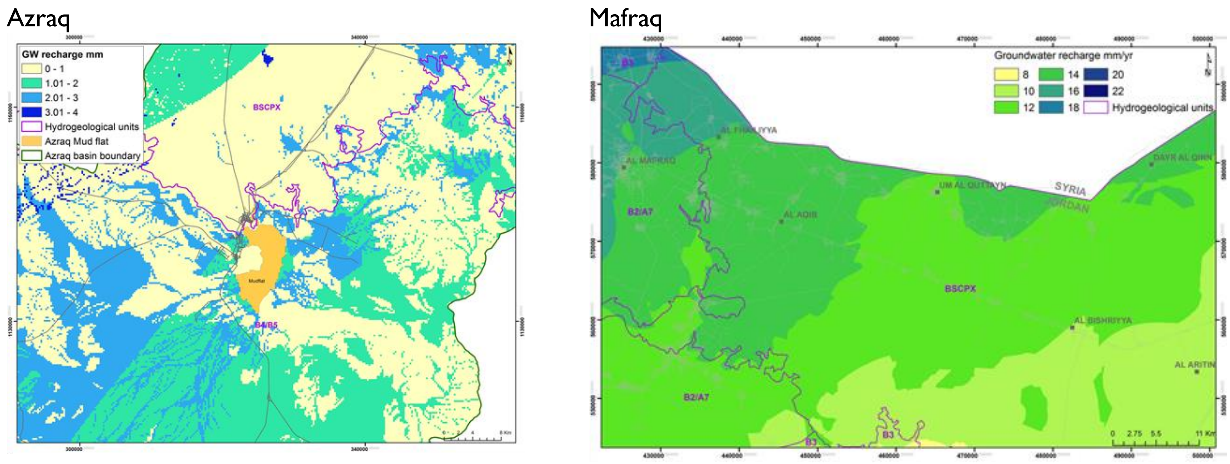
Figure 11. Concept of the J2000 model for water balance calculation at (after Krause 2001)

The groundwater system receives its input from the unsaturated soil zones that differ in thickness and hydraulic properties. The recharge process starts after the soil column is saturated. J2000 model calculates the soil water storage (Kralisch et.al. 2007) with an onset of maximum infiltration rate functions. As this onset is crossed, the surplus water takes two paths: to be delivered to the groundwater system or to be stored in depressions such as drainage ditches.

Changes in soil water storage were calculated by using the soil module with soil physical and hydraulic parameters of all the soil units and types represented by soil pore volume classified as fine (neglectable with minimum water movement), middle (stored water that is extractable water using suction potential for evapotranspiration) and coarse (macro-pores percolating water for recharge and channel storage) (Scheffer & Schachtschabel 1984, hydraulic parameters shown in Annex 1). Soil module input variables include soil type, depth, range of permeability coefficient and depth of the horizon above the horizon with the smallest permeability coefficient from USAID-MWI Soil mapping project (1995). This work provides an acceptable data coverage in north Jordan with lower resolution in Azraq area. Average soil thickness was found to be 62 cm in Mafraq while it goes up to more than 80 cm in Azraq area. This can be justified by the flat topography of Azraq which holds more soil with less erosion. Another factor is the soil source-rock. In Mafraq, Basaltic flows are with less erosion rates and hence soil formation is lower. The lime stone of Azraq is more vulnerable to erosion.

Runoff Curve Number method (Hjelmfelt, 1991; SCS, 2004) was used to calculate runoff by using data from six gauging stations for more than 146 runoff records. Upstream gauging stations provided precipitation records for 1970-2017 period. These records were plotted versus the generated runoff recorded at the gauging station giving an average runoff coefficient of 5.8% and 4.6% of the total rain in Mafraq and Azraq respectively.

Recharge is distributed as zones reflecting the amount of rainfall in each zone. The maximum amounts are found in NW parts of Mafraq while in Azraq maximum recharge is taking place along the wadi systems due to a higher hydraulic conductivity (Figure 12).


Azraq

Mafraq

Figure 12. Modelled groundwater recharge in Azraq and Mafraq areas

The groundwater modeling was conducted using the MODFLOW (USGS modular three-dimensional finite-difference groundwater flow code, McDonald and Harbaugh, 1988, and Harbaugh and McDonald, 1996) and the graphical interface Model-Muse (Winston, 2009) that runs at daily basis with horizontal grid block dimensions of 30 m x 30 m and vertical discretization for one layer of variable thickness (ranges from 50 m to 700 m). Head measurements are given in meter above mean sea level, hydraulic conductivity values are in meter per day (m/d), and flow values are reported in cubic meter per day (m^3/d).

The stratigraphic settings were derived from BGR cross-sections and isopach maps of all the geological formations (Isopach maps 1.1 to 1.16, Volume 3, Part 2; Appendix 1, Margane and Hobler, 1994). Fence diagram of all boreholes and cross-sections is shown in Figures 13-14.

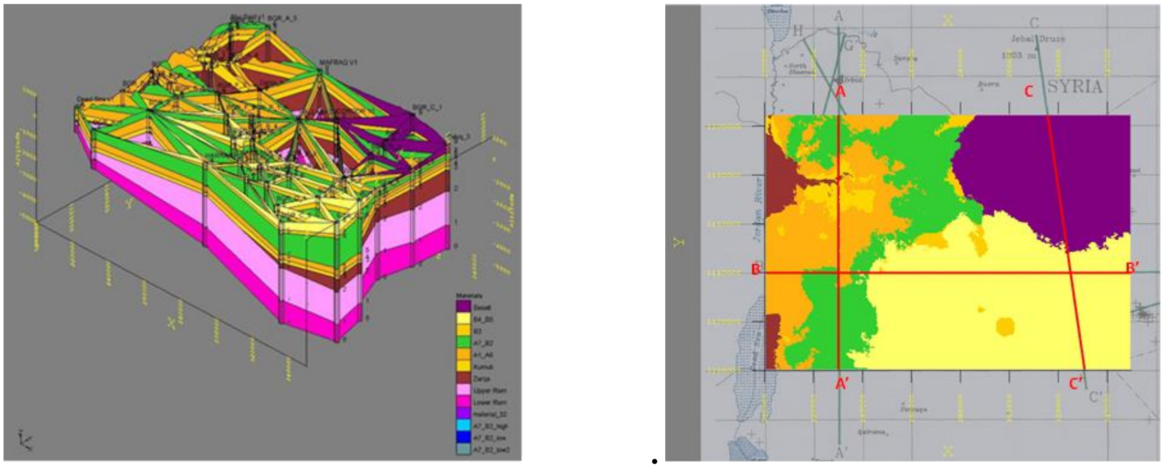


Figure 13. Fence diagram (ledt caption) and positions of the cross-sections (right caption) for Azraq and Mafraq areas (MWI, 2011)

Model layers are mapped to different hydrogeological formations using equivalent parameter values to separate the choice of number of model layers from number of hydrogeological formations. Simulations include recharge, evaporation and evapotranspiration, extraction by wells and relation to the surrounding aquifer systems.

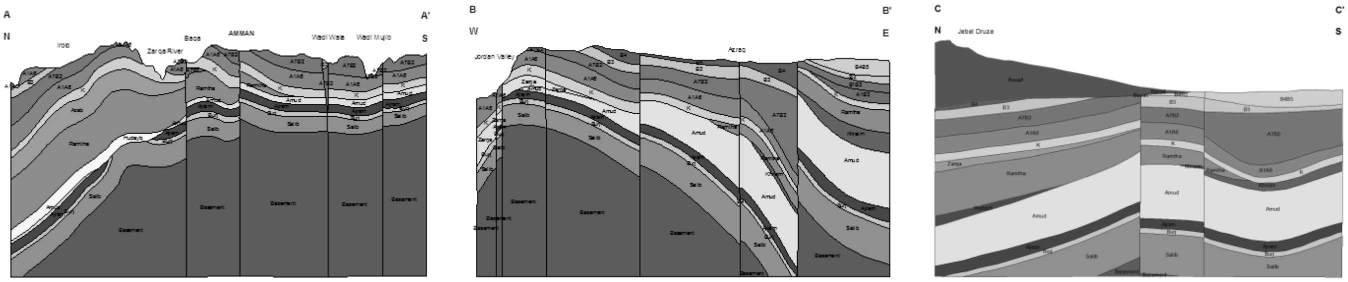
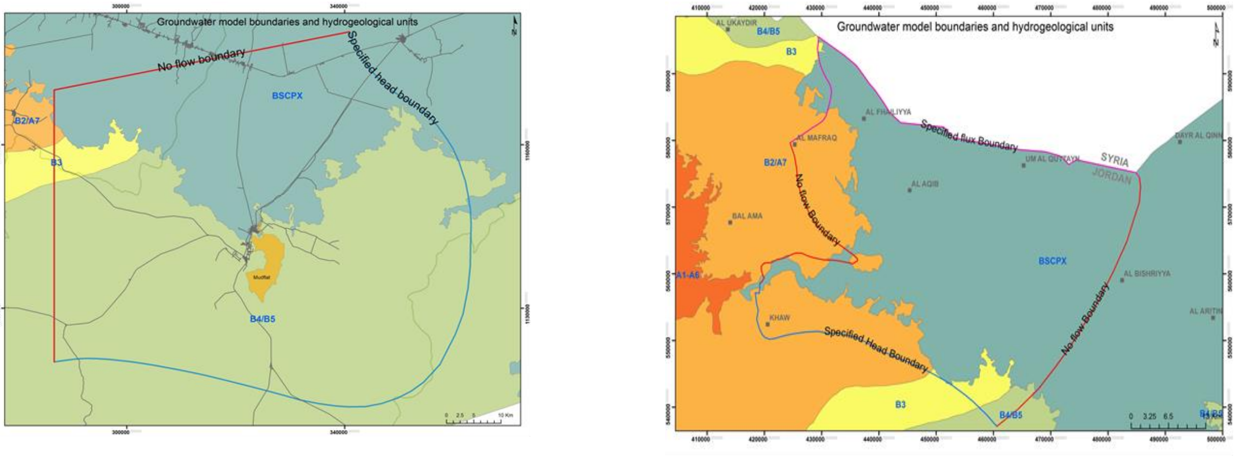


Figure 14. Geological cross-sections AA', BB' and CC' (left, middle and right caption, respectively) for Azraq and Mafraq areas (BGR, 1994)

Available pumping tests were analyzed using AquiferTest 3.5. The drawdown in the pumping well is compared to analytical drawdown for confined (Theis equation) and unconfined (Neuman equation) aquifers, with parameters adjusted to provide the best fit. Comparison of fitted drawdown curves allows the choice of hydrogeological condition and hydraulic conductivity was selected.

Boundary conditions were set according to the geological model constructed previously and available time series water level measurements close to the boundaries (Figure 15). Western and Northern boundaries of Azraq groundwater model were selected as no flow boundary, as both represent groundwater flow lines. The Northern flow line is generated due to high recharge rate from the Syrian parts of Azraq basin and represents part of the water divide with Amman Zarqa basin. Based on stable water level at the eastern and southern boundaries (no pumping) the boundary selected to be specified head boundary.



Azraq

Mafraq

Figure 15. Boundary conditions in Azraq and Mafraq.

5.2. Model calibration, parametrization and uncertainty

The model was initialized under steady state conditions of 1980, which represented conditions before substantial groundwater pumping, followed by a transient historical period simulation of 40 years during which historical groundwater diversions were applied. Data sets available for calibration include several time series of observed head values at different locations in the study area (subset of filtered head time series and head data collected by DAH in 2010), pumping test data (discussed earlier), and head data of around 400 wells collected from WAJ and MWI. The latter are single points in time which are generally ignored in transient calibration studies. Available time series have shown high degree of noise. Consequently, data filtering was necessary. Data were averaged per year, and any single year with less than four measurements or with high variance was ignored. The model was calibrated to observed water level data and estimates of discharge springs (in Azraq oasis during 80s) (Figure 16). Calibration was achieved using both trial-and-errors and automatic calibration (inverse problem) methods for the first aquifer in the first model layer. The first aquifer defined to be *B4 Basalt Complex* in Azraq and B2/A7 Basalt complex in Mafraq.

During the calibration process, the areas at the eastern parts were problematic with high differences due to absence of monitoring wells and the probable input flux from Syria. Several hypotheses were tested to get the best fit to available data, including varying influx rates slightly in order to achieve a better model calibration.

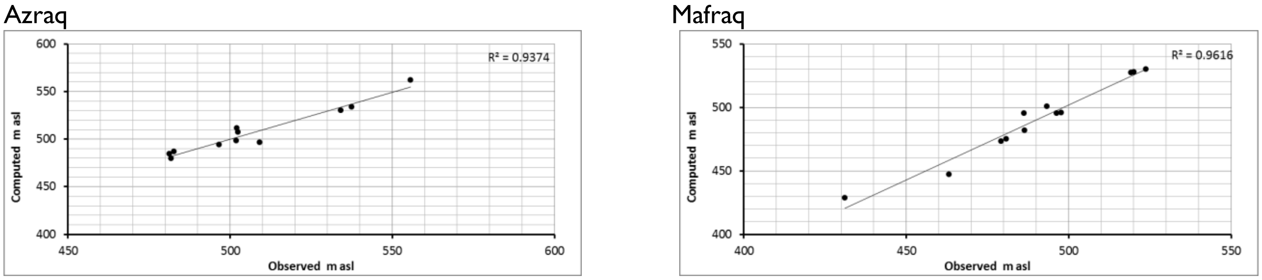
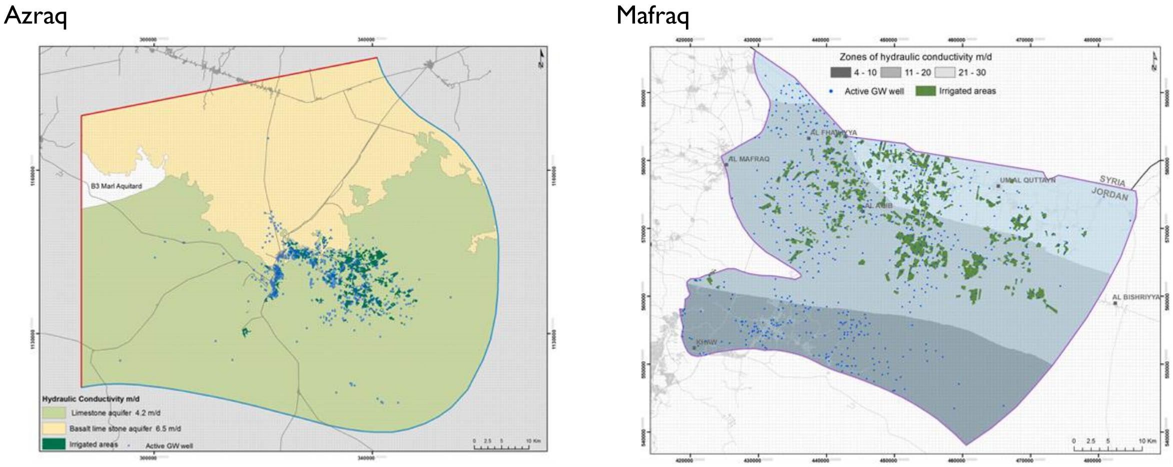


Figure 16. Computed versus observed head values of used head time series

Parameterization indicates how governing flow parameters would vary in space. It was here based on zonation that is used to map spatial variability of governing hydraulic parameters. Zonation method is based on surface geology, pumping wells density and observation data. It allows defining zones of uniform horizontal hydraulic conductivity and storage coefficients (automated calibration process using inverse problem solution). Some manual adjustments of other parameters (e.g., anisotropy factor) were also performed. Zones indicating uniform hydraulic parameters are chosen primary on surface geology, which were then subdivided according to the density of pumping wells, and finally available head measurements are used to discriminate among areas of different hydraulic parameters. Total number of zones defined was 2 zones for Azraq and 3 Zones for Mafraq. (Figure 17).


Azraq

Mafraq

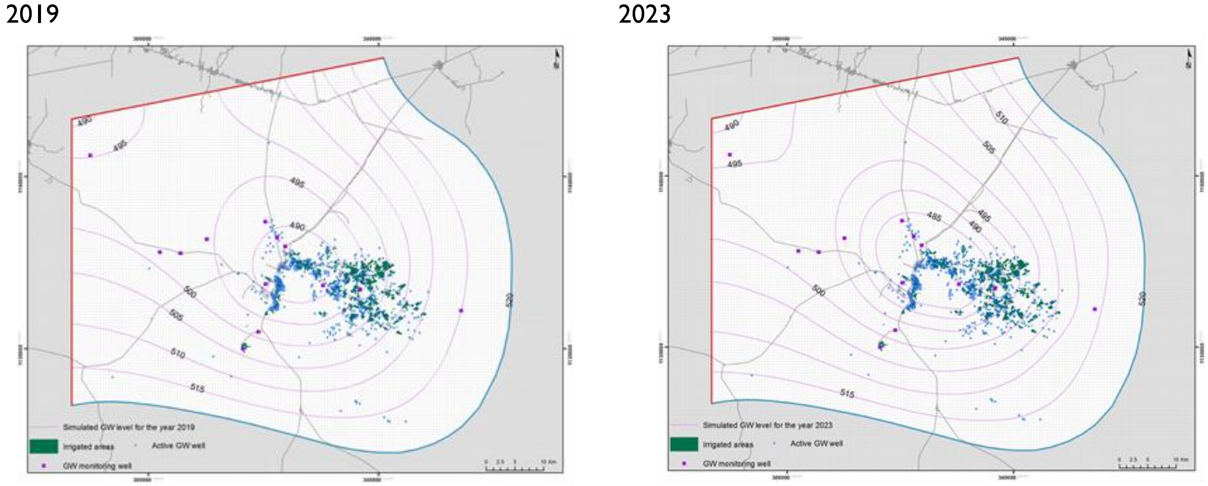
Figure 17. Distribution of hydraulic conductivity values in Azraq and Mafraq.

6. Simulation of impact of irrigation practices on groundwater abstraction and salinity

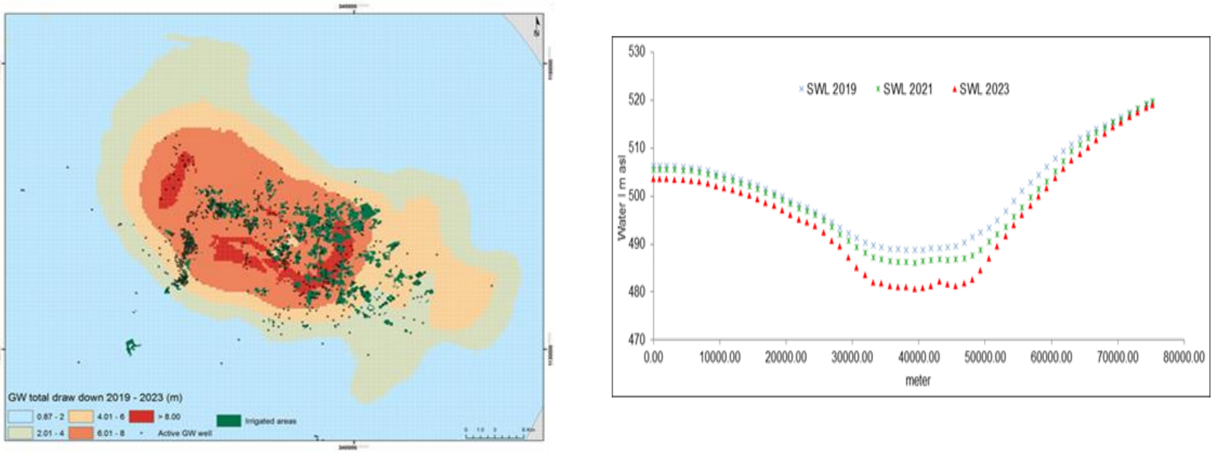
The calibrated model is used to forecast response of the groundwater flow system during 2019-2023 period. In this analysis, stages at the specified head boundaries are kept at their value of end of 2017 through the years of forecasting period. Abstraction rate of private and governmental wells were fixed while recharge rate is assigned the average value except for the last scenario.

6.1. What if irrigation practices do not change (baseline scenario)?

The first scenario, "Scenario A", here indicates keeping all, private and WAJ wells with their last recorded pumping rates at the end of 2017. Simulations were done for years 2019, 2021 and 2023 as per the WIT project duration. Simulations in Azraq showed that average drawdown will be 4.33 m for the period. The maximum drawdown of 8.79 m is expected in the central part of the basin due to excessive agricultural uses (Figure 18).


2019

2023



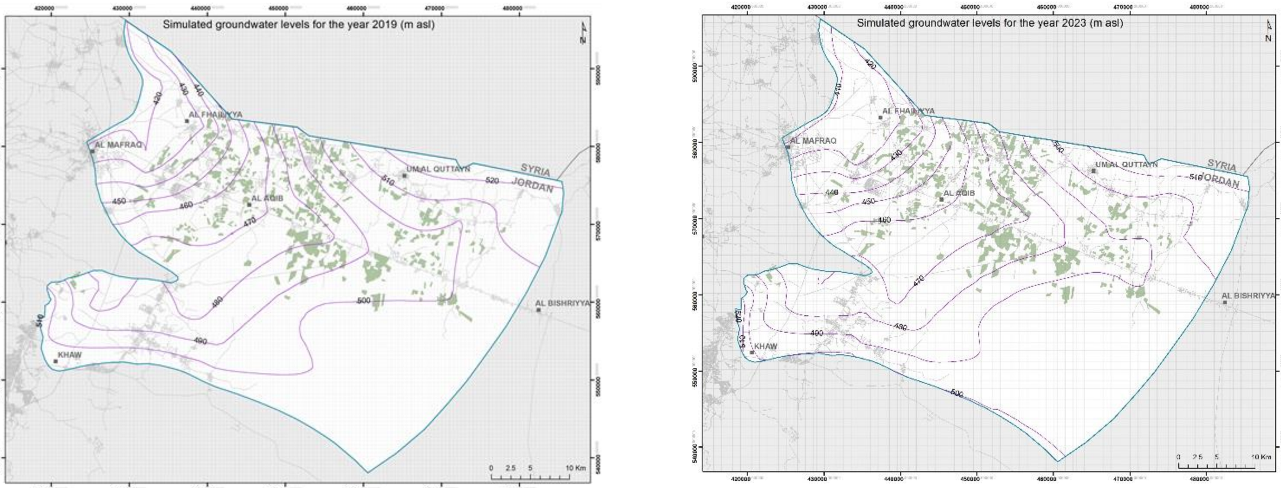
Total drawdown

Cross-section level

Figure 18. Simulated groundwater level and drawdown in total and on the Azraq cross-section under baseline scenario.

Simulations in Mafraq showed an average drawdown of 9.12 m for the period. The maximum drawdown of 14.21 m is expected along Baghdad road which is the area of highest agricultural and domestic pumping (Figure 19).

2019 2023



Total drawdown

Cross-section level

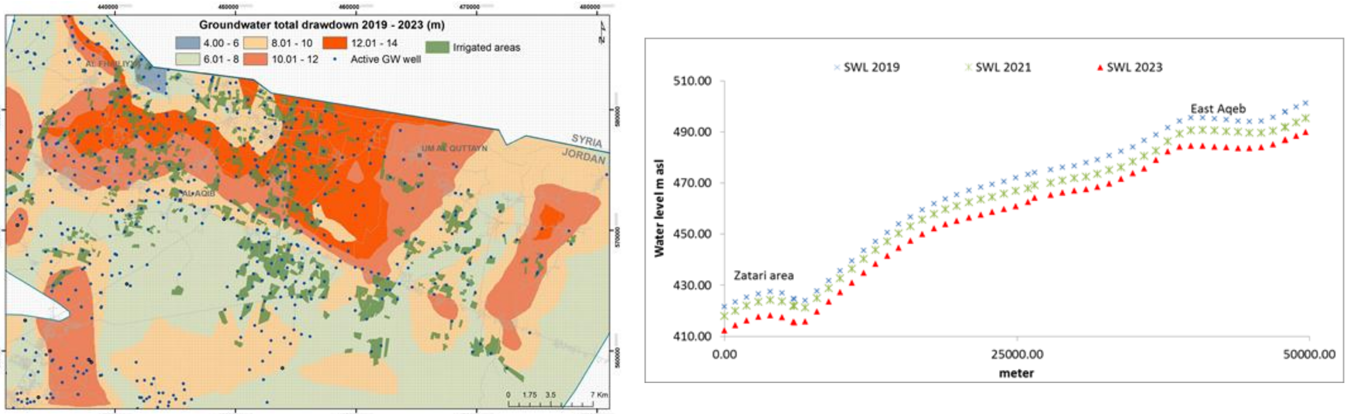


Figure 19. Simulated groundwater level and drawdown in total and on the Mafraq cross-section under baseline scenario.

Basic chemical analyses (EC, pH, Ca, Mg, Na, K, Cl, HCO_3, SO_4 and NO_3) were performed on 70 groundwater samples (38 in Azraq and 32 in Mafraq). EC is highly correlated to Mg, Na, K and Cl content (main salt evaporites, water-soluble mineral sediment that results from concentration and crystallization by evaporation from an aqueous solution). Ca is strongly correlated with Mg, which is also expected as they both are components of the $CaMg_2$ calcium magnesium compound. The Mg is also strongly correlated with Na, K, and Cl. This is also expected as the Mg forms the $MgCl_2$ hydrate in brines. There is also a strong correlation between Cl and k as they form the KCl salt. Na is strongly correlated with Cl implying the Halite (NaCl) dominancy in the system. Water is a good solvent for salts and rock forming minerals. The amounts and types of the dissolved constituents reflect the water quality which is the main factor for determining the groundwater uses and especially for domestic supply.

Azraq **Mafraq**

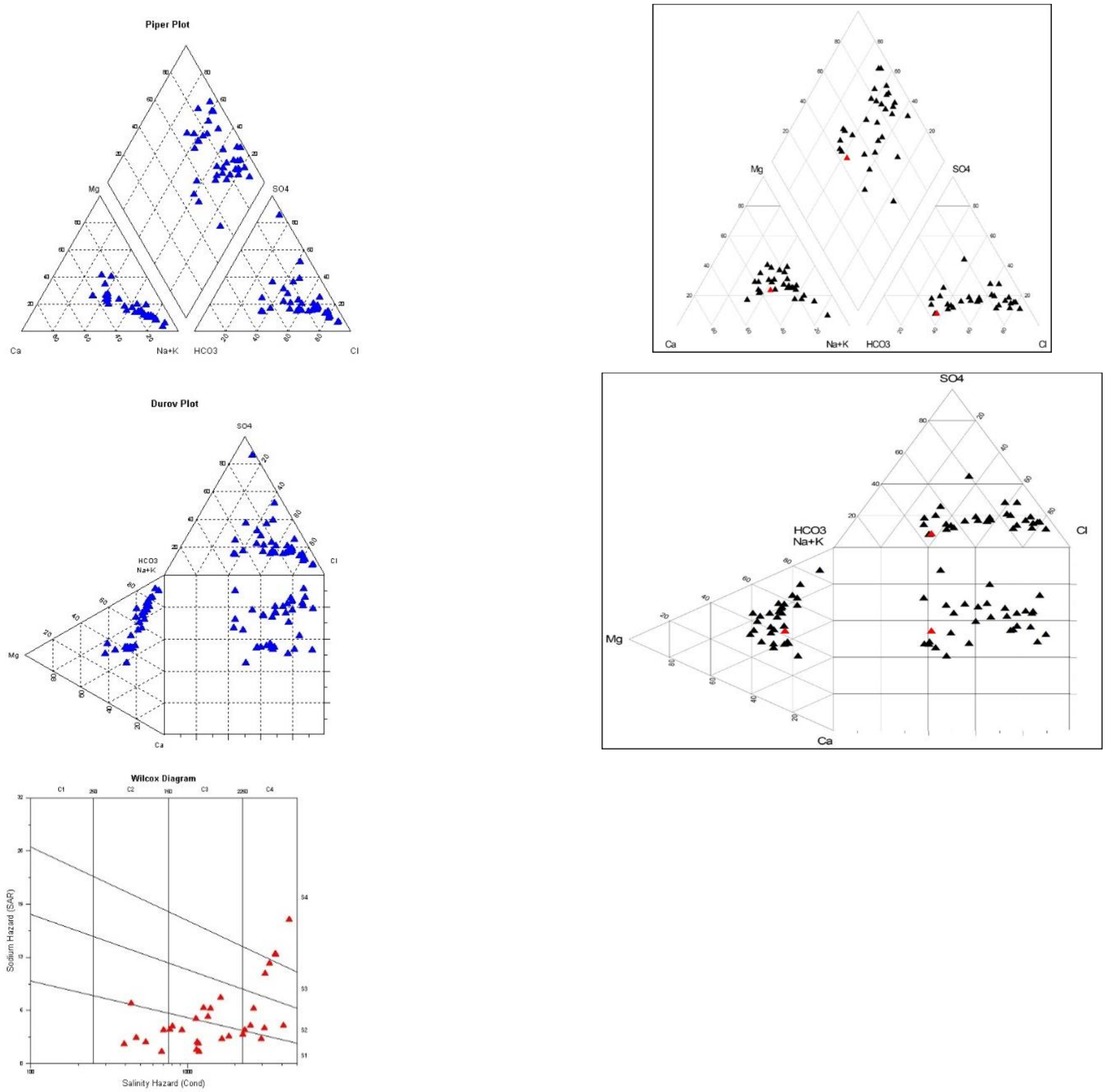


Figure 20. Piper, Durov and Wilcox diagrams for Azraq and Mafraq samples (top, middle and bottom plots, respectively).

Groundwater represents the main source for quality water supply in Jordan. Distribution of Azraq and Mafraq samples shows that the main water type is earth alkaline to alkaline water with prevailing bicarbonates, sulfate and chloride. This clarifies the origin of sulphur in the waters to be associated with Gypsum dissolution (Figure 20). Durov diagram shows that the main geochemical processes affecting water are ionic exchange processes with simple dissolution or mixing. Gypsum dissolution and mixing with irrigation return flows indicate high impact of agriculture on the groundwater system in irrigated areas. Wilcox diagram shows samples are in medium to very high salinity slots (most of the samples). Most of the samples are in the low and medium alkali hazard zone, while few samples show high to very high alkali hazards. Excess salinity causes a reduction in the osmotic activity of plants and thus interferes with the absorption of water and nutrients from the soils. SAR represents the alkali hazard and is ratio of sodium to the root square of half calcium and magnesium content. If groundwater is rich in sodium and poor in calcium, cation exchange system will witness sodium enrichment that could destroy soil structure (clay particles dispersion).

The potential for a chemical reaction to take place can be determined by the chemical equilibrium of water with mineral phases. Saturation Index is estimated as the logarithm of the ratio between ionic activity product and mineral equilibrium constant at a given temperature. If SI equals zero, then the water is in equilibrium. If SI is negative, water is under saturated with respect to the mineral phase and it will dissolve the mineral phase to reach the equilibrium. In case SI is positive, water system is over saturated and mineral precipitation is possible. SI was measured using laboratory and field measurements and was modelled using PHREEQC interactive software (USGS 2003). The most common mineral phases of Azraq and Mafraq aquifer are calcite, aragonite, gypsum, anhydrite and dolomite. Results indicated an oversaturation in Aragonite (CaCO3), Calcite (CaCO3) and Dolomite (CaMg(CO3)2), while Anhydrite (CaSO4) and Gypsum (CaSO.2H2O) are generally under-saturated. This composition is justified by the over irrigation process. Irrigation water dissolves Carbonates from the soil profile to the groundwater body leading to a case of over saturation. As halite is one of the last minerals that crystallized in the soil after irrigation, it is rarely formed due to excessive irrigation.

Timeseries salinity measurements in monitoring wells were used to identify trends during 1984-2015 period for Azraq and 2010-17 period for Mafraq. Annual increase in salinity was considered in the projection period. Interpolation was achieved using natural neighbourhood model. There is a clear increasing trend in salinity starting from the eastern part of the basin and moving towards the west during 1990-2017 period. Salinity expansion is due to irrigated agriculture expansion (Figure 21).

Salinity trend was simulated using GW wells EC data (1 mg/l = µS/cm*0.65, with 1 dS/m=1,000 µS/cm). Increased over-exploitation of the groundwater resources in Azraq during the last 3 decades has led to a dramatic drop in the groundwater levels by more than 30 m in some wells. This drop has been accompanied by increasing groundwater salinity, exceeding, in some wells, 3,500 µS/cm, which is the upper limit for irrigating vegetables in Leptosols. In Mafraq, TDS maximum value increased from ~1750 in the year 1990 to 1998 mg/l in 2017. Overtime degradation in water quality resulted from over-exploitation, which has led to disturbances in the groundwater flow regimes and mobilization of neighbouring and underlying salty bodies. This has allowed the salty groundwater to irreversibly reach the production wells.

Simulated salinity for the year 2050 provided an alert for a rapid increase in the GW salinity which will affect the whole GW system (Figure 22). This increasing trend in salinity can be attributed to several current acts and factors affecting the Azraq Basin. Increased over pumping associated with the decline in GW levels will pose threats to agricultural practices and even domestic use of the GW. Increasing GW salinity will result in the deterioration of the GW system which will eventually affect the soil capability and the ecosystem.

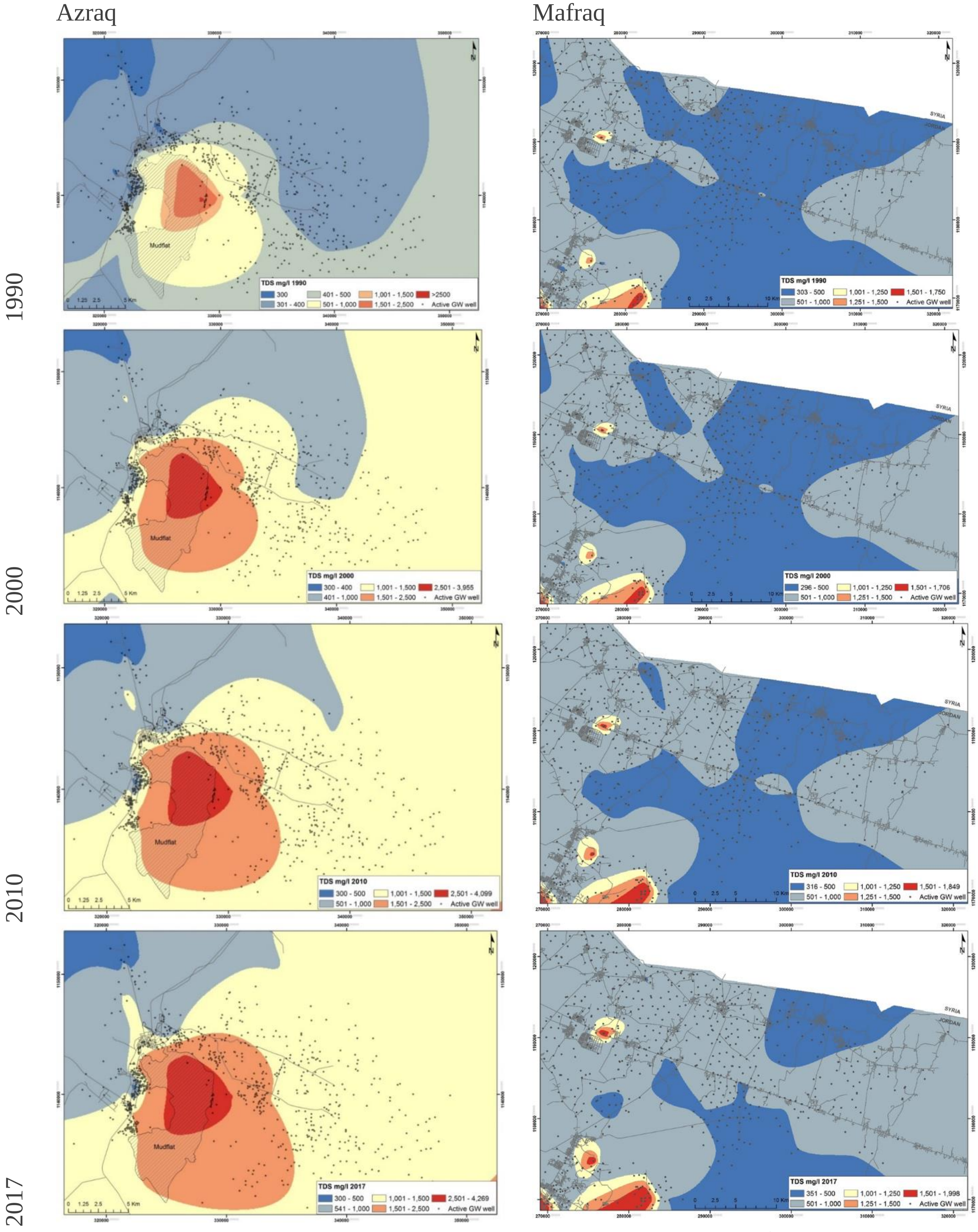
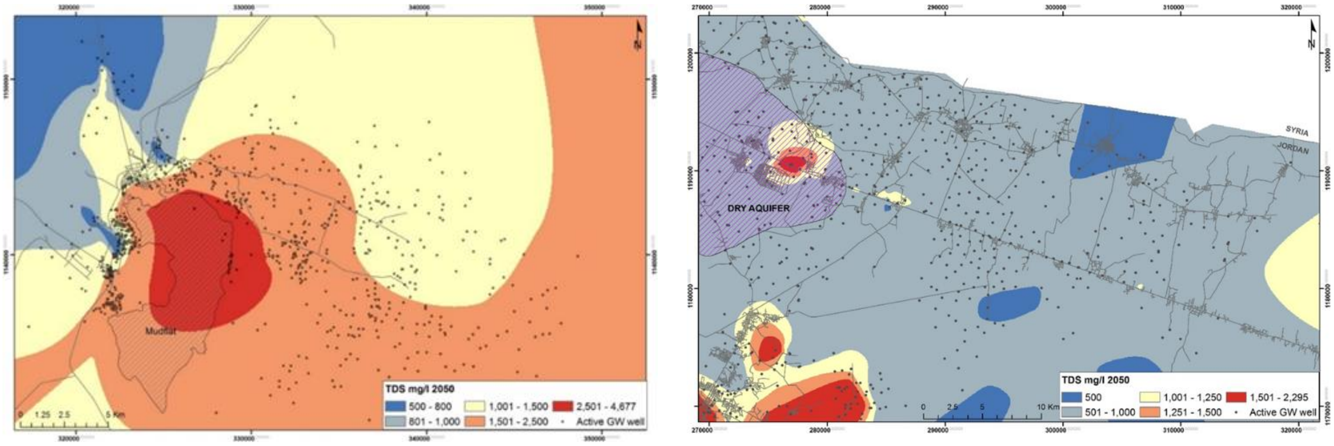


Figure 21. Water salinity expansion over 1990-2017 period in Azraq and Mafraq basins.



Azraq

Mafraq

Figure 22. Projected groundwater salinity in Azraq and Mafraq by year 2050.

6.2. What if water innovation technologies are introduced in 20% of the orchards to all farms covering more than 200 dunams, with savings of 50% on average?

Scenario B is defined as water innovation technologies are introduced in 20% of the orchard's farms covering more than 200 dunams, with savings of 50% on average. In Azraq, as per WAJ records, wells irrigating farms more than 200 Dunums found to be 365 with a total abstraction of 90.22 MCM/yr used mainly for olives and alfalfa. Applying this scenario (B), a total of 5.75 MCM can be saved (Table 6).

Table 6. Expected saving from large farms by introducing WITs

Variable / Area	Azraq	Mafraq
No. Farms > 200 Dunum	365	283
Average area Dunum	229	342
Main crops	Olive and alfalfa	Olives and stone fruits
Total agricultural abstraction MCM*	90.22	186.28
Abstraction by farms >200dun. MCM*	57.6	89.2
Scenario B saving MCM	5.76	8.92
Scenario C saving MCM	28.8	44.6

*Abstraction is based on actual irrigation measured by WIT

WIT project would have a tangible impact in central Azraq with a yearly reduction in drawdown of 20-25%. In Mafraq, pumping from large farms is taking place from 283 wells pumping more than 89 MCM mainly for olives and stone fruits. Applying 50% saving in 20% of the farms will lead to 8.92 MCM saving.

Scenario C is defined as water innovation technologies are introduced in all orchard's farms covering more than 200 dunams, with savings of 50% on average. Saving potential using irrigation management found to have a significant value in both Azraq and Mafraq areas. This scenario is expected to save 44 and 28 MCMs in Azraq and Mafraq respectively.

6.3. What if irrigation amounts are increased by 20% under 2-3-degree projections of climate change (2050)?

This scenario assumes a domestic supply growth of 3 % per year in Mafraq and fixed in Azraq. Results shows severe depletion in groundwater resources by 2050 in both Azraq and Mafraq if no water saving technologies are introduced. The expected drawdown in 2050 is found to be more than 30 meters in Azraq while it goes more than 60 meters in Mafraq.

Introducing water saving technologies as per scenario C can contribute to coping with climate change impact and can reduce expected drawdown by 8 to 10 meters. The same situation applies for Mafraq which will face a dry aquifer conditions in the western parts by 2025. Drawdown in Mafraq in 2050 will be more than 70 meters in Aqeb area. WIT can contribute in reducing stresses over the groundwater system (Figure 23).

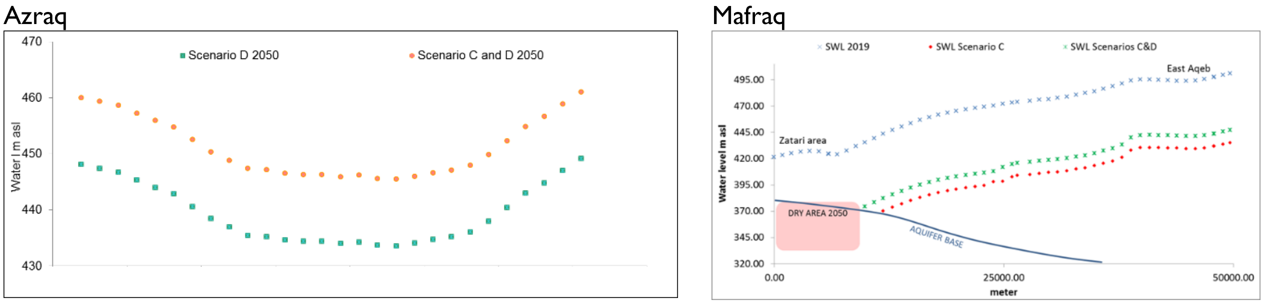


Figure 23. Simulated groundwater levels in Azraq and Mafraq

7. Recommendations

Aquifers geomorphology is complex, so it is difficult to estimate its countenance in water based on a single monitoring method. Hence, estimating groundwater abstraction is a challenging task that requires cross-checking different data sources including aquifer environment physics for modeling water movement and piezometers for measuring water level at various check points. These two methods are classically combined to estimate yearly and overall basin abstraction.

In the project intervention area, there are 1766 used wells, 968 wells in Azraq and 798 well in Mafraq area. Available Ministerial data for 2000-2017 estimated annual agricultural abstraction in Azraq and Mafraq to be 42–53 and 105-136 MCM, respectively. Regarding governmental wells (AWSA well field), pumping over the last 20 years was constant for Azraq about 18 MCM/yr and increased from 25 to 42 MCM/yr in Mafraq. Abstraction for agricultural use is estimated by WAJ to be 70% of the total. In addition, many illegal wells are not recorded especially in Azraq with an indicative value of 10-15 MCM in Azraq. In this study agricultural abstraction was corrected using WIT data and previous datasets from MWI (Bakri, 2013). However, records of governmental wells were maintained as per the records of WAJ.

These methods, when used by MWI and the actual modeling exercise, estimated groundwater abstraction for agricultural use to be 204 to 276 MCM, 67% in Mafraq. This number is higher than the estimates of groundwater abstraction obtained by using net crop water requirements averages for main crop types (129 MCM) and even 20% higher than estimates obtained by using an average irrigation efficiency coefficient. This means that irrigation efficiency is lower and can be obtained from on-farm water audit. The use of outputs from agronomic studies as an additional source of data is highly recommended. This consists in crop type map and average crop water use determined from on-farm water audits. Water audit data interpolated over a crop type map showed a total groundwater abstraction of 359 MCM (Table 7).

Methods based on net crop water requirements estimated using Kc from FAO56 and the usage of a constant irrigation efficiency coefficient underestimate groundwater abstraction.

Table 7. Estimation of crop water requirements, water use and irrigation-based groundwater abstraction using net crop water requirements, irrigation efficiency factor and water audit results in Azraq and Mafraq.

		Groundwater abstraction (MCM/yr) based on:				
Intervention area	**Area grown (ha)**	**CWR**	**IE**	**WA**	**MWI modeling**	**Actual modeling**
Azraq	4,738	49	64	108	68	90
Mafraq	10,617	80	104	251	136	186
Total	15,355	129	168	359	204	276

CWR, crop water requirement estimated using MWI weather station data for calculating ETo and average Kc from FAO-56 standard table.; Net CWR, net crop water requirements; IE, 70% irrigation efficiency; WA, water audit conducted in 100 farms in 2018.; WA, water audit achieved in 100 farms in 2018.; IE-CWR, Crop water requirements calculated using an irrigation efficiency factor.

Water audit-based estimate of groundwater abstraction is an unusually high number that need to be verified. Several sources of uncertainty may depend on:

- **Crop classification:** The study area covers in total 15,355 ha whereas the latest previous study showed a total area of 22,081 ha (Bastiaanssen, 2014). The difference of 6,726 ha could be mainly due to errors in the baseline crop type classification by MWI and to the decline in Mafraq's farm lease for vegetable production of investors from Southern Jordan Valley. This is a key reason for revising the crop type mapping and updating it using Sentinel 10-m resolution. However, both reasons need to be verified using a higher resolution crop type mapping based on a wide sample of GPS localized farmers' fields as collected during the WIT water audit study.
- **Sources of uncertainty in modelling** Azraq and Mafraq areas include boundary conditions, abstraction rates (especially private wells and illegal wells), recharge rates and distribution, and uncertainty associated with heterogeneity of governing hydraulic parameters (especially hydraulic conductivity). Boundary conditions used in this study is based on updating the water level map published by BGR (Margane and Hobler, 1994 and BGR 2013) for *B2/A7* Aquifer and BGR 1995 for the *B4* Aquifer in Azraq. **Model boundaries** in Mafraq found to be more complicated due to the complex aquifer settings and variability of flow regimes within the

basaltic unit and the lower limestone unit. The transboundary flux coming from Syria was a big challenge due to lack of data. Salameh (2012) estimated a total flux of 27 MCM from Jabal Druze towards Mafraq area. This value was assigned for the northern model boundary as specified flux while the eastern and western boundaries assigned as no flow boundary. Western boundary is the limit of saturation of the aquifer (BGR 1995).

- **Abstraction data:** Several time series data of observed heads showed fluctuation in groundwater level that should be related to change in abstraction data while abstraction data did not have such fluctuation. This in fact reflects uncertainty in abstraction data.

To reduce these uncertainties, we suggest working on developing a high-resolution crop type map and a dynamical estimation of actual ET and soil water balance for every hectare and daily, which allows an accurate, near-real time, near-continuous estimation of water use.

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