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Scenario Simulation and Analysis in the Transboundary Yarmouk River Basin Using a WEAP Model

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Prepared by:

Hassan Al SABEH

Supervisor: Dr. Chadi ABDALLAH

وَهُوَ الَّذِي مَدَّ الْأَرْضَ وَجَعَلَ فِيهَا رَوَاسِيَ وَأَنْهَارًا ﴿ الرَّعْد 3 ﴾

“And it is He Who spread out the earth, and placed therein firm mountains and rivers’’

Qur'an - 13:3

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The work done would not have been possible without the help of several individuals who all contributed in their own ways

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Finally, I would like to express my deep gratitude for my family and friends for their continuous support throughout my years in the faculty of engineering

Abstract

Water is a finite resource but an essential one. The continuously increasing demand lead to competition and conflict over limited water resources. Syria, Jordan and the occupying state of Israel (OSoI) compete over the water resources in the transboundary Yarmouk river basin where two water agreements dictate the allocation of water. The two water arrangements are far from being efficient and fair (Zeitoun et al. 2019a). Little cooperation is made over sharing water resources that are being over-exploited. In this study, the water sustainability was investigated under projected developments and trends based on the current use and allocation regime in the watershed and under possible future scenarios. A one bucket soil moisture model was adopted and used to build and optimize the ever-changing hydrology of basin using Water Evaluation and Planning (WEAP) tool. Demands along with the existing water infrastructure and their operation were modelled despite the lack of many data and the huge uncertainty in some.

Simulation of business as usual scenario showed that continuing with the current use cannot be sustainable in the short and long term. Growth of both agriculture and population produced huge water shortage in all sectors. Under climate change scenarios RCP 4.5 and RP 8.5, surface water availability and the retention of dams reduced significantly. The share of Jordan from the Yarmouk River was more vulnerable to climate change scenarios than that of OSoI. Enhancing irrigation efficiency and a more stable population based on the UN medium variant population projection showed improvements in water coverage within all demand sectors. Analysis of future scenarios suggest that water shortage is expected in all riparian states of the basin but can be mitigated by reducing demands.

Keywords: Yarmouk, Watershed, Syria, Jordan, Occupying state of Israel, Transboundary, WEAP, Scenario, Water management,

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List of Abbreviations

BAU	Business as Usual
CBS	Central Bureau of Statistics
DoS	Department of Statistics
ET	Evapotranspiration
FAO	Food and Agriculture Organization
GIS	Geographic Information System
GW	Ground Water
IWRM	Integrated Water Resource Management
JVA	Jordan Valley Authority
KAC	King Abdullah Canal
Kc	Crop coefficient
MCM	Million Cubic Meter
OSoI	the Occupying State of Israel
PFD	Preferred Flow Direction
RCP	Representative Concentration Pathway
RRF	Runoff Resistance Factor
RZC	Root Zone Conductivity
SW	Surface Water
SWC	Soil Water Capacity
UN	United Nations
WEAP	Water Evaluation and Planning
WWTP	Waste Water Treatment Plant
Z1	Top bucket relative storage

Chapter I: Introduction

1.1. General

Water is the most essential component for life on our planet. Without water, life would not exist and no civilization would have prevailed. The need for water extends beyond the biological requisite for survival. Water is necessary for the sustainability of ecological systems and for the growth of crops and trees. In addition, water is utilized for domestic purposes and for transportation, tourism and recreation. It is also required in various industries and is exploited for the production of renewable energy.

The majority of water on the blue planet is salty. Only 2.4% of earth's water is fresh while less than 0.01% of it exists as surface water in lakes and rivers. Unfortunately, fresh water is not distributed equally throughout the world. Water availability is a major concern for many countries facing water scarcity; according to the United Nations (2018a), 2 billion people live in countries experiencing high water stress.

The availability of fresh water has been increasingly threatened by pollution and climate change. Accompanied with the increase in population and the expansion of agricultural lands in the past century, the rapid rise of water demand has led in many cases to the over exploitation of water resources.

The proper management of water resources plays a significant role in achieving water security within each country. It is an essential need for its progress and prosperity. The management process is developed through an integrated water resource management (IWRM) approach that is accepted worldwide. The approach provides a universal framework to develop and manage water resources through a set of principles that helps in creating and implementing better policies (UNEP, 2012).

Access to clean water and sanitation is an internationally recognized right, but providing it is not always an easy duty. In 2017, 785 million people around the globe lacked a basic drinking-water service (WHO & UNICEF, 2017). Many countries are continuously trying to secure their rightful water resources whether they come from internal or external origins.

Some water resources are shared between countries but most parties initially seek to keep their control over these resources for their important economic and political value (ASCE, 2013). The contest for fresh water have often led to the deterrence of relations between neighboring nations and have pushed some countries to threaten their counterparts. Nonetheless, most countries have ended such contest through mutual water agreements and treaties. However, such agreements are not always equitable (Zeitoun & Warner, 2006).

To build policies and achieve water security, it is essential to study the hydrology of a watershed while taking into consideration all its characteristics and incorporating its complex processes. Planning cannot be done without realizing the magnitude and impact of any change whether it affects the demand or supply side of the equation. Today, the best preparation that could be done, is to look into the future.

1.2. Objective and Scope

The aim of the study is to investigate the long term impact of different changes that may occur in the trans-boundary Yarmouk river basin and assess the compatibility of current water policies in the future. The study shall provide further insight upon the future of the basin in light of the various transformations that could be managed or not.

The study also intends to establish a system that represent the current water exchange and exploitation in the basin that is affiliated with the water agreements between riparian countries and to create a water balance of the basin by modelling both the water resources and demands then simulating the hydrology of the basin.

Several scenarios that incorporate variations in agriculture, land use and climate are to be simulated and analyzed against a baseline reference of projected historical data. The results will serve as a forecast of the water resources demand and supply in the years ahead.

The study focuses on the Yarmouk River and its basin which is a trans-boundary watershed and a sub-watershed of the Jordan River watershed. It will generate different scenarios that continue up to the end of the century.

Chapter II: Literature Review

2.1. Hydrological Modelling

Hydrological modelling is an approach that aims to represent the hydrological processes through a set of mathematical equations and relations. The challenge of managing water resources and establishing water policies need the assistance of hydrological models to ease the complications in hydrology.

Computer software are the best tools for modelling watersheds and simulating is hydrology. The ability to capture the temporal and spatial references in addition to fast data processing is essential for analyzing the hydrology of watersheds.

Two software were mainly used in the study:

2.1.1. Geographical Information Systems

A geographic information system (GIS) is a conceptualized framework that provides the ability to capture and analyze spatial and geographic data (Wikipedia, 2020a). GIS has a wide range of applications such as urban planning, disaster management and statistics. In addition, GIS is widely used in hydrology and is increasingly utilized in many hydrological modeling software. The ability to use GIS data to deal with valuable info such as land cover, topography and climate data mean that it can be a great asset for watershed modeling.

ArcGIS is a software developed by Environmental Systems Research Institute (Esri). ArcGIS provides a set of tools that help analyze, develop and visualize geographic data and allows the extraction of valuable data from satellite imagery. Furthermore, the software is capable of generating, processing and representing large datasets of geospatial data.

2.1.2. WEAP

Water Evaluation and Planning Model Version 21 (WEAP21) is an integrated water resource management (IWRM) tool designed to evaluate user-developed scenarios that accommodate changes in the bio-physical and socio-economic conditions of watersheds over time (Yates et al., 2005)

Developed by Stockholm environmental institute (SEI) in 1988, WEAP is a platform to model watersheds with all its components and characteristics. WEAP can model the supply and demand and then manage water allocations based on priorities and limits. The software is also used to analyze transboundary basins and provide equitable sharing between riparian countries.

WEAP is capable of analyzing various aspects regarding water management such as hydrological, environmental and financial aspects. It can also model water infrastructures and their operation and can simulate the different interactions between soil, crops and water. WEAP is used to build a baseline reference scenario of the usual water system operation in addition to other scenarios that include various changes. It will then be used to compare and assess these changes to provide further insight on such changes.

2.2. Water Status in Jordan and Syria

a) Syria:

The Syrian Arab Republic is located on the eastern Mediterranean and is 185,180 Km2 in area. The country is bordered by Iraq to the east, Turkey to the north, Jordan to the south, OSoI to the southwest and both Lebanon and the Mediterranean Sea to the west.

The total water withdrawal per capita in Syria is 853.7 m^3/capita/year while the total renewable water resources is 855.7 m^3/capita/year (Aquastat, 2016). Syria is thus considered under water stress conditions as defined by FAO for having between 500 and 1000 m^3 of water available annually per capita.

There are 16 rivers in Syria of which 6 are transboundary. The Transboundary Rivers are the Euphrates, the Orontes, the Afrin River, El-Kabir River, Tigris River and the Yarmouk River.

More than 50% of the Syria's total renewable water resources are from external origin. The Syrian Arab Republic have secured its share of transboundary water through formal and informal agreements with Turkey (1987), Iraq (1990), Lebanon (1994) and Jordan (1987).

The agricultural sector in Syria has had a great priority for the state and has been increasingly developed since the 1980's for the purpose of achieving food security. The Water sector thus has been continuously developed by the Syrian government through infrastructure and irrigation systems. Agriculture consumes up to 87.5% of the water withdrawal is Syria, while domestic and industrial usage consume 8.8% and 3.7% respectively. (Aquastat, 2016)

b) Jordan:

Jordan on the other hand, is located south of Syria and is bordered by Iraq to the north east, Saudi Arabia to the south and east, in addition to Palestine and the occupying state of Israel to the west. The country is divided into 15 basins and has twelve aquifers. The Jordan River draws the border with Palestine and the occupying state of Israel while the Yarmouk tributary draws part of the northern border with Syria. The only significant river in Jordan, other than the Jordan River and its tributary Yarmouk, is the Zarqa River. It flows along with several other smaller rivers to the Jordan valley from the mountains in the east.

Jordan is ranked the second poorest country in water resources where less than 100 m^3 of renewable water are available annually per capita (MWI, 2017). The country suffers from water scarcity and is exploiting its non-renewable resources at high rates. Water availability is a main concern of the Jordanian authorities, as a result the authorities have constructed dams and wastewater treatment plants to maximize water availability. Additionally and due to the high variability of water resources throughout Jordan, the government have developed supply networks that carries water for over 300 Km to reach some destinations. The consumption of different sectors in Jordan is 52% for domestic and municipal use, 45% for agricultural use and 3% for industrial use.

Water shortage is a reality in Jordan and with the very limited internal water availability accompanied with a high population growth and huge refugee influx, more pressure is being placed on water resources.

Jordan has a highly dependent on water from outside its borders. Its share and allocation is dictated by two treaties signed with both Syria (1953, 1987) and the occupying state of Israel (1994).

2.3. Water Conflict in Yarmouk Basin

Water resources of Yarmouk have been directly related to the geopolitical situation in the region during the past century. The conflict around Yarmouk started after the fall of the Ottoman Empire when the River was recognized as the boundary of French Syria and British Transjordan. The Zionists started lobbying the British authorities concerning both the Litani and Yarmouk Rivers and their resources. Zionist businessman Pinhas Rutenberg was given privileges regarding investments of the river. (UEA, 2018; Etana, 2015)

During the 1940's each of the three states started developing their own plans, each with own international backers (Zeitoun et al. 2019b). 1948 marked the year when OSoI became a recognizable side in the conflict. The United States and Britain delegates were involved in several plans of sharing and developing of the Yarmouk River. The most significant plans in the basin are the Johnston, a US representative, plan and the Bunger plan. In 1952, Miles Bunger suggested building a dam at Maqarin where five of the 6 tributaries of Yarmouk meet. A diversion weir at Adassiyeh, located few kilometers upstream of Yarmouk confluence, and a small dam at al Himmeh upstream the suggested weir was also proposed.

In 1953, Syria and Jordan made an agreement regarding the sharing of Yarmouk water in which they adopted a modified version of the bunger plan. The following period is when the conflict took another shape; the plans of different sides were halted by military interventions. Israeli plans were stopped by Syrian bombings in 1953 while in 1964, the Syrian-Egyptian plans to divert Jordan River's head flows were bombed by the Israeli side. Israel also bombed the construction site of a Jordanian dam and the irrigation canals in the Jordan valley in 1966 and 1967 respectively. (UEA, 2018)

During the six-day war in 1967, Israel occupied the Syrian Golan Heights and thus Israel's control along the Yarmouk River was extended to the confluence of the Raqqad tributary. The Golan Heights control the main water sources of the State of Israel. Israel's only lake and its main source of fresh water, supplying the country with a third of its water, is fed from the Golan Heights. OSoI unlawful administration over Golan has not been recognized by the UN Security Council (FAO, 2008).

During the following two decades, each country continued with its own hydraulic plan independently. In 1987, Syria and Jordan made a new agreement regarding the sharing of Yarmouk, but until today, no agreement of any kind is signed between Syria and OSoI. The two countries are in a state of hostility since the Nakba in 1948 and were engaged in several wars since then. However, Jordan has signed a peace treaty with OSoI in 1994; a treaty that discussed the sharing of the Yarmouk and Jordan rivers.

2.4. Water Agreements in Yarmouk Basin

2.4.1. Syria-Jordan water agreement 1987

Signed on the third of September 1987 in Amman, the agreement discussed the utilization and development of the Yarmouk River. The agreement had similar clauses to the 1953 agreement. Both countries agreed to build the Wehdeh dam in Maqarin on the separating border in order to collect and store the flows of the Yarmouk (Article II). The purpose of the dam is to generate electricity and irrigate lands in Jordan and Syria. The agreement also states that Jordan is to finance every stage of the studies, plans, construction, operation and maintenance for the establishment of the Yarmouk scheme (Article III).

In (Article VI), the agreement states that Jordan is to build the Wehdeh dam up to a total height of 100 meters. It also states that the dam is to be filled by water after the filling of the 25 Syrian reservoirs specified in the annexed table of the treaty.

Regarding water rights the agreement states that “Syria shall retain the right to the use of the waters of all springs welling up within its territory in the basin of the Yarmouk and its tributaries, with the exception (with unknown scientific reason) of the waters welling up above the dam below the 250-metre level, and shall retain the right to use water from the river and its tributaries below the dam for the irrigation of Syrian land along the course of the river” (Article VII, a). It is also stated that Jordan shall have the right to use the overflow from the Wahdah dam reservoir and generating station to generate electricity (Article VII, b).

Moreover, the generated electric power is to be divided between Syria (75%) and Jordan (25%) (Article VII, c). Another clause calls for the establishment of a joint Syrian-Jordanian committee to implement the agreement’s provisions (Article IX).

2.4.2. OSoI-Jordan Peace treaty 1994

The peace treaty between Jordan and the occupying state of Israel was signed on 26 October 1994 in Wadi Araba. Jordan became the second Arab country to sign a peace treaty with Israel. The treaty tackled several issues including peace, security, economic relations, refugees and international boundary. The treaty also discussed water issues concerning both countries. These clauses are found in Annex II in the signed treaty.

The clauses regarding allocation of water from Yarmouk River are:

1. Israel pumps from Yarmouk 12 MCM in the summer period (15th May to 15th October) and 13 MCM in the winter period (16th October to 14th May) (Article I, 1.a,b). Thus Israel is to pump a total of 25 MCM annually.

2. Jordan is entitled to the rest of the flows but is to concede an additional 20 MCM to Israel in winter (Article I, 1.b) to be returned to Jordan as per (Article I, 2.a)
3. Israel and Jordan may use, downstream of point 121 /Adassiyeh Diversion, excess flood water that will go to waste unused. (Article I, 1.c)

The clauses regarding allocation of water from Jordan River are:

1. Israel concedes to transfer to Jordan in the summer period 20 MCM from the Jordan River directly upstream from Deganya gates on the river (referring to Lake Tiberias). Jordan shall also pay for the operation and maintenance of such transfer. (Article I, 2.a)
2. Jordan is entitled to store for its use a minimum average of 20 MCM of the floods in the Jordan River south of its confluence with the Yarmouk during winter season. (Article I, 2.b)
3. Israel is entitled to maintain its current uses of the Jordan River waters between its confluence with the Yarmouk and its confluence with Tirat Zvi/Wadi Yabis (northern border of the west bank). (Article I, 2.c)
4. Jordan is entitled to an annual quantity equivalent to that of Israel, provided however, that Jordan's use will not harm the quantity or quality of the above Israeli uses. (Article I, 2.c)
5. Jordan is entitled to an annual quantity of 10 MCM of desalinated water of saline springs now-diverted to the Jordan River. (Article I, 2.d)

Other clauses regarding water allocation:

- Israel shall retain the right to use the wells in Wadi Araba inside Jordanian borders and may increase the abstraction rate from wells and systems in Jordan by up to 10 MCM per year. (Article IV, 1,3)

The treaty also discussed the protection of the quality of water exchanged:

- The quality of water supplied from one country to the other at any given location shall be equivalent to the quality of the water used from the same location by the supplying country (Article III, 3)

The treaty also states that Israel and Jordan are to cooperate in building a diversion/ storage dam downstream Adassiyeh (the now Adassiyeh weir) to improve diversion efficiency and water allocation for Jordan and possibly Israel. (Article II, 1), In addition, the lands of baqura at the confluence of Yarmouk were leased to OSoI.

To sum things up, Israel is to pump 45 MCM of Yarmouk flows (25 MCM as Israel’s share and 20 MCM as additional flows conceded by Jordan) and to return 20 MCM to Jordan from Lake Tiberias. Both countries are to build a diversion dam at Adassiyeh and both have the right to use the unused excess flood flows downstream the diversion. Additionally, Jordan is to lease part of its lands and wells in exchange.

2.5. Water Conflict and Transboundary Rivers Laws and Conventions

With the never stopping development and population growth around the globe, water demand is increasing and countries are becoming more concerned with securing their water resources. Such task may face many hurdles in the shape of technical problems, pollution, droughts and sometimes the simple lack of renewable water resources. Other problems may appear in the shape of water conflict between 2 or more countries.

Water bodies, rivers and aquifers may traverse international borders, and sometimes the allocation and sharing of these waters could turn into competitiveness that may develop into a conflict between several countries. Such water is referred to as "Transboundary waters" which is defined by UN (1992) as any surface or ground waters which mark, cross or are located on boundaries between two or more States.

Across the world, 153 countries share rivers, lakes and aquifers. Transboundary basins cover more than half of the Earth’s land surface and account for an estimated 60 per cent of global freshwater flow and are home to more than 40 per cent of the world’s population (UN, 2018b).

Countries involved in a dispute over water may choose violent conflict to establish their share of water or may revert the diplomatic approach by negotiating an agreement (Dableko et al. 2004). However, signing treaties does not necessary put to an end to the conflict. Treaties and agreements may not always be fair and may be very far from being a model agreement. Some treaties lack clear allocation mechanisms and neglect many aspects of water cooperation that must be defined such as those in the Yarmouk basin (Zeitoun et al, 2019a). Other issues regarding ambiguity, cooperation and neglect of uncertainties appear in many treaties.

Since 1948, the historical record documents only 37 incidents of acute conflicts (i.e., those involving violence) over water (30 of these events were between Israel and one or another of its neighbors, the last of which occurred in 1970), while during that same period, approximately 295 international water agreements were negotiated and signed.(Giordano, Wolf, 2001)

Water treaties must not only allocate water and divide shares, it should also set a framework to ensure that the treaty’s clauses are fulfilled as well as another framework to allow the revision of clauses in the treaty and another to work on resolving any conflict that might arise.

Water conventions were brought up by international organizations to provide a reference for riparian countries to ensure a fair and equitable allocation of water resources. The 1997 UN Convention on the Law of the Non-Navigational Uses of International Watercourses and the 1992 UNECE Convention on the protection and use of Transboundary watercourses and international lakes include provisions that help develop an ideal treaty that assigns, protects and develops water shares.

The UN (1997) convention calls for a joint management mechanism. Such mechanism certainly provides some flexibility in dealing with water issues as it warrants the ability to accommodate through different scenarios or uncertainties. The convention also calls for an equitable and reasonable use of the watercourse while taking into consideration the interests of the concerned states. Other factors are to also be considered such as availability, needs and the natural climatic and hydrological factors. Both UN conventions (1992, 1997) discuss the communication and exchange of data between riparian countries. The protection of ecological systems and the environmental by controlling the emission of pollutants is also tackled.

The 2 conventions are considered the finest legal frameworks for transboundary water cooperation and have had great influence on water treaties in the past decades.

Chapter III: Methodology

3.1. Study Area

The Yarmouk watershed is a sub-watershed of the larger Jordan River watershed that extends over 5 countries with an estimated area of 18,285 Km2. The Yarmouk River meets the lower Jordan River south of Lake Tiberias at Baqura.

The Yarmouk Basin is considered Transboundary as it extends over three riparian countries; Syria, Jordan and the occupying state of Israel (Figure 1).

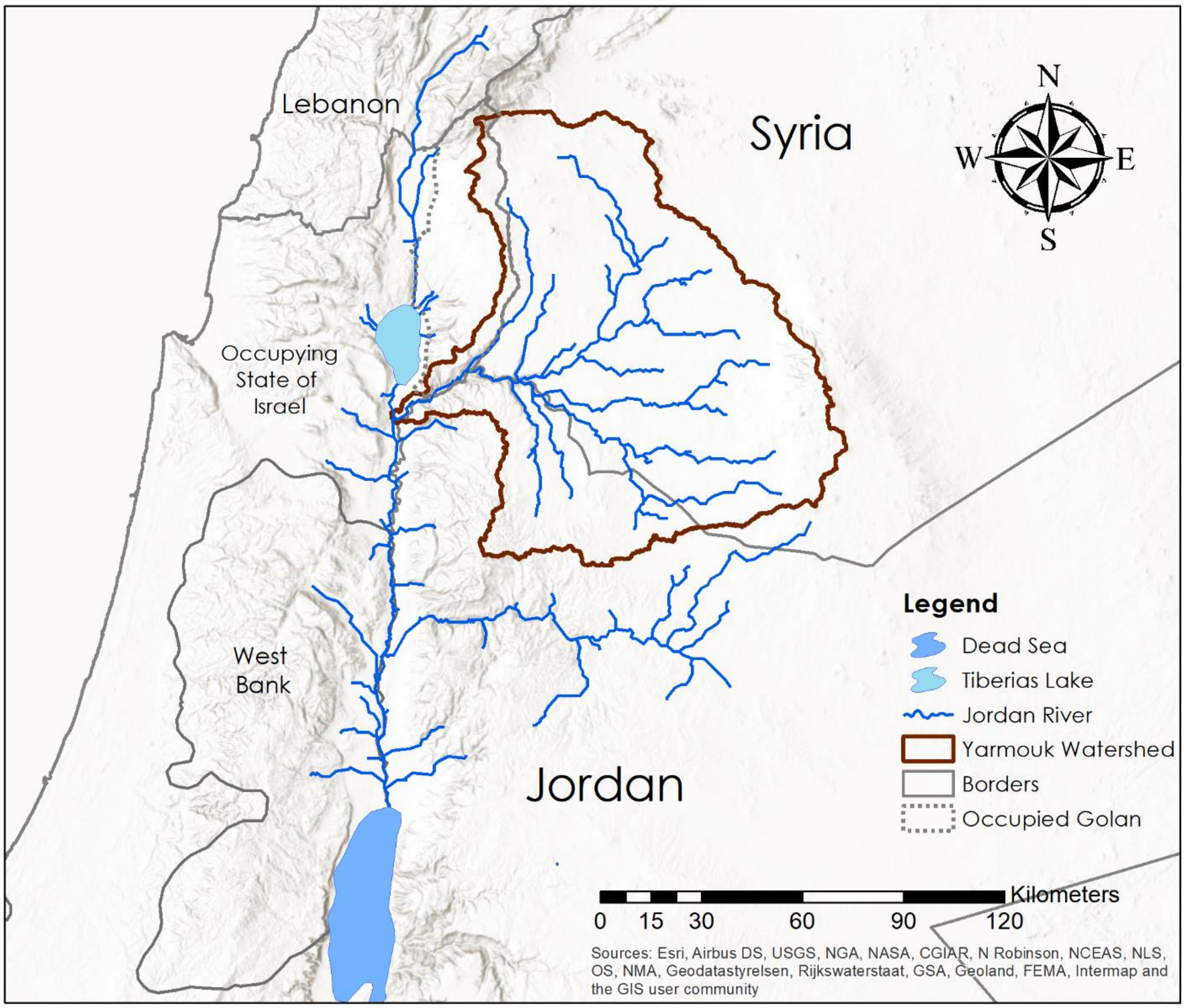

Figure 1: Yarmouk basin as part of the Jordan River basin

i. Geographical Characteristics

The Yarmouk watershed is located in the southern part of Syria and northern part of Jordan, it extends to Jabal al Arab to the east, Jabal al sheikh to the northwest and Ajloun Mountains to the south. The basin includes the Hauran plain and areas from the eastern and southern part of Golan Heights.

The basin is located between longitudes 35°56′27″ E and 36°77′56″ E, and between latitudes 32°31′18″ N and 33°32′99″ N.

The area of the basin is estimated to be 7,386 Km2 with 80% of it being in Syria (Occupied Golan represents 4.5%), 19.7% in Jordan and 0.3% in the Occupying state of Israel. The basin has a low slope except in the areas near Jabal al Arab and Jabal al Sheikh and at the Yarmouk valley.

ii. Hydrological Characteristics

The length of the Yarmouk river is 147 Km from its main source in Jabal al Arab. Several Tributaries contribute to the water flow of Yarmouk; Wadi Raqqad, Wadi Al Allan, Wadi Al Hareer and Wadi Thahab all contribute exclusively from Syria, Wadi Shallala contributes exclusively from Jordan while Wadi Zeidi contributes from both countries. Tributaries fed by springs are perennial and flow throughout the year, however most parts of the river network become dry in the summer.

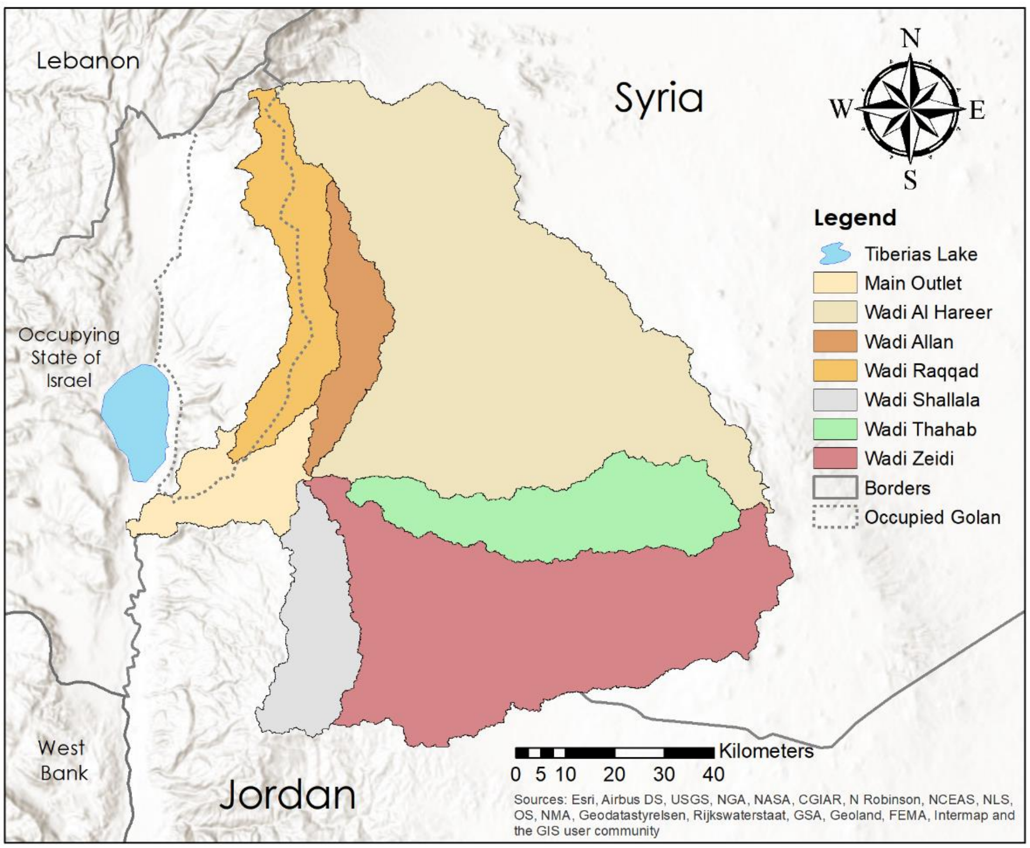

Figure 2: Sub-basins of Yarmouk watershed

The tributary of Wadi Thahab joins joins Wadi Zeidi stream at Tal shihab. Eventually Wadi Zeidi and the rest of the tributaries except Raqqad join the Yarmouk mainstream at Maqarin where the Wehdeh dam is built. Wadi Raqqad is the most important tributary in the basin, it is supplied with water from the melting snow in Jabal al sheikh and joins the mainstream near the colony of Kibbutz Meitsar in the occupied Golan (UEA, 2018). The Yarmouk River, upstream of the Raqqad confluence separates Syria and Jordan while along the downstream, it separates Jordan and the areas occupied by Israel in Golan and Palestine.

The hydrological basin is divided into 7 sub-basins (Figure 2), 6 basins correspond to each tributary while the last one correspond to the Yarmouk mainstream. The mainstream's average annual flow at Maqarin according to JVA data between 1989 and 1998 was 114 MCM, the average flow has decreased since then and reached an average of 28.65 MCM between 2007 and 2015. In Adassiyeh the average flow decreased from 72 MCM per year between 1989 and 1998 to 39 MCM between 2008 and 2015. (UEA, 2018; JVA, n.d.)

iii. Climate

The climate in the Yarmouk basin is a Mediterranean climate with cold rainy winters and hot dry summers. Rainfall levels vary throughout the basin and range between 200 and 450 mm/year, the levels are higher near Jabal al sheikh, Jabal al Arab and Yarmouk gorge areas and lower near Mafraq in Jordan (UEA, 2018).

The temperature varies greatly on a day-night basis inside the basin. The lowest temperatures are recorded in January that reach on average 8°C while the highest are recorded in August and reach 37°C in some areas.

iv. Geology and Aquifers

The aquifers in the Yarmouk basin are divided into 3 aquifer systems (UEA, 2018).

The upper aquifer system:

This system consists of two formations; the basalt formation and the B4/B5-Pg22/Pg23 formation. The basalt is the most recent formation from the neogene and quaternary eras. The basalt outcrops mostly in the Syrian part of the basin and is considered the main source of groundwater in Syria. The groundwater in the basalt has been over exploited leading to the deepening of the wells and huge decrease in the springs discharge.

The B4/B5-Pg22/Pg23 formation consists of limestone and marl and is from the Eocene age. The formation outcrops in the Jordanian part of the basin where it is recharged from rainfall. The formation is also recharged from the basalt aquifer and is exploited in north Irbid area.

B3 - Pg1-Pg21 aquitard:

The B3 - Pg1-Pg21 aquitard is found between the upper and middle aquifer systems, however it only separates them partially which leaves some areas where the basalt aquifer connects with the A7/B2 aquifer of the middle system. The aquitard outcrops in Syria near dara'a and in Yarmouk valley area in Jordan.

The middle aquifer system:

The middle aquifer system is formed of the A7/B2- Cr2cn-cp/Cr2m-d formation and a sequence of successive formations of aquifers and aquitards called A1/A6 - Cr2cm-t. Both formations date back to the upper cretaceous period.

The A7/B2- Cr2cn-cp/Cr2m-d formation is an aquifer consisting of permeable limestone from the Coniacian - Maastrichtian ages and is mainly exploited in Jordan.

The lower aquifer system:

Called the K - Cr1-Cr2 t aquifer, it dates to the lower cretaceous age and is rarely exploited.

v. Socio-Economic and Administrative Characteristics

The Syrian part of the basin includes areas in the governorates of Daraa, Suweida, Quneitra and Rif Dimashk. The main cities and towns in this side are Daraa, Nawa, Quneitra, Suweida and Busra al sham. Agriculture in the basin is one of the main sources of living in the area.

In March 2011 the Syrian war started, a war that expanded to all regions in the country. The war in the Yarmouk basin area included several factions and sides that fought against each other for land control. The war was effectively put to an end in July 2018. The war left the country torn with huge losses in lives and property. Thousands of homes in the basin were destroyed or damaged alongside many industries, in addition hundreds of thousands of people were displaced. Most of the infrastructure existing in the basin were damaged or destroyed.

The Jordanian part of the basin is located in areas within the governorates of Irbid, Mafraq, Ajloun, and Jarash. The main cities in the basin are Ramtha and Mafraq. The Yarmouk basin is considered one of the main agricultural zones in Jordan. In 2011, agricultural sector employed 124,000 people, which is 2.1% of the total population and 7.7% of the total labor force of Jordan (EU, 2012).

vi. Population

Data from the 2004 censuses in Syria and Jordan show that the total population back then was 1,442,117. The values have greatly increased due to the relatively high growth rates in both countries. According to (UN, 2019) the average annual growth rate in Jordan and Syria between 2000 and 2010 is estimated to be 3.49% and 2.64% respectively. After the start of the Syrian war in 2011, thousands of people in Syria were displaced. It is estimated that 6 million were displaced internally and more than 5.5 million became refugees across the region (UNHCR, 2019). Many Syrians chose seeking refuge in neighboring countries such as Jordan, Turkey and Lebanon.

During the war (2011- to date) the number of Syrian inhabitants of the basin decreased while the Jordanian population increased at a higher rate because of the refugees that settled in areas near the Syrian border especially in the governorates of Irbid and Mafraq. Out of the 657,287 Syria refugees still in Jordan, 262,115 of them originate from the governorate of Daraa (UNHCR, 2020). The number of refugees in Jordan have been stable even after many regions in Syria became safe, however, thousands of people have started to return voluntary from Jordan to Syria.

vii. Water Infrastructure

a) Dams in Syria:

32 dams are built in the Syrian part of the Yarmouk basin (Figure 3). The total capacity of the dams is 205.54 MCM and are distributed over all the sub-basins within Syria. The stored water is utilized in irrigation, livestock watering, drinking and domestic use. The largest two dams are Al Mantara and Kudnah with respective capacities of 40.2 and 30 MCM are located on the Raqqad tributary (UEA, 2018).

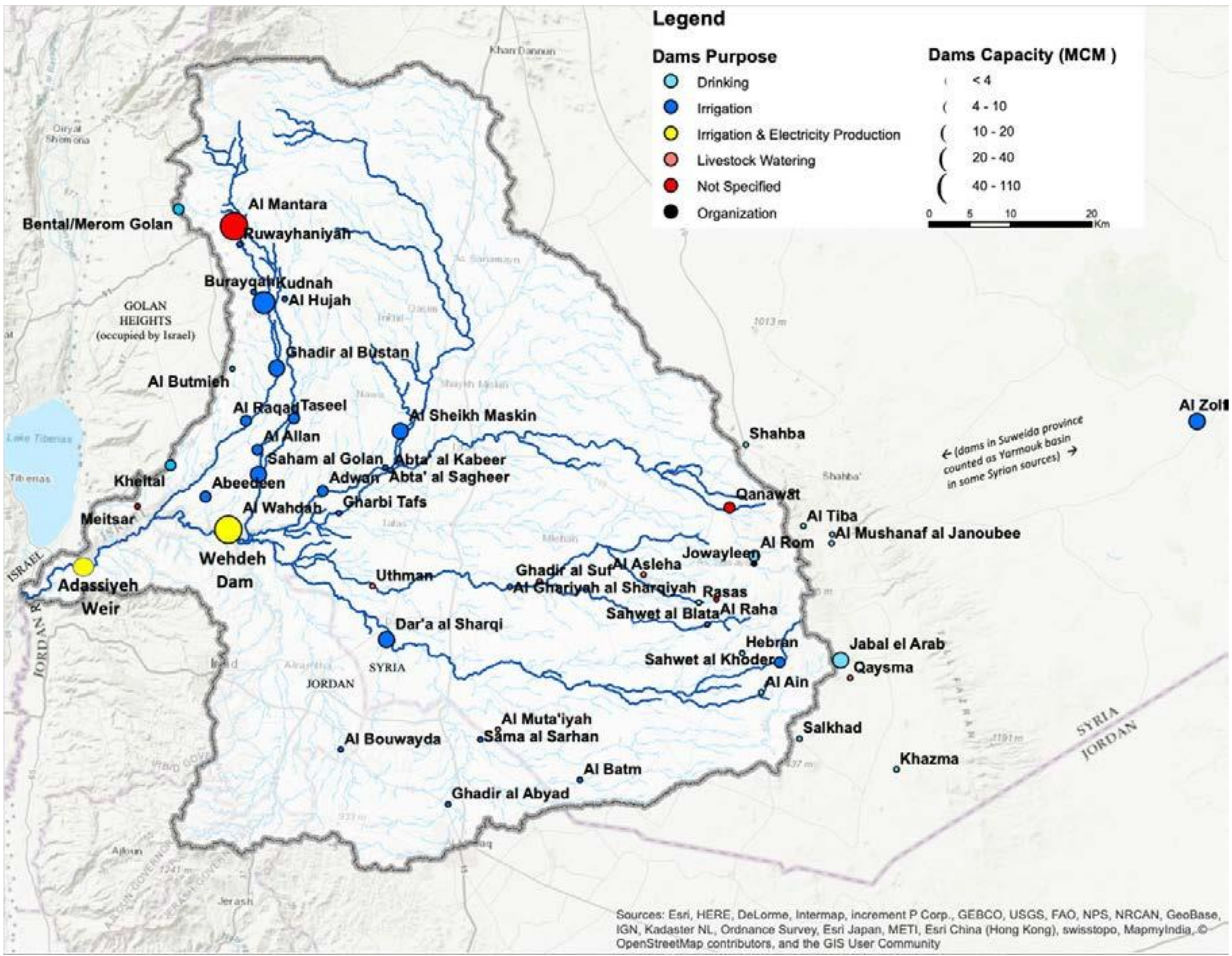

Figure 3: Location, storage capacity and purpose of dams in Yarmouk basin, retrieved from (UAE, 2018)

Several dams are polluted and some are out of service. During the Syrian war a number of dams were damaged and did not retain water for several years.

b) Dams in Jordan:

3 dams are built in the Jordanian side of the basin on the Zeidi tributary. The maximum theoretical capacity of the dams is 3.1 MCM, however the dams contain sediments and only 1.7 MCM can be filled. The dams are used for irrigation and livestock watering (UEA, 2018).

c) Dams in Occupied Golan:

4 dams are built by Israel in the occupied heights of Golan near the Raqqad tributary with a maximum capacity of 10.1 MCM (UEA, 2018).

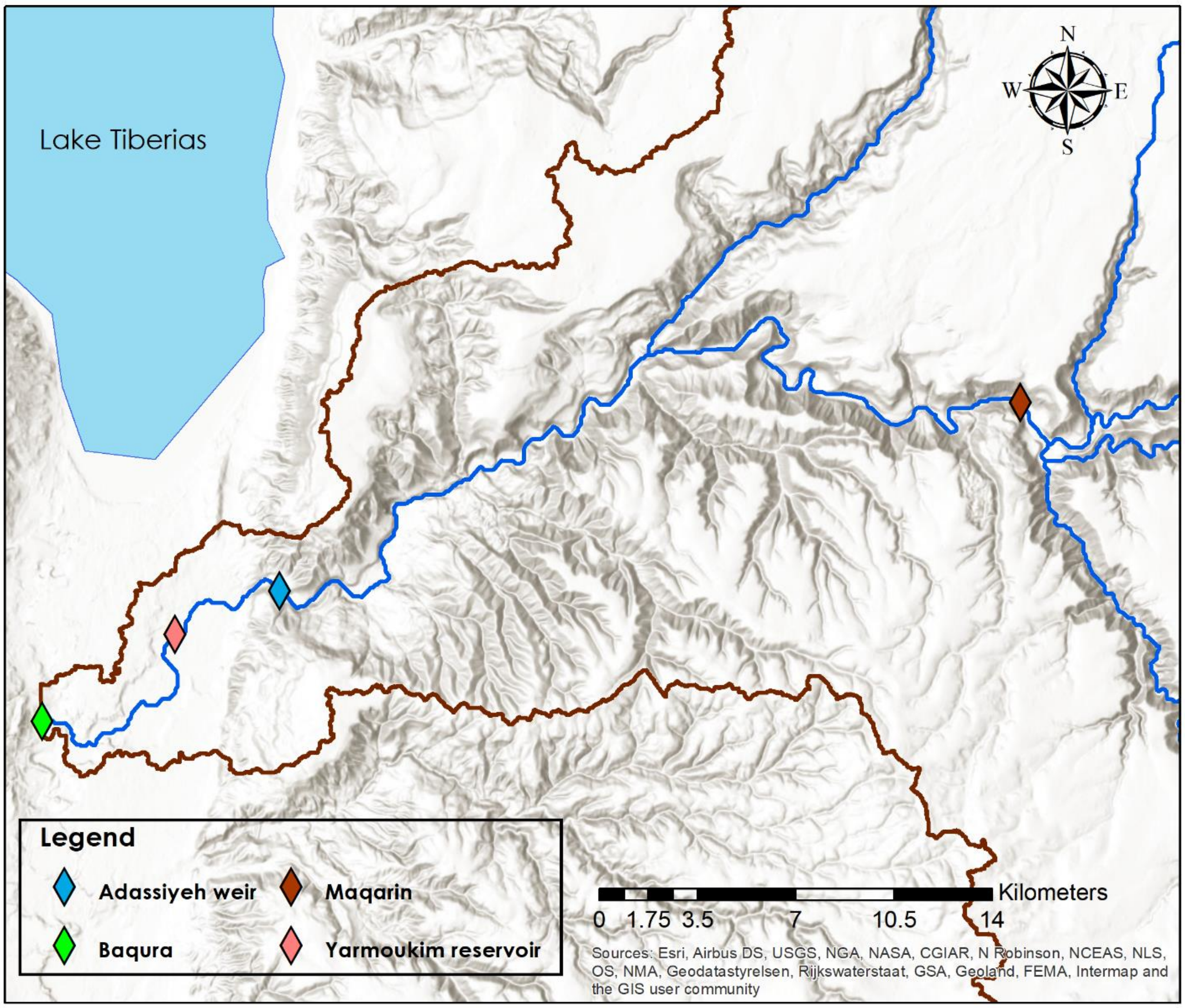

Figure 4: Locations of Maqarin, Adassiyeh, Baqura and Yarmoukim reservoir

d) Al Wehdeh dam:

Wehdeh dam was agreed on in the 1987 Syria-Jordan water agreement and is located near Maqarin (Figure 4) on the border between the 2 countries. The dam is the largest in the basin and can withhold 110 MCM of water. The construction of the dam finished in 2006, however it retained little volumes until the start of the Syrian war in 2011.

The dam is made of roller compacted concrete and is 100 m high spanning across the river for 485 m which captures the flows of 5 tributaries: Zeidi, Al Hareer, Allan, Thahab and Shallala.

e) Adassiyeh weir:

The construction of Adassiyeh weir was completed in 1999 just downstream the occupied village of al Himmeh (Figure 4) and is operated by the Jordan valley authority (JVA). The weir was agreed on in the 1994 peace treaty between Jordan and Israel, however the idea of the weir originated from the 1952 bunger plan.

The weir diverts the flows of the Yarmouk River into King Abdullah canal while the rest of the flows bypass the weir either by over spilling the weir or by passing through special gates after entering KAC. The flows can overspill the crest of the concrete weir during high floods whereas when the flow is low the special gates are used to divert part of the flows back into the river mainstream through a gauged transmission pipe.

f) King Abdullah Canal (KAC):

King Abdullah canal (or the east Ghor canal) is a 110 Km long channel that runs parallel to the Jordan River in the eastern Jordan valley. The canal is used to supply surface water from the Yarmouk River and other sources for agricultural use in the valley and domestic use in the greater Amman region (Wikipedia, 2020b).

g) Yarmoukim reservoir:

"Today, the Yarmouk has been diverted into that big pond. For all intents and purposes, that is the end of the Yarmouk" (Nathan (pers. comm.), 2017 as cited in UEA (2018).

The Yarmoukim reservoir is located upstream of the Yarmouk confluence with the Jordan River (Figure 4) and is the place where the Yarmouk River essentially ends. The flows of Yarmouk are stopped by an earthen dam and pumped into the 750,000 m^3 reservoir. With four pumps each with a capacity of 6500 m^3/h (or combining into a total maximum pumping capacity of 16,000 m^3/h, OSoI can capture and exploit all the flows bypassing Adassiyeh weir (UEA, 2018).

Part of the pumped flows are stored in Tiberias lake as agreed on in the 1994 peace treaty, the rest of the flows are used for drinking and local irrigation in OSoI.

3.2. Implementation of Water Agreements

Syria - Jordan:

Starting from Syria; the country with the largest share of the basin; 32 dams were built in the basin, 7 more than the 25 dams mentioned in the annexed table in the 1987 treaty. The Syrian state is therefore benefitting from a higher storage capacity than agreed on; however, these dams have never reached their maximum capacity.

The construction of Wehdeh dam finished in 2006 but has remained empty for several years after when the flow at Maqarin reached one of its lowest levels. The dam only started to fill after the start of the Syrian war. Historically, and before the dam construction, the water releases from Syrian dams were limited and after finishing Wehdeh dam, it only stored flows originating from areas downstream of the Syrian dams.

The Jordanian authorities have long held the notion that Syria is violating the treaty's terms. On the other hand, the Syrians believe that any additional flows that may reach Jordan will benefit OSoI. Both countries are still abided by the signed agreement but Syria is continuously hindering Jordan's share by increasing their wells and GW pumping. However, GW was not acknowledged as part of the transboundary watercourse in the signed agreement (Zeitoun, et al. 2019a) and no limit was placed on the groundwater abstraction.

Another aspect of the agreement impacting the allocation in Yarmouk is that the Syrian and Jordanian governments agreed that Syria has the right to use all the springs welling 250 meters above the sea level; the level which most Syrian springs well above. In addition, there are several articles within the agreement can be interpreted to limit the share of Jordan to just releases from Wehdeh dam and surface water within its territory (UEA, 2018).

Jordan - OSoI:

In 1999, the Adassiyeh weir was built as per the 1994 Jordan-OSoI treaty and has been diverting flows into King Abdallah Canal. The flows diverted by the weir into KAC are mainly water that flow naturally from Raqqad River and from regions downstream Wehdeh dam, in addition to Wehdeh dam releases and Mukheiba wells discharge. Mukheiba is located in Jordan near the Yarmouk tributary between the Raqqad confluence and Adassiyeh. Artesian wells with high discharge were discovered there and were used for local agriculture but after the 1994 treaty the authorities diverted the wells discharge into the river mainstream to be then shared with OSoI (UEA, 2018).

The Adassiyeh weir itself does not function as it was expected to because it allows more flow to bypass it, especially during floods. The construction of the weir benefited OSoI greatly since the rock and sandbag weir that existed before allowed more water to be diverted into Jordan. In addition, according to (Ghureir, 2018; Ghantous, 2018 as cited in Zeitoun et al. 2019b), the Jordanian JVA operator of the weir ensures that a minimum of $1m^3/s$ flows through the two bypass gates used to channel the flows around the weir, an act that further hinders the flows diverted into KAC.

It is important to note that the design and operation of the weir means that OSoI proportion of 25 MCM (as agreed in the 1994 treaty) is always supplied even when the river flow is low while also being the only side benefiting of flood flows especially in wet years. This implies that the flows diverted to the Jordanian side are not consistent and that Jordan is not benefiting from the flood flows that are solely exploited by OSoI. Also, the share of Jordan did not increase even after building Wehdeh dam, as the regulated releases were still allowed to bypass the weir. The extra fresh water that reach OSoI from Yarmouk is usually compensated by OSoI with additional water from the lake of Tiberias which is of lesser quality.

The flows not diverted to KAC continue their way to Yarmoukim reservoir. The reservoir can pump up to 140.16 MCM/year, consequently, OSoI can use all the water that reach Yarmoukim. On average, 19 MCM are pumped from Yarmoukim to Tiberias Lake (20 MCM stored during winter for Jordan) whereas an average of 47 MCM are pumped from Degania dam on the Sea of Galilee to Beit Zara reservoir and then returned to KAC by gravity. The reason for that returned flow are higher than the 20 MCM agreed on in the peace treaty is that

Flows returned by OSoI to Jordan are included under several accounts: additional flows that bypass Adassiyeh weir, 25 MCM promised by the then Israeli Defence Minister Ariel Sharon to King Hussein in 1997, 10 MCM labelled as desalination from Lake Tiberias and water purchased by Jordan from Israel and range between 0 and 16 MCM (Zeitoun, et al. 2019a). The water exchange operation between Jordan and OSoI is inefficient as it requires pumping water for long distances instead of allowing Jordan to divert its share directly from the Adassiyeh weir.

3.3. Water Use

a) Syria:

Official data on Syria's use of Yarmouk are non-existent. Most numbers available are estimations of this use. The total use of Syria was estimated to be 453 MCM/year divided to 92 MCM for domestic use, 34 MCM as industrial use and 327 MCM for agriculture (UN-ESCWA and BGR, 2013). These values however, correspond to the administrative boundary of the basin which include more areas from outside the hydrological basin. It is estimated that a total of 325 MCM/year inside the hydrological basin in Syria (UEA, 2018).

Syria use Yarmouk waters from three sources: dams, springs and groundwater. Spring discharge in Yarmouk basin has been continuously decreasing. The total spring discharge in 2002 was 92.58 MCM, it decreased to 67.26 MCM in 2009 (Central Bureau of Statistics, n.d.). Most of the springs discharge is exploited by Syrians as evident by the little flows reaching Maqarin.

The aquifer tapped in Syria is the shallow basalt aquifer where thousands of legal and illegal wells are dug. 4186, 1001 and 947 wells were reported in Daraa, Suweida and Quneitra governorates respectively (MoAAR, 2014). The number is said to be much higher up to 11000 well (Etana, 2015). GW use in Syria is estimated to be around 170 MCM/year (UEA, 2018). The abstraction volume could be much higher due to the armed conflict in the basin.

Dams in Syria store the flow of the tributaries, though their retention volumes varies annually. The average volume stored between 2004 and 2009 in the Syrian dams was estimated at 70.3 MCM.

b) Jordan:

Jordan main use of Yarmouk SW is from the KAC diversion that also include Mukheibeh wells discharge. The diverted flows are completely exploited but the quantities vary on an annual basis. The average flow diverted by KAC between years 200 and 2010 is 62.1 MCM/year.

The A7/B2 aquifer is the main aquifer tapped in Jordan and is exploited for domestic use and irrigation. According to the Jordanian MWI (2017), 54.53 MCM were pumped in the Jordanian part of Yarmouk basin in 2017, what is equal to 136.3% of the basin's aquifer safe yield (MWI, 2017). Small amounts of treated wastewater are also used in Jordan.

c) OSoI:

OSoI use Yarmouk water from four sources. The main source is the volumes pumped from Yarmoukim that bypass Adassiyeh weir. The quantity varies annually but on average the volume is nearly 71 MCM per year (UEA, 2018). Other sources include spring discharge in occupied al Himmeh accounting for 14 MCM annually and an estimated 5 MCM per year from dams in the occupied Golan Heights (UEA, 2018). GW is also tapped in Golan where 2 MCM are abstracted annually from wells in Meitsar.

3.4. Syrian War Impact and Aftermath

The Syrian war had a huge impact on the water resources in the Yarmouk basin. Damages done to dams, wells and pump stations in addition to mismanagement of dams by factions controlling different areas in the basin led to the decrease of SW utilization. Lack of maintenance also contributed to putting dams out of service. The population of Yarmouk were forced to rely on GW to satisfy their water demand. More unlicensed wells were dug in the basin during the war under no supervision or regulations. The change in SW utilization and the increased reliance on GW was evident in the stored volumes in Wehdeh dam which filled with much more volumes than it did before the war.

Spring discharge in Syria were also affected by increased GW exploitation. The natural lake of Muzeirib, a main tourist attraction point and a source of fishing is also utilized for agriculture. The lake which is located north east of Daraa city and is supplied by spring discharge, started to dry during the summer season (Cooke, 2017). The number of illegal wells in the basin also increased causing many wells to dry up and for GW levels to lower (Etana, 2015).

The Syrian general commission of water resources (GCWR) reported that the dams of saham al Golan, ghadir al bustan, adwan, taseel, al allan and raqqad were rehabilitated. Pump stations in daraa and quneitra were also rehabilitated and maintained. Irrigation networks in the basin were also fixed and maintained (GCWR, 2020a, 2020b).

3.5. WEAP Methodology

WEAP represents a supply-demand system through a set of nodes connected by three types of links. River systems can be drawn as reaches connecting river nodes while demand sites, catchments, reservoirs and aquifers are represented by nodes. Links between a river, aquifer or a reservoir and a demand site are transmission links while links between a catchment and an aquifer or a river are runoff/infiltration links. A return link can also be used for flows not consumed by a demand site. WEAP also allows to model diversions from rivers, wastewater treatment plants and additional/external sources of water.

WEAP calculates both the supply and demand for a monthly or daily time-step. It then allocates the available water to demand sites based on their priorities and supply preferences.

The catchment node is where all the hydrological modeling occurs, it functions as a watershed unit and is also considered a demand site when irrigation is practiced within. A catchment uses data of land use, climate, soil and irrigation to simulate all hydrological processes in a watershed. It will calculate runoff, infiltration, evapotranspiration and irrigation demands using built in algorithms.

WEAP provides 5 different method to simulate these processes with varied complexities:

1. Irrigation Demands Only Simplified Coefficient Method
2. The Rainfall Runoff Simplified Coefficient Method
3. The Rainfall Runoff Soil Moisture Method
4. MABIA Method
5. The Plant Growth Model or PGM

Both the PGM and MABIA methods use a daily time step and since there is lack of available data on a daily basis these methods were not considered. Between the first 3 methods the soil moisture method is considered the most complex and was chosen for modeling the Yarmouk basin.

Soil moisture method:

This one dimensional, 2-compartment (or "bucket") soil moisture accounting scheme is based on empirical functions that describe evapotranspiration, surface runoff, sub-surface runoff (i.e., interflow), and deep percolation for a watershed unit. This method allows for the characterization of land use and/or soil type impacts to these processes. (SEI, 2011)

This method divides the soil into two layers; the top layer is called the root zone layer (or upper soil layer) while the bottom layer is called the deep soil layer. The exchange between these 2 layers are dictated by a set of parameters that characterizes the soil-water interactions. Other interactions such as rainfall and evapotranspiration are also modelled using crop coefficients and climatic data.

The bottom bucket purpose is to represent aquifer storage and discharge, however it does not allow abstraction from the volume stored in it. The two bucket model may be a better fit in a watershed where GW discharges at a consistent rate and is not an important source for use. In the Yarmouk basin, the aquifer discharge is affected by GW withdrawals while the GW is one of the main sources of water. The bottom bucket was thus neglected in the modeling of Yarmouk basin, and was substituted by an external GW node. The model therefore became a one-bucket soil moisture model (Figure 5).

A watershed unit can be divided into N fractional areas representing different land uses/soil types, and a water balance is computed for each fractional area, j of N. Climate is assumed uniform over each sub-catchment, and the water balance is given as (SEI, 2011):

$$Rd_j \frac{dz_{1,j}}{dt} = P_e(t) - PET(t)k_{c,j}(t)\left(\frac{5z_{1,j} - 2z_{1,j}^2}{3}\right) - P_e(t)z_{1,j}^{RRF_j} - f_j k_{z,j} z_{1,j}^2 - (1 - f_j)k_{z,j} z_{1,j}^2$$

Where z1, j is the relative water storage given as a fraction of the total effective storage of the root zone (mm) for a land cover fraction, j. Pe is The effective precipitation while PET(t) is the reference potential evapotranspiration calculated using a modified Penman-Monteith equation. kc,j is the crop coefficient for each fractional land cover and RRFj is the runoff resistance factor of the land cover. ks,j is an estimate of the root zone saturated conductivity (mm/time) and fj is the preferred flow direction; a coefficient used to partition the flow out of the first bucket into interflow and flow to the deep soil layer or GW.

The term $PET(t)k_{c,j}(t)\left(\frac{5z_{1,j}-2z_{1,j}^2}{3}\right)$ is the evapotranspiration losses.

The term $P_e(t)z_{1,j}^{RRF_j}$ is the total surface runoff.

The term $f_j k_{z,j} z_{1,j}^2$ is the interflow (runoff due to horizontal flow in the upper layer).

The term $(1 - f_j)k_{z,j} z_{1,j}^2$ is the deep percolation (infiltration to the deep layer from the upper soil layer). These flows are directly transmitted to the aquifer node when the catchment is connected to it by an infiltration link and thus interactions inside the deep (bottom) layer are neglected effectively turning the method into a one “bucket” system.

Thus total surface and interflow runoff, RT, from each sub-catchment at time t is (SEI, 2011):

$$RT(t) = \sum_{j=1}^{N} A_j \left(P_e(t)z_{1,j}^{RRF_i} + f_j k_{z,j} z_{1,j}^2\right)$$

When an aquifer is introduced into the model and a runoff/infiltration link is established between the watershed unit and the groundwater node, the recharge R (volume/time) to the aquifer is:

$$R = \sum_{j=1}^{N} A_j \left(1 - f_j\right)k_{z,j} z_{1,j}^2$$

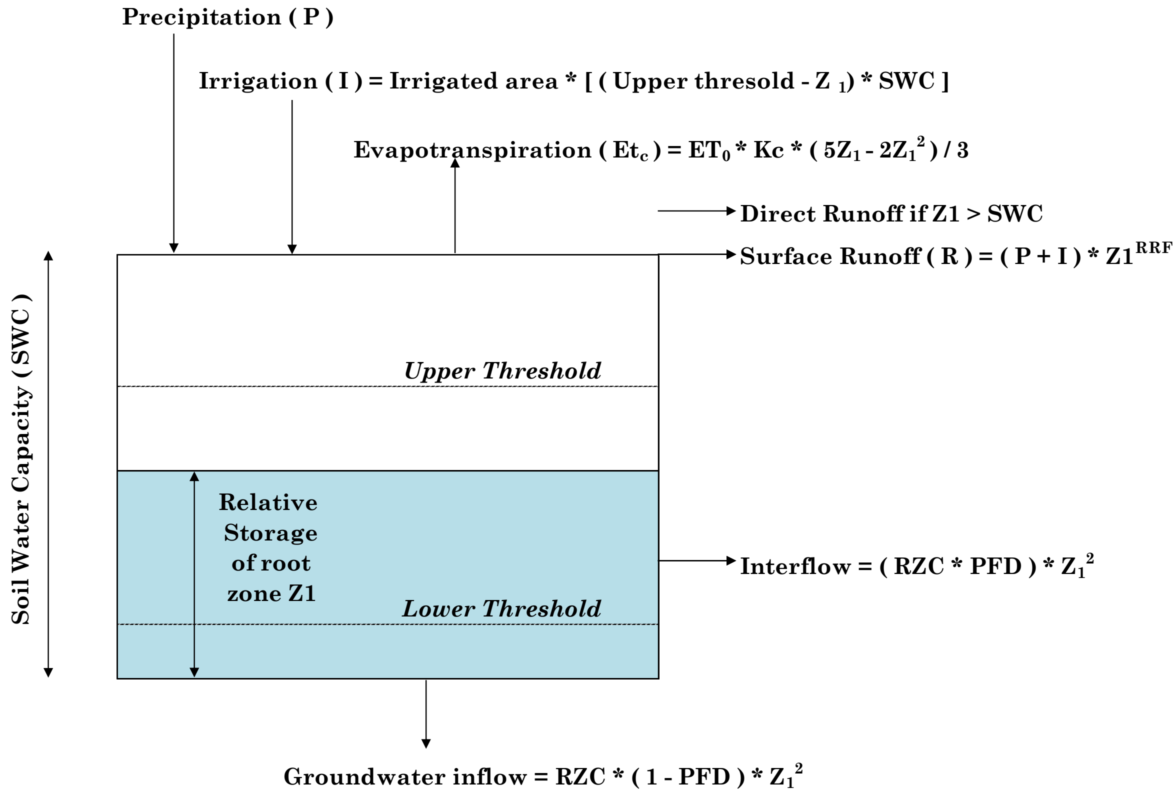

Figure 5: Conceptual diagram of the one-bucket soil moisture model

Evapotranspiration:

The reference potential evapotranspiration (ET_0) is calculated using a modified Penman-Monteith equation. ET_0 is the rate of evapotranspiration of a hypothetical 0.12 m high grass crop with a 69 s/m surface resistance and can be calculated under any climatic conditions. This value represents the potential water losses through the evaporation and transpiration processes whenever water is available. The modified Penman-Monteith equation used in WEAP:

$$E_{rc} = \frac{\Delta}{\Delta + \gamma^*}(R_n - G) + \frac{\gamma}{\Delta + \gamma^*}\frac{900}{T + 275}U_2 D$$

Where:

- Rn = net radiation exchange for the crop cover, mm/day
- G = measured or estimated soil heat flux, mm/day
- T = temperature, ^{0}C
- D = vapor pressure deficit, kPa
- U_2 = wind speed at 2 m, m/sec
- Δ = temperature gradient of saturated vapor pressure, kPa.$^0C^{-1}$
- γ = psychometric constant kPa.$^0C^{-1}$

The actual evapotranspiration losses are estimated using the following equation:

$$ET_c = K_c * ET_0$$

Where Kc is the crop coefficient; a ratio that varies according to the land cover and the type of crop or tree planted and its growth stage.

In WEAP actual evapotranspiration is calculated as a function of the relative storage of the root zone layer:

$$ET_c = K_c * ET_0 * \frac{5z_1 - 2z_1^2}{3}$$

Irrigation:

In the soil moisture method, irrigation is dictated by two thresholds (upper and lower) that represent a value of the relative soil moisture z1 of the root zone layer. When the relative soil moisture goes below the lower threshold irrigation is applied until the relative soil moisture reaches the upper threshold value. The rate in which irrigation is applied is therefore dictated by the crop evapotranspiration and the losses through seepage and runoff.

Scenarios:

WEAP starts its simulation from a “current account” year, which is a year where required data are available and the system’s conditions are well known. Based on the current account year, WEAP builds a reference scenario, a scenario which represents the natural trends and standard changes occurring in the basin that can also be called the “business as usual” scenario. The reference scenario inherits the data of the current account year and then by applying various trends and changing certain conditions, other scenarios are created and used to explore the impact of developments on supply, demand or even the infrastructures in the system.

Reservoirs:

WEAP models the allocation of water and the operation of a reservoir based on the water level in the reservoir. A reservoir is divided to four zones that dictate the releases of water stored in a dam. The top zone is the flood control zone in which any inflow that surpass the top of conservation level is directly released. Water available in the second zone named conservation zone are allowed to be released freely to satisfy downstream demands. When water levels reach the buffer zone, water availability is then restricted by the buffer coefficient, a value that ranges between 0 and 1 which control the monthly percentage of water in the buffer zone available for allocation. The volume of water in the inactive zone is not available for any release. The four values, top of conservation, top of buffer and top of inactive defines the range for each zone (Figure 6).

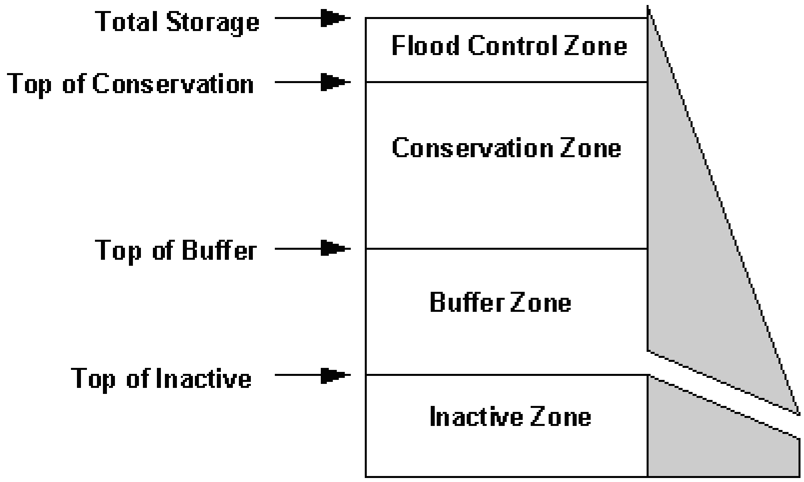

Figure 6: Reservoir zones in WEAP (SEI, 2011)

Losses from reservoirs such as evaporation and seepage can also be modelled. The monthly evaporation rate can be positive or negative to account for the difference between evaporation and precipitation on the reservoir surface, seepage losses can be similarly entered as monthly values (SEI, 2011). WEAP uses a volume-elevation curve to calculate the monthly evaporation from the reservoir where it assumes a cylindrical shape to convert the curve into a surface area.

3.6. Data

The availability of data is a major problem in the Yarmouk basin. Little data is available from the Syrian side concerning water flow in tributaries, dams and GW use. In addition, many available information had gaps in them or were too general to have any usefulness. Moreover, some information were of low confidence and were in need of more verification.

3.6.1. Climate

Monthly precipitation data were acquired for the years 1981 to 2015. Table 1 shows the precipitation levels for each sub basin for the water year of 2005, the year chosen as the current accounts year. The acquired rainfall data were generated by coupling data available from remote sensing (CHIRPS) and ground gauging stations. (UEA, 2018)

The humidity and wind data were acquired from the NASA Power meteorological data sets. The data sets are derived from GMAO Modern Era Retrospective-Analysis for Research and Applications (MERRA-2) assimilation model products which are available at 0.5° spatial resolution. The collected data are point monthly averages measured at a 2m elevation. The values were taken at latitude = 32.68° and longitude = 36.13° and are shown in Table 2.

Temperature data were acquired from NASA FLDAS Noah Global data products released by NASA GES DISC. The dataset contain climatological data available at 0.1° spatial resolution. The data were extracted using ArcGIS and calculated for each sub basin (Table 3).

Year	Month	Precipitation (mm)						
		Raqqad	Allan	Al Hareer	Thahab	Zeidi	Shallala	Main outlet
2004	OCT	15.0	12.8	12.1	10.1	9.4	10.9	11.4
2004	NOV	112.9	90.0	66.7	49.2	46.7	78.3	88.9
2004	DEC	67.9	56.5	41.3	31.9	28.2	48.1	54.8
2005	JAN	118.8	91.4	57.6	43.5	39.3	78.2	97.6
2005	FEB	162.6	123.8	102.9	81.1	60.9	88.4	110.7
2005	MAR	42.9	37.0	28.1	31.4	34.4	62.8	50.7
2005	APR	32.6	24.1	23.2	17.0	10.7	13.8	19.5
2005	MAY	11.6	8.5	7.9	7.5	6.4	4.7	6.7
2005	JUN	0.6	0.4	0.4	0.4	0.4	0.3	0.6
2005	JUL	0.2	0.1	0.1	0.0	0.0	0.0	0.1
2005	AUG	0.1	0.1	0.1	0.1	0.0	0.0	0.1
2005	SEP	1.0	0.8	0.8	0.9	0.5	0.5	0.8
Sum		566.2	445.5	341.3	273.0	236.8	386.0	441.8

Table 1: Monthly precipitation in current account year in sub-basins

Month	Relative humidity (%)	Wind speed (m/s)
OCT	45.94	2.53
NOV	55.82	2.62
DEC	54.27	2.86
JAN	69.18	3.02
FEB	62.73	2.99
MAR	55.08	2.79
APR	52.59	3.11
MAY	37.77	2.44
JUN	33.6	2.68
JUL	43.91	3.34
AUG	40.33	2.74
SEP	39.45	2.55

Table 2: Relative humidity and wind speed in current account year

Year	Month	Temperature (°C)						
		Raqqad	Allan	Al Hareer	Thahab	Zeidi	Shallala	Main outlet
2004	OCT	19.4	20.6	20.5	20.0	20.2	21.1	23.0
2004	NOV	13.9	15.1	14.7	14.2	14.5	15.9	17.8
2004	DEC	9.2	10.3	9.9	9.4	9.6	11.1	13.1
2005	JAN	7.3	8.4	8.0	7.5	7.7	9.1	11.1
2005	FEB	7.8	9.0	8.7	8.3	8.5	9.8	11.7
2005	MAR	10.5	11.7	11.5	11.2	11.4	12.4	14.3
2005	APR	14.9	16.2	16.1	15.8	15.9	16.7	18.5
2005	MAY	18.9	20.2	20.4	20.0	20.0	20.5	22.3
2005	JUN	22.0	23.4	23.7	23.1	23.0	23.4	25.3
2005	JUL	23.8	25.1	25.5	24.8	24.7	25.1	27.0
2005	AUG	24.1	25.3	25.7	25.0	24.9	25.4	27.3
2005	SEP	22.4	23.7	23.9	23.3	23.3	23.8	25.7

Table 3: Monthly surface air temperature in current account year for each sub-basin

3.6.2. Population Growth

The population data were based on the 2004 censuses in Syria and Jordan while the population trends are based on the growth rate of each country. Information on the growth rates during the pre-war and war periods in Syria were obtained from the UN 2019's population growth rate estimates (UN, 2019). The average growth rate between 2000 and 2010 was 2.64% while between 2010 and 2019 the average rate was -2%.

The growth rates in Jordan were obtained from the Jordanian department of statistics (DoS, 2018) for the governorates inside the basin. The pre-war rate was 3.03% and 5.55% during war due to the incoming refugees.

3.6.3. Land Use and Cover

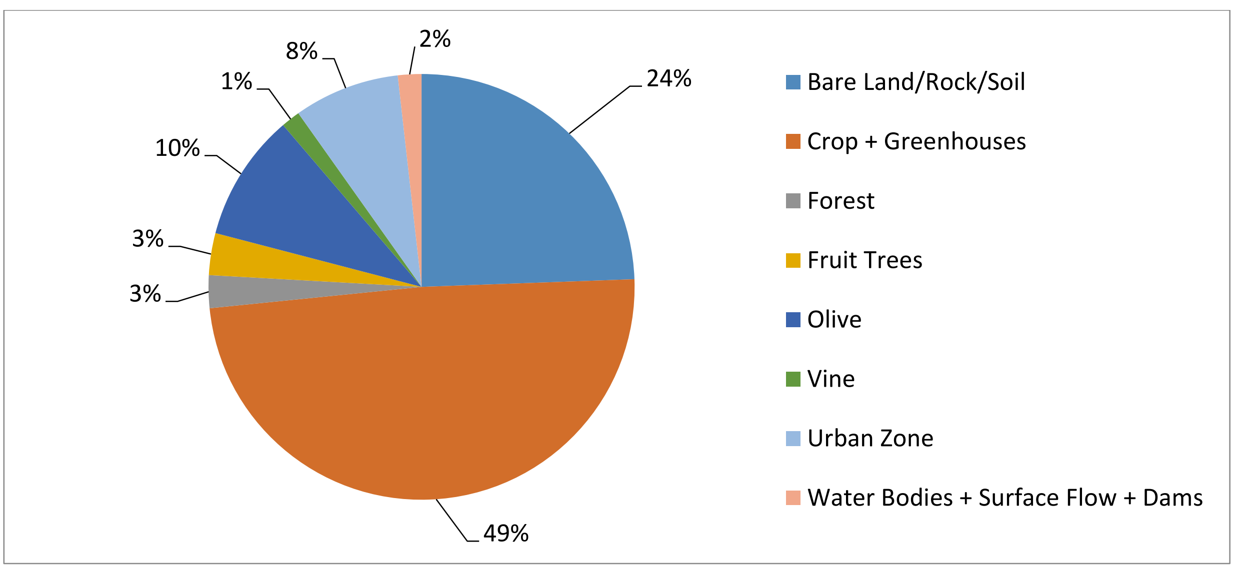

Figure 7: Distribution of each LUC inside Yarmouk basin (UEA, 2018)

The land use/land cover (LUC) map provide information on the spatial distribution of various land covers and are acquired through analysis of remotely sensed imagery. Land cover is essential in watershed studies and water balances, it impacts different processes such as runoff, infiltration, and evapotranspiration. The distribution of LUC classes throughout the whole basin are shown in Figure 7.

The Land cover use map used in the study is based on the ESRI base maps of GEOEYE 2011 (50 cm resolution and 1:20000 scale). The map identifies 13 classes of land cover: Bare land, bare rock, bare rock and soil, forest, crops, fruit trees, olive, vine, green house, urban zone, water bodies, dams and surface flow.

3.6.4. Soil

Soil map was obtained from FAO Digital soil map of the world (Figure 8). The map classifications are based on the FAO-UNESCO soil classification that contain 26 major soil groups and 106 sub-order groups. Soil profiles and textures vary throughout the basin but the vertic cambisols is the most abundant class, mainly in the Hauran plain.

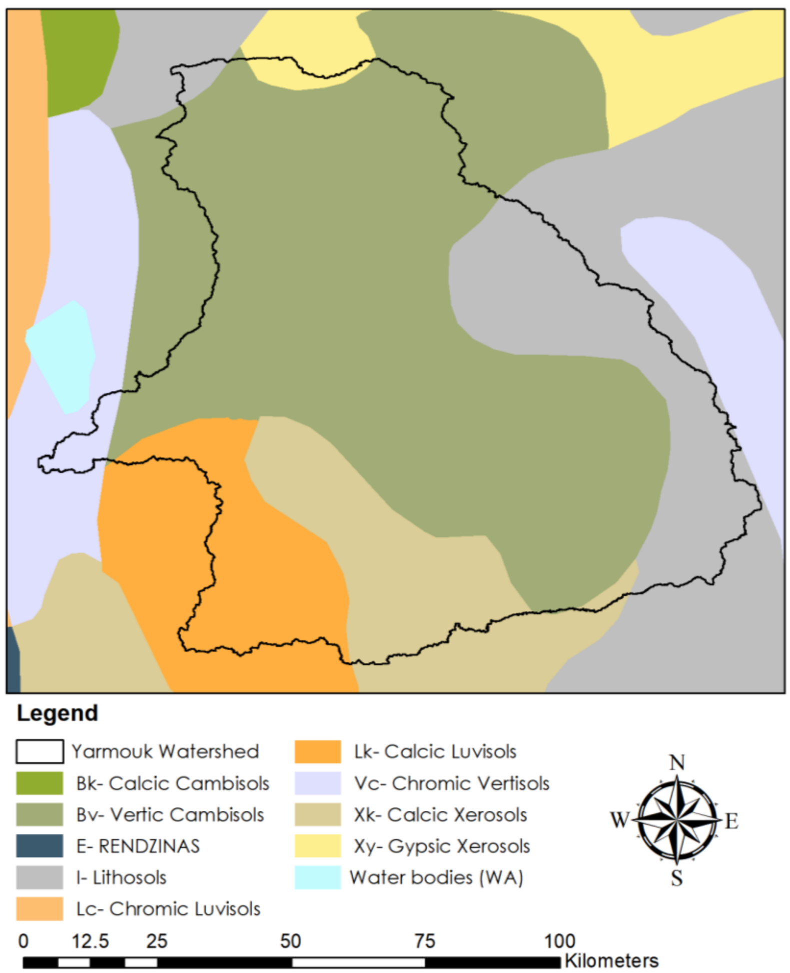

Figure 8: Dominant soil classes in Yarmouk basin (FAO soil map)

3.6.5. Stream Flow Gauge Data

Syrians consider their water data a part of their national security and thus the only available gauging stations records are from the Jordanian side. Gauging data measuring the flow at Maqarin and the outflows of the Wehdeh dam after it started operating are monitored by the Jordanian Jordan valley authority (JVA). Streamflow data at the outlet of Shallala tributary and at the outlet of al Shummar, the main part of Zeidi tributary inside Jordan were also available.

Gauging records at Adassiyeh give the total inflow into KAC (alpha flows) and the flows bypassing the Adassiyeh weir (beta flows). The alpha flows are measured from three separate sources; the natural Yarmouk flow, Wehdeh dam releases and the Mukheibeh wells discharge that is diverted into the Yarmouk mainstream. The water sent from OSoI back to the KAC from the Lake of Tiberias are also gauged by JVA.

3.6.6. Waste Water Treatment Plants

Several wastewater treatment plants exist inside the Jordanian part of Yarmouk basin. The plants are connected to wastewater networks in urban areas, mainly Ramtha and Mafraq. Some plants exist on the borders of the basin but no certainty about their source of water can be obtained. The treatment plants supply 3.8 MCM that are used for irrigation in the basin (Al Bakri, 2016).

The four WWTP: Ramtha, Mafraq, Shallala and Wadi Hassan were identified to be existing inside the boundaries of the basin. The total daily capacity of the 4 plants is 26800 m^3/day; however the supply delivered to the WWTPs is much less (MWI, 2015).

3.7. Stream flow Analysis

The building of dams along the tributaries feeding the Yarmouk River have suppressed the flows in the mainstream river throughout the past five decades. The flow of the Yarmouk River during the dry season originates mainly from springs in the region east of Daraa where several springs such as Muzeirib, al-Ashaary, Zayzoun and others that discharge from the basalt aquifer. The baseflow of the Yarmouk River have declined throughout the years and especially after 2006. This change can be justified by the increased GW abstraction and increased pumping and utilization of the natural discharge of the aforementioned springs. Figure 9 shows the variations in flow at Maqarin where the runoff increased after 2011 as a result of the armed conflict in Syria as will be discussed later.

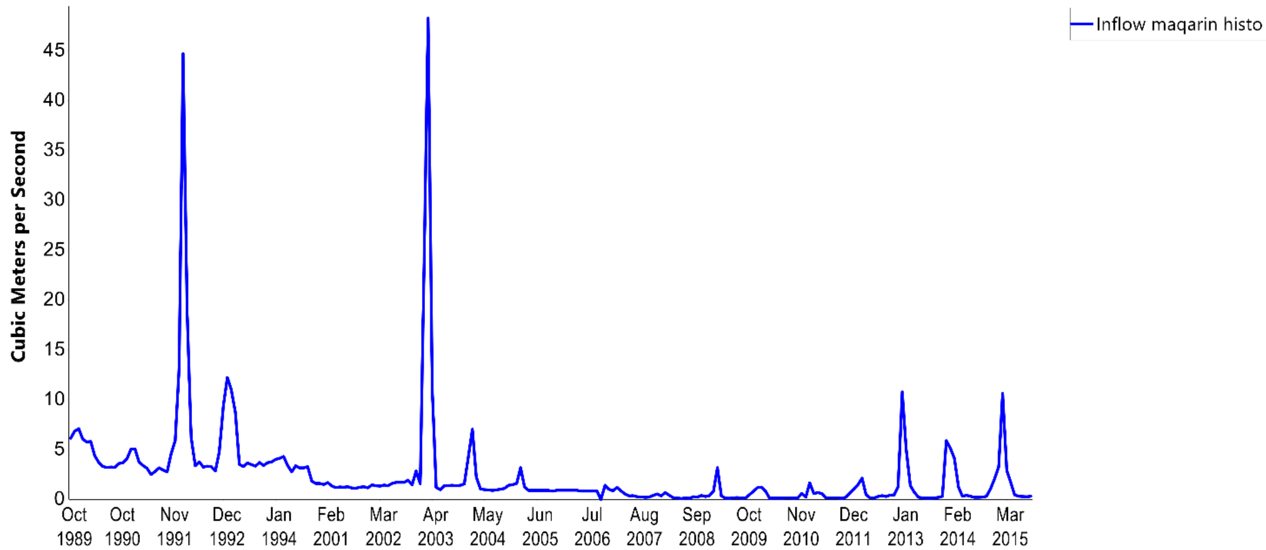

Figure 9: Historical flow of Yarmouk River at Maqarin

3.8. Model Development

3.8.1. Model Setting

The model was set to have a monthly time-step and the water year was set to begin from October and end in September. The water year 2004/2005 was chosen as the current account year. The last year of simulations was set to 2100. Due to the huge impacts of the Syrian war on the water sector in Syria, the reference scenario was partitioned into three different periods; the pre-war period (2005-2011), the war period (2011-2018) and the post-war period (2019-2100). The first two periods are characterized by the general trends and developments that occurred in the basin during each of the two while the last period is used to explore the future impacts of our scenarios.

3.8.2. Demand Nodes

i. Domestic demand:

Domestic and municipal water usage is represented by demand nodes in each sub-basin for both Syrian and Jordanian demands. Demand nodes use two properties to calculate the monthly water demand of the domestic sector. The first property is the annual activity level that characterizes the consumption units whether they are houses, factories or people. The second one is the annual water use rate which describes the yearly water demand per consumption unit.

A demand node was created for each sub-basin's population except for the Main Outlet and Zeidi where 2 nodes were created for each country's population. Population data were then entered for each node.

The consumption rate was set to 64% for the Syrian domestic demand nodes based on the domestic return water volume that was on average around 36% of the demand. The domestic demands was considered to be constant throughout the year. The consumption of Jordan's domestic demand was set to 58%, the average consumption rate in Mafraq and Irbid governorates (MWI, 2013).

The World Health Organization (2003) suggest that the water requirement for domestic use in order to meet the drinking, food, bathing, laundry and all hygiene and sanitation needs is at least 100 liter/capita/day. By taking into consideration the physical losses in supply networks that surpass the 50% level in some countries, this value may go up to 200 liter/capita/day.

Based on data of the total domestic demand in the Syrian part of the basin and the population in the considered area, the water demand per capita in Syria was taken as 83.05 m^3/capita/year (227.5 liters/day/capita). While in Jordan, the domestic supply usually ranged between 130 and 145 liters/day/capita (JVA, 2015) thus the water demand was set to 49.28 m^3/capita/year.

ii. Industrial demand:

Similar to the domestic demand, one industrial demand node was used for the Syrian industrial use with an annual demand rate equal to 32 MCM. The reuse rate of the industrial node in Syria was 80% thus a consumption rate of 20% was entered. The industrial demand in Jordan is not significant and was neglected.

iii. Diversion demand:

Either a demand node or a supply requirement node are needed to force releases from Wehdeh dam. But since the allocation of Jordan and OSoI is a function of the incoming flow and the functioning and operation of the Adassiyeh weir which cannot be easily quantified, and because the monthly diversion during the current account year do not fit with the expected monthly allocation after Wehdeh dam was built and operated, the monthly demand was set to be equal to the annual demand mince the delivered monthly supply around the year. Two nodes were used for OSoI pumping and Jordans' diversion through KAC.

3.8.3. Catchments

Seven catchments each referring to a sub-basin were created. Each catchment was set to have irrigated areas thus it was considered by WEAP as both a watershed unit and a demand site.

a. Land Use Parameters

i. Area:

Each catchment was divided into several land cover classes and were entered for each of the 7 sub-basins. The Land classes of water bodies, dams and surface flow were combined into one category and the classes of green houses and crops were combined similarly.

Crop areas were also divided within each catchment by two criteria: country and the seasonality of the crop. Classes of olive, vine, fruit trees and crops were divided into rainfed and irrigated areas. The average irrigated areas in Syria is around 35,000 hectares before the start of the war. The majority of the crop lands in Syria are of wheat, barley and chickpeas. Some vegetables are also grown, mainly tomatoes and melons. The actually planted crops in the Yarmouk basin were identified by comparing the planted crops statistics in Syria (CBS, n.d.) and Jordan (DoS, 2020) with the crop LUC map area and their distribution over the Jordanian and Syrian governorates.

ii. Crop Coefficient (Kc):

Values of crop coefficients for various crops and trees are provided by the food and agriculture organization. FAO Irrigation and Drainage Paper No. 56 (Allen et al. 1997) gives the variation of Kc values during the growth stages of the crop or tree (Table 4 and Table 6) in addition to the length of each stage (Table 5 and Table 7). Crops are considered to go through 4 stages, the initial stage start crops or trees are planted or start to grow until it reach 10% of ground cover, the development stage where the plant grow to reach full cover, the mid stage from when the plant or tree stops growing till it starts to mature. The late season stage continue to when the crop or tree is harvested, dries out or its leaves fall.

The growth stages are the initial stage, development stage, mid-season and late-season. Each type of planted crop and tree were thus assigned to a crop coefficient curve.

Crop	Kc_{ini}	Kc_{dev}	Kc_{mid}	Kc_{late}
Wheat	0.7	>>	1.15	0.4
Barley	0.3	>>	1.15	0.25
Lentil	0.4	>>	1.1	0.3
Chickpeas	0.54	>>	0.97	0.29
Tomato	0.6	>>	1.15	0.8
Potato	0.5	>>	1.15	0.75
Melons	0.5	>>	1.05	0.75
Peas	0.5	>>	1.15	0.3
Beans	0.5	>>	1.15	0.75
Squash	0.5	>>	0.95	0.75
Cabbage/Cauliflower	0.7	>>	1.05	0.95
Eggplant	0.6	>>	1.05	0.9
Maize	0.3	>>	1.2	0.35
Alfalfa	0.4	>>	0.95	0.9

Table 4: Crop coefficients of various crops and vegetables planted in Yarmouk basin (Allen et al. 1998)

Crop	L ini	L dev	L mid	L late	Plantation date
Wheat	30	140	40	30	November
Barley	30	140	40	30	November
Lentil	25	35	70	40	November
Chickpeas	80	35	40	35	December
Tomato	30	40	45	30	April/May
Potato	25	30	45	30	February
Melons	20	30	30	30	April
Peas	20	30	35	15	March/April
Beans	20	30	35	15	March/April
Squash	25	35	25	15	April
Cabbage/Cauliflower	40	60	50	15	September
Eggplant	30	45	40	25	May
Maize	20	25	25	10	May/June
Alfalfa	10	20	20	10	January

Table 5: Plantation date and growth stage lengths of crops (Allen et al. 1998)

Tree	Kc ini	Kc dev	Kc mid	Kc late
Olive	0.65	>>	0.7	0.7
Vine	0.3	>>	0.85	0.45
Apple/Pear/Cherries	0.9	>>	0.95	0.75
Apricot/Peach	0.55	>>	0.9	0.65
Almond	0.4	>>	0.9	0.65
Citrus	0.75	>>	0.7	0.75
Walnut	0.5	>>	1.1	0.65

Table 6: Crop coefficient of various trees planted in Yarmouk basin (Allen et al. 1998)

Tree	L_{ini}	L_{dev}	L_{mid}	L_{late}	Growth start
Olive	30	90	60	90	March
Vine	20	50	75	90	March
Apple/Pear/Cherries	30	50	130	30	March
Apricot/Peach	30	50	130	30	March
Almond	30	50	130	30	March
Citrus	60	90	120	95	Jan
Walnut	20	10	130	30	April

Table 7: Growth start date and growth stage lengths of trees (Allen et al. 1998)

Crop coefficients for other land use and cover classifications were adapted based on crop coefficients from Nistor (2018) and Amato et al. (2006) (Table 8).

Land classification	Annual crop coefficient Kc
Bare areas	0.23
Forest	1
Urban zone	0.77
Water bodies	0.6
Fallow/Pastures (non-planted crops area)	0.7

Table 8: Applied crop coefficient for various LUC classes

iii. Runoff Resistance Factor (RRF):

The runoff resistance factor is a parameter used to control the direct surface runoff response. The factor can be attributed to different properties of a catchment or land class but is mainly a function of Leaf area index (LAI) and land slope. Initial values of RRF (Table 9) were adopted from Scurlock et al. (2001) and Amato et al. (2006).

Land classification	Initial RRF values
Bare areas	1.31
Forest	5.18
Crops	4.22
Fruit trees	4.63
Olive	4.63
Vine	4.63
Urban zone	8
Water bodies	0.1

Table 9: Initial runoff resistance factor for different LUC classes

b. Soil Parameters

i. Soil water capacity (SWC):

This parameter characterize the capacity of the upper soil layer to withhold water and is represented as depth of water (mm). The capacity is considered of moderate sensitivity in WEAP. The capacity can be attributed to certain physical properties of the soil that represent water availability.

The relative soil water storage, z1, is given as a fraction of the total effective storage and varies between 0 and 1, where 0 represents the permanent wilting point and 1 field capacity. (Yates et al., 2005)

Field capacity (FC) is defined as the amount of soil moisture or water content held in the soil after excess water has drained away and the rate of downward movement has decreased (VEIHMEYER, 1931). While permanent wilting point (PWP) refers to the water content of a soil that has been exhausted of its available water by a crop, such that only non-available water remains (FAO, 2003).

Catchment	FC (%)	PWP (%)	Root zone storage (%)
Al Hareer	36.01	25.95	10.06
Zeidi	28.95	18.83	10.12
Shallala	17.32	10.46	6.86
Thahab	38.73	28.51	10.22
Allan	40.40	30.20	10.20
Main Outlet	34.57	24.87	9.70
Raqqad	39.69	29.51	10.18

Table 10: Average field capacity and permanent wilting point in each sub-basin

These values where estimated based on the dominant soil classes in the basin using SWC (Soil Water Characteristics) software based on the clay, sand, silt and organic matter contents of the topsoil layer.

After finding the FC and PWP of each soil type (Table 10), initial values of SWC were assigned to each land class based on the average rooting depth of each LUC class. The rooting depth is the depth from which roots can extract water. Even though several LUC classes do not have roots, this value represent the depth of the top soil layer where evapotranspiration can occur. The rooting depth values were adapted from (Dickinson et al. 1993) and (Liu & Smedt, 2004).

ii. Root zone conductivity (RZC):

The root zone conductivity is defined as the conductivity rate of the upper soil layer when fully saturated and is represented in mm/month. This parameter dictates the quantity of water that leaves the root zone layer though infiltration or interflow. This parameter can be attributed to the physical property of saturated hydraulic conductivity of the upper soil layer. Estimates of this property were derived by Soil Water Characteristics software using the information on the topsoil layer of each soil texture.

"Water holding capacity" and "hydraulic conductivity" as they are used as input variables for the WEAP model do not correspond to "field capacity" (FC) and "saturated hydraulic conductivity" (Ksat) as they are defined within the scope of soil science; both physical values are used as WEAP-specific items. (ASCAD, 2008)

It is important to note that the soil water capacity and root zone conductivities do not exactly represent the measurable physical properties of the soil but can be considered as an indicator to determine the variability of such parameters throughout the sub-basins. This difference can be justified by the soil-water interaction mechanisms used in the WEAP model and by the adopted monthly time-step.

In sub-basins having more than one soil texture, each LUC class was partitioned to several categories based on the soil map and LUC map intersection. Each category was then assigned its designated soil's initial RZC value (Table 11).

Soil texture	Saturated hydraulic conductivity (mm/hr)	Initial RZC (mm/month)
XY	26.91	19375
I	8.90	6408
BV	0.91	655
VC	0.67	482
LK	25.54	18389
XK	10.43	7510

Table 11: Initial RZC values per soil texture

iii. Preferred flow direction (PFD):

This parameter partitions the soil moisture of the top bucket into interflow and infiltration. The factor is a unit-less coefficient that ranges between 0 and 1. All PFD values were initially set to 0, implying that water leaving the upper layer can only be infiltrated to GW.

iv. Initial z1:

The initial z1 is the relative soil moisture present in the top layer of soil at the beginning of WEAP's simulation. A value of 30% was set to all catchments and LUC classes.

3.8.4. Groundwater

Little information is available about the basalt aquifer in Syria and its properties. The GW in the basin was represented by two GW nodes, the first represent the basalt aquifer that is tapped by Syria and OSoI while the other represent the A7/ B2 and the Jordanian abstraction. The storage capacity of the node was left blank, which indicate an unlimited storage. GW initial storage was roughly estimated using the equation:

$$\text{Volume} = \text{Porosity} * \text{Aquifer thickness} * \text{Aquifer surface area}$$

The average porosity of the saturated basalt aquifer in Syria was taken at 29% (Asfahani, 2017). The basalt saturated aquifer thickness varies from area to another but was taken equal to 8 m. The aquifer initial storage was thus estimated at 14000 MCM.

The porosity of the A7-B2 is estimated at 4%. The surface area of the aquifer was estimated to be equal to Jordan's area inside the Yarmouk basin. The thickness of saturated aquifer was equal to 45 m at Hussein airforce base near Mafraq (Margane et al. 2015). The initial volume was thus estimate to be equal to 2370 MCM.

In both Syria and Jordan, the GW use is above the sustainable limits. It is estimated that Syria use 170 MCM from GW while in Jordan official data estimate it to be around 35 MCM, however abstraction is estimated to be much more. The total withdrawal was estimated at 250 MCM by both Syria and OSoI and 50 MCM by Jordan. The maximum monthly withdrawal limit between April and September was assumed to be 35% higher than the limit between October and March.

3.8.5. Dams

The 40 Dams in the basin are modelled as a reservoir node in WEAP. The dam node requires several information regarding the dam's storage capacity, initial storage and startup year. Data on losses to evaporation and groundwater seepage can also be included.

The dams located on the same tributary were considered as one reservoir that collects the catchment's runoff (Table 25).

The storage capacity of each reservoir node on the Allan, Hareer, Raqqad, Thahab and Zeidi tributaries was set as the total storage of all reservoirs on each tributary. The startup year of Wehdeh dam was set to 2007, and a 110 MCM storage capacity was assigned.

The initial storage of the reservoir nodes was estimated with the help of remote sensing methods. The storage of the 21 dams with a total capacity of 283.58 MCM were estimated using satellite imagery. Landsat 4, 5, 7 and 8 images were analyzed using GIS tools to find the surface area of the water body behind each dam. Landsat images contain several bands with different detected properties, the Near Infra-red bands were used to detect the surface area of the major dams in the basin. The areas were then delimited and measured and using a linear volume-area relationship the storage of each dam was calculated.

The volumes were calculated for spring and late summer seasons when the dams are at their highest and lowest capacities respectively. The retained volumes in the Syrian dams were studied during the war period when several dams were damaged, mismanaged and lacked maintenance. They were also calculated for the years prior to the Syrian war. The estimated values used to modify the capacities of dams in Syria during the armed conflict.

The volume-elevation relation were set for each dam node using a linear relationship using data of maximum height and surface area of the dams in Syria (CBS, n.d.). Monthly evaporation rates were derived from FAO water productivity open access portal database (FAO, n.d.).

The lack of any data about the dam operation, a series of assumptions were made based on the estimated volumes in the spring and summer seasons. Conservation level was set to be equal to the total storage capacity for each dam. Top of inactive level was set to 5% of the total storage capacity while the top of buffer level was assumed to be at 40% of it. Buffer coefficient was initially given a value of 0.2.

3.8.6. WWTP

The daily hydraulic capacity of the plants was entered as 26800 m^3/day. The consumption of the WWTPs was set to 47% based on the reported supply and reuse of the treated water in Yarmouk.

3.8.7. Priority

The model depends on the different priorities set for the demand sites and dams to determine the allocation order of each node. In WEAP, priorities range between 1 and 99 where the higher value represent a lower priority while a lower value gives a higher importance in allocations. The priorities also play a role in dividing water resources during water shortages such that lower priority demands are more prone to water shortages. Equal priorities mean water is supplied equally until no more water is available for allocation.

Country	Node	Priority
Syria + Jordan	Domestic demand	2
Syria + Jordan	Industrial demand	2
Syria + Jordan	Agricultural demand	2
OSoI	Dam demand	2
OSoI	GW demand	2
Syria + Jordan + OSoI	Dams allocation except Wehdeh	Nov to Feb: 1 Mar to Oct: 3
Jordan + OSoI	Beta minimum flow requirement	5
OSoI	OSoI diversion	6
Jordan	KAC diversion	6
Syria + Jordan	Wehdeh dam	Nov to Mar: 4 Apr to Oct: 99

Table 12: Priority values applied in WEAP

In Syria, Jordan and OSoI, the domestic, industrial and agricultural demands were all given an equal priority since these demands are supplied simultaneously from GW and SW throughout the basin.

The last release from any dam into another country was when Syria released 16.5 MCM between 1999 and 2002 (UEA, 2018). Thus, it is assumed that no interchange or releases will occur between the three states. The dams constructed on the Yarmouk tributaries by the three riparian states were then given an equal priority value but one higher than the demands downstream of them, however, these dams were assumed to not release any water from November to February and were given a priority value lower than other demands during these months.

OSoI and Jordan diversion demands from the river were given an equal priority value but one higher than the beta flow requirement that represents the operation of the weir at Adassiyeh. Last, the Wehdeh dam was given two priorities, one from November to March and one from April to October based on the observed volume in the years 2007- 2015. The priority values are presented in Table 12.

3.8.8. Supply Preference and Maximum Supply

Similar to the priorities, the supply preference ranges from 1 to 99 but is assigned for transmission links. The supply preference value sets the order of allocation from different sources feeding the same demand node. Both the priority and supply preference control the allocation mechanism in the Yarmouk model.

Source	Time period		
	Pre-war	War	Post-war
Surface water	1	2	1
Ground water	1	1	1

Table 13: Supply preferences in WEAP

Sources of water were classified into either SW (dams and return flows) or GW sources. SW and GW were given an equal preference during pre-war and post-war periods since both supply the agricultural demands simultaneously. During the war period however, GW preference was set higher (Table 13).

Constraints can be placed on transmission links to as a maximum limit of supply from each source whether physical or conceptual. A maximum flow can be set as either as a max volume per time or as a percent of the demand. The Agricultural lands in Syria are supplied from either GW or SW so a limit was placed as a percent of demand, 55% for SW transmission links and 45% for GW ones. In the sub-catchments where Syrian and Jordanian irrigated areas exist, the limits were placed based on the demand of each country.

In addition, Jordanian domestic demands are further supplied from sources outside the Yarmouk basin. Thus it was assumed that the maximum supply from internal sources in the basin is equal to 70% of the demand.

3.8.9. Building Model

The model was built and refined in order to fully represent the supply-demand system in the basin. Several compromisations were needed to accommodate to the available data.

First, layers of the basin, sub basins and the river network were added to WEAP in order to serve as a background and a spatial reference for the model. The mainstream river and the tributaries were drawn along their path as a set of connected nodes. The groundwater nodes were added to the schematic in addition to the catchments of each sub watershed. The catchments were then connected to the groundwater node using a runoff/infiltration link.

Next, the dam nodes were placed on their respective tributaries downstream of the runoff inflow node with the exception of the Yarmouk main outlet catchment. Wehdeh dam was positioned downstream the confluence of the 5 tributaries. The Yarmoukim reservoir was also placed upstream of the Yarmouk confluence. Two runoff/infiltration links were made for the dammed tributaries one flowing upstream of the dams and one downstream of it. The runoff percentage to each link was set according to the ratio of the catchments' area downstream of the dams.

The Syrian and Jordanian domestic and industrial demand nodes were added in their respective sub-basins. The share of OSoI from Yarmouk water was represented by three demand node; one for the surface water flow that bypass the Adassiyeh weir, another for its use of the four dams in the Raqqad sub basin and the last for its groundwater use from wells and GW in the occupied areas of Golan Heights and Al Himmeh. The annual activity level and water use rate were then entered for each demand site.

To compensate the changes in the baseflow of the basin, the headflow of Yarmouk River was entered as the minimum flow in each year as GW inflow. King Abdullah canal was modeled as a diversion that starts from the Yarmouk River at Adassiyeh and continues south. Mukheibah wells monthly discharge was entered as GW inflow in the reach upstream of Adassiyeh weir.

An "other supply" node was added to represent the flows sent by OSoI to Jordan into KAC, and the transferred flow was set as the node's inflow.

A supply requirement node was added on the mainstream river, downstream of the Adassiyeh diversion and was given a minimum flow requirement of 1 m^3/s in order to represent the manner in which the weir is operated by JVA. The supply requirement is placed in the river and treated like a demand node that draws water into the river.

A WWTP node was created in Jordan and was connected by return flow links from Jordanian domestic demand nodes. A transmission link was then created between the WWTP and the catchments of Shallala and Zeidi.

Finally, the demand sites were connected to water sources. Catchments were connected to the groundwater node and to their corresponding dam node. Hareer catchment was also connected to

Allan and Raqqad tributaries dams due to the hydraulic connection through inter-dams connections and the extension of irrigation networks inside the three sub-basins.

The direct use of surface water from rivers is negligible in the basin, thus no direct surface water transmission from the tributaries was used. The main outlet and Shallala catchments were not connected to any dam. Domestic demand nodes in Syria and Jordan were connected only to the groundwater node; their main source of water. A return flow link was then drawn from each Syrian domestic demand sites into their respective tributaries and catchments for reuse. The Syrian industrial demand node was connected to groundwater. The OSoI demand nodes were connected accordingly while their pumping from Yarmouk River was represented by a demand node that combines their irrigation use and the volume stored in the lake of Tiberias. The node was connected to the Yarmoukim reservoir node and given a water use rate equal to the diverted flows in the current account year. The link used in all of the demand sites connections is a transmission link.

3.9. Model Optimization

Running the model using initial values of soil and land class parameters yielded very low ET values and high runoff. The results were expected due to the monthly temporal of the model and the non-realistic soil-water interactions in it. Thus, the parameters of the soil moisture method were in need of adjustment and optimization to fit the available observations.

Due to the little information available about the tributaries and dams in Syrian territories, the temporal of the available data and the number of variables in the soil moisture method, results from the automatic parameter estimation tool (PEST) could not be validated against the available data from Maqarin and upstream of it simultaneously. Inconsistencies and gaps found in the gauged data during many years in addition to complex changes in stream flow due to the armed conflict or to natural changes, restricted the ability to calibrate and validate the model. The model was then optimized for the period between 2004 and 2011 using the available info, mainly, the gauge data at Maqarin and the estimated retained volumes in dams by manually adjusting the variables using specific step adjustments.

The RZC, SWC and RRF were the parameters most focused on during the optimization process. Soil water capacity values were assigned for each LUC class. The SWC of the land classes of urban area, forest, water bodies, crops, fruit trees, olive and vine where all assigned one value since the variation in the initial soil capacities was small between the soils of the sub-basins. SWCs of bare areas were however assigned for each sub basin. SWC values were then adjusted by the order of 50 mm. SWC and PFD parameters of the sub-basins of al Hareer, Raqqad, Allan, Thahab and Zeidi were adjusted based on the maximum retention in the dams between the years 2004 to 2010 (Table 14 and Table 15).

Catchment	Land Classification	Soil water capacity (mm)
All	Urban zone	50
All	Forest	200
All	Water bodies/dams/surface flow	100
All	Crops, Green houses	350
All	Olive, vine, fruit trees	450
Al Hareer	Bare areas	1050
Zeidi	Bare areas	500
Shallala	Bare areas	680
Thahab	Bare areas	200
Allan	Bare areas	400
Main Outlet	Bare areas	400
Raqqad	Bare areas	400

Table 14: Final soil water capacity values

Catchment	PFD values
Al Hareer	0
Zeidi	0.1
Allan	0.35
Thahab	0
Shallala	0
Raqqad	0.05
Main Outlet	0.65

Table 15: Preferred flow direction values in each catchment

The initial values of RZC for each soil texture were very high and thus were adjusted to fit the range between 0 and 1000 mm/month.

Soil texture	Initial RZC (mm/month)	Adjusted RZC (mm/month)
XY	19375	646
I	6408	214
BV	655	22
VC	482	16
LK	18389	613
XK	7510	250

Table 16: Initial and adjusted root zone conductivity values

The RRF values were adjusted based on the actual flow at Maqarin. Parameters of Shallala sub-basin were adjusted based on the measured flow at its mouth. The mainstream sub-basin was the last sub-basin to be optimized based on the streamflow at Adassiyeh (Table 17).

Land classification	Adjusted RRF values
Bare land	2.8
Bare rock/soil	2.38
Bare rock	1.63
Forest	9.52
Crops	8
Fruit trees	8.5
Olive	8.5
Vine	8.5
Urban zone	8.2
Water bodies	1.1

Table 17: Adjusted runoff resistance factor values for each LUC class

The buffer coefficient of dams were also adjusted based on the estimated volumes in spring and summer seasons. For Wehdeh dam however, the buffer coefficient was set to 0.15 while its top of inactive volume was set to 7 MCM based on actual observed retention in the dam (Table 18).

Dam Node	Top of conservation (MCM)	Top of inactive (MCM)	Top of Buffer (MCM)	Buffer coefficient
Raqqad	102.43	5.1215	51.215	0.2
Al Hareer	39.95	1.9975	19.975	0.35
Allan	32.72	1.636	16.36	0.2
Thahab	4.78	0.239	2.39	0.2
Zeidi	31.59	1.5795	15.795	0.15
Wehdeh	110	7	110	0.15

Table 18: Reservoirs operation parameters

Irrigation thresholds were initially estimated then adjusted based on crop and tree water requirements estimations of irrigation demands in the basin. The thresholds varied between 40% and 65% for crops and 40% to 70% for trees and vines.

Observations vs. Simulations:

Simulated retained volume in Wehdeh dam (Figure 10) showed satisfactory results relative to the observed retention during the period from 2006-2015 (NSE=0.65 > 0.5).

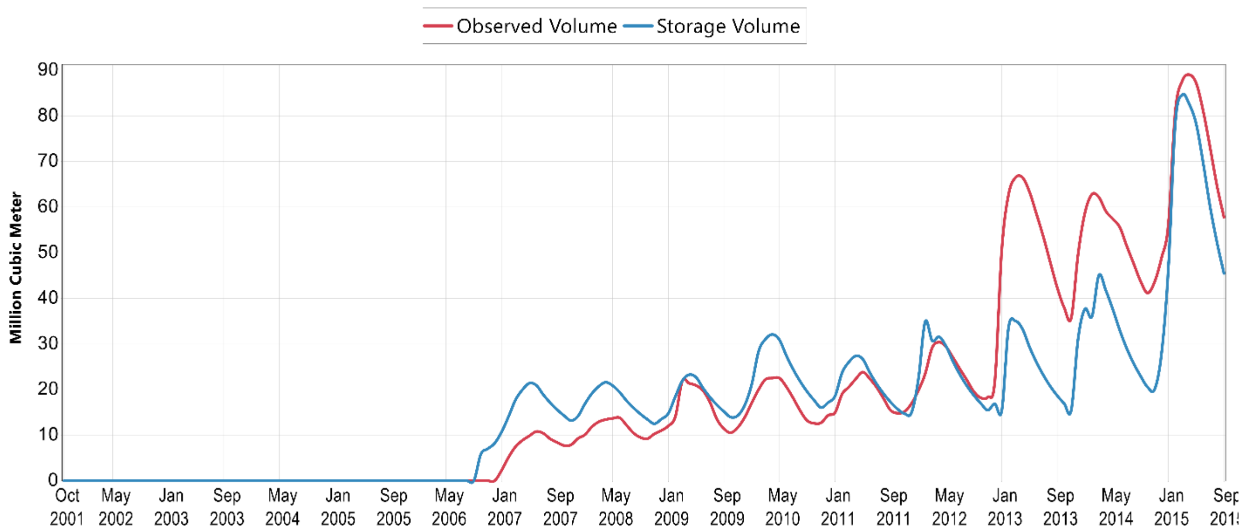

Figure 10: Observed vs. simulated retention storage of Wehdeh dam

The peak volumes retained in the dams of Raqqad, Allan and Zeidi sub-basins showed good consistency (80% to 90%) with the estimated volumes in the spring season during most years (refer to section 3.8.5). Retention of dams on Al Hareer tributary was over-estimated.

The model produced decent results for most years and on a monthly basis (Figure 11, Figure 12, Figure 13 and Figure 14). Peak flows were not very well represented in the wet years 2003 and 2004. The year 2003 was an exceptionally wet year in the basin.

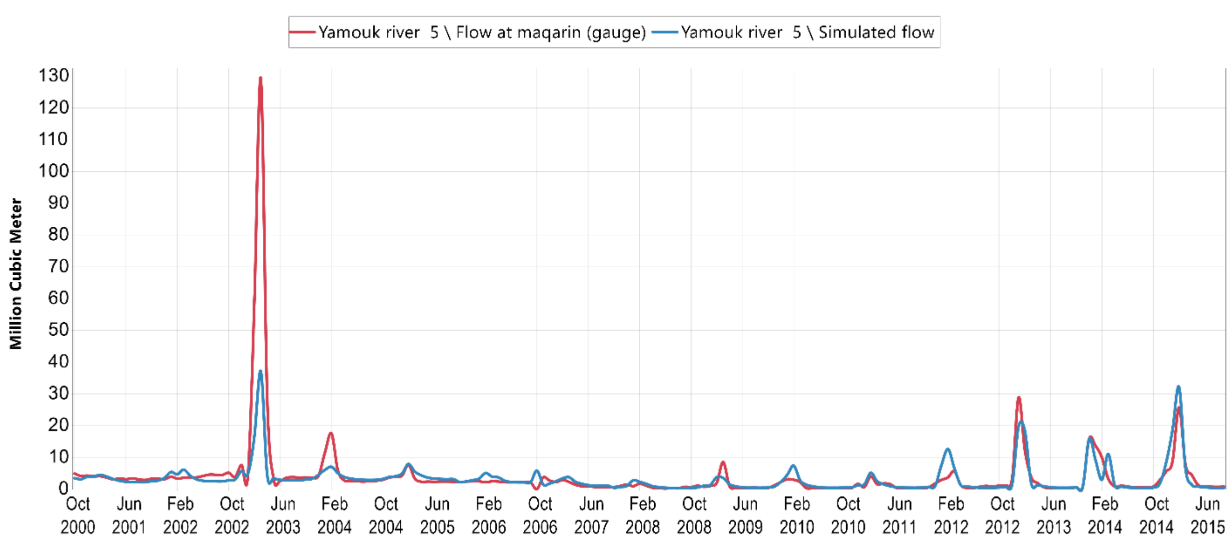

Figure 11: Simulated flow vs. gauged flow at Maqarin

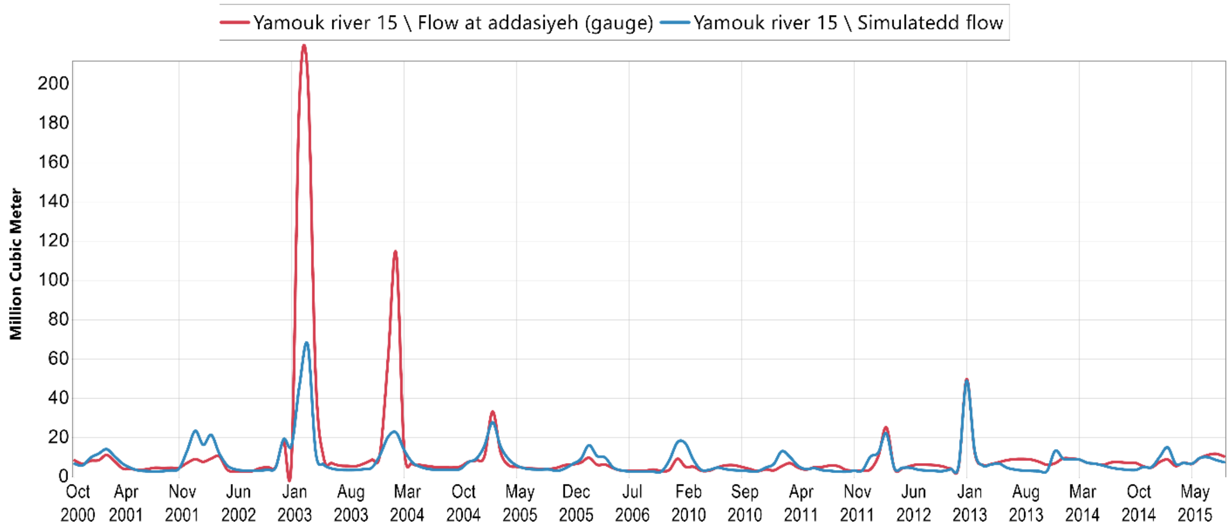

Figure 12: Simulated vs. gauged flows at Adassiyeh

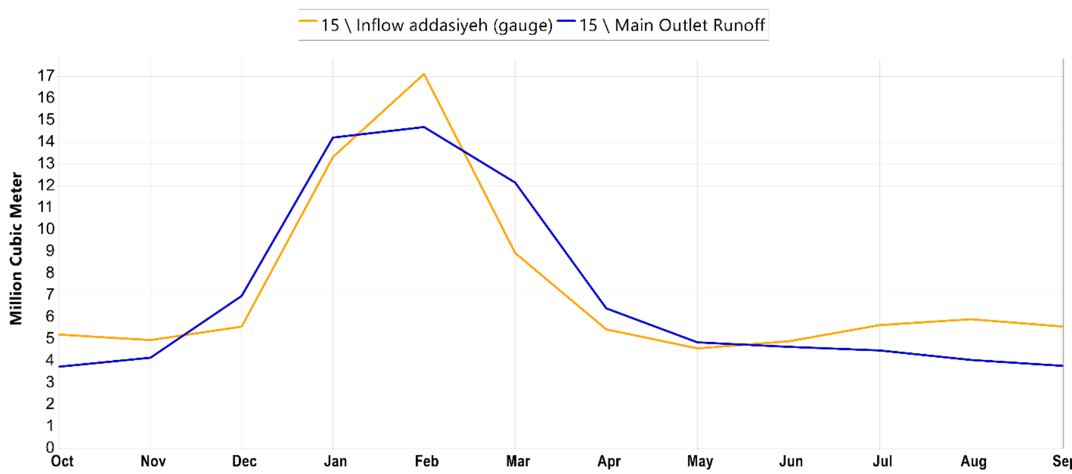

Figure 13: Monthly average of flow at Adassiyeh (without 2003)

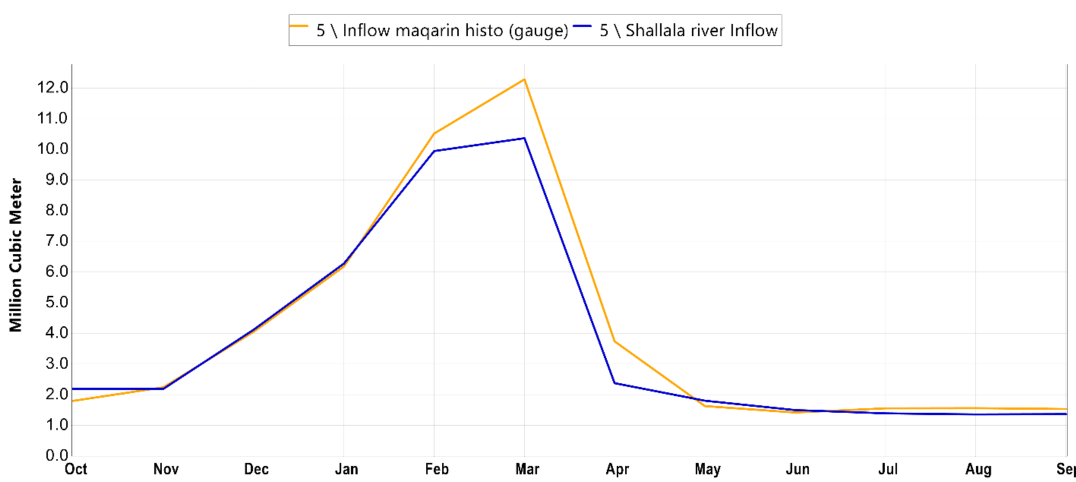

Figure 14: Average monthly flow at Maqarin (without 2003)

3.10. Scenarios

3.10.1. Reference Scenario

The reference scenario will assume a “business as usual” in the post-war period. The population growth rates in the basin were assumed to return to the same levels in the pre-war period and to remain constant.

For the War-period, the population growth in both Syria and Jordan were modified. The growth in Syria was set to -2% while in Jordan it increased to 5.5%. Agriculture in Syria was thus assumed to decrease by 30% throughout the war period.

The dams located in Syria that were affected by the war had their capacities modified according to the estimated retention during that period. In addition, supply preference of GW was set higher than that of SW since it became the main supply source in Syria.

Analysis of satellite images, after the end of the armed conflict in the Yarmouk basin in the years 2019 and 2020, showed that most of the dams started to retain water and have returned to their usual retention levels. In 2019, the estimated volume in spring season was 115 MCM while in 2020, the volume was estimated to have reached 128.1 MCM. Backed by reports of dam rehabilitation in the basin (Gcwr, 2020a, b), it is assumed that the Syrian dams will return to their normal functioning as before the start of the war. It will also assume that the Syrian dams return to be utilized the same manner as before. Thus the dams were considered to return to their full capacity and the supply preference of SW use was adjusted accordingly.

For the pre-war period, no change in land use and cover were assumed. Agricultural areas were considered to return to pre-war levels and remain constant while population growth rates were set to be equal to the rates before the war. In addition, the scenario will assume no change in land cover. Regulation of withdrawals from water infrastructure and maximum abstraction from GW were also assumed to remain constant.

3.10.2. Climate Change Scenario RCP 4.5

Representative Concentration Pathway (RCP) 4.5 is a scenario that assumes an increase in greenhouse emissions that will reach a concentration of 650 ppm CO_2-equivalent or a radiative forcing of 4.5 W/m2 in 2100 (Thomson et al. 2011). The scenario takes into consideration socio-economic changes and its impact on land cover use and emissions. The RCP4.5 scenario in particular assumes that a climate policy is to be introduced to limit greenhouse emissions.

The RCP 4.5 shows a decrease in precipitation and mean temperature in the Jordan River basin. The scenario assumes a 1.2°C increase in mean temperature by 2050 and 1.5°C by 2100 in the Jordan River basin and a 7 % decrease in precipitation by the end of the century. (ESCWA et al. 2017)

3.10.3. Climate Change Scenario RCP 8.5

Similarly the RCP 8.5 scenario assumes that the radiative forcing will reach 8.5 W/m2 by 2100. The scenario is considered pessimistic and is viewed as the worst case scenario regarding climate change.

According to the RICAAR report, the RCP 8.5 scenario shows a 1.5°C decrease in temperature by 2050 and a 3.2 $^{\circ}$C by 2100. It also projects a 7 % decrease in rainfall by 2050 and 13% by 2100. (ESCWA et al. 2017)

3.10.4. Irrigation Systems Enhancement Scenario

Irrigation systems in the Syrian part of the yarmouk basin are efficient to a certain extent. Sprinkler, drip and direct surface watering are the methods used in irrigation in Syrian part of Yarmouk basin (Table 19). According to Brouwer et al. (1989), field application efficiencies of 90%, 75% and 60% should be used for drip, sprinkler and surface irrigation methods respectively in case of no local data is available. GW use in irrigation was assigned a 97.6% utilization efficiency while SW was set to 70.3%.

Governorate	Irrigation method used (%)		
	drip	sprinkler	surface watering
Dara'a	44.5	14.0	41.5
Suweida	77.3	2.6	20.1
Quneitra	47.1	2.0	50.9

Table 19: Pre-war average of Irrigation methods used in Syrian governorates (CBS, n.d.)

Based on the intersection of crop area inside the basin and the crop areas in the Syrian bureau of statistics (CBS, n.d.) data, the total efficiency of irrigation in the Syrian part of Yarmouk was estimated at 65.2%.

The scenario will assume an increase in field application systems that reach 70%, 20% and 10% in drip, sprinkler and surface watering methods respectively. In addition, improved utilization of surface and ground water that reaches 85% for SW use. The total efficiency will thus be set to increase to 76.5%. In Jordan, a similar improvement was also assumed.

3.10.5. Agricultural Intensification Scenario

With the increasing population in the basin, the need for food will grow. The quality and quantity of the crop and tree yields varies in rain-fed agriculture depending on rainfall levels, but is much better in an irrigated one. Irrigation demand is expected to continue rising in the developing countries in addition to rainfed agriculture. This scenario will assume an increase in both rainfed and irrigated agriculture at a rate of 0.5% per year in Syria and Jordan.

3.10.6. UN Medium Variant Population Projection

In projecting future levels of fertility and mortality, probabilistic methods were used to reflect the uncertainty of the projections based on the historical variability of changes in each variable.

The method takes into account the past experience of each country, while also reflecting uncertainty about future changes based on the past experience of other countries under similar conditions. The medium-variant projection corresponds to the median of several thousand distinct trajectories of each demographic component derived using the probabilistic model of the variability in changes over time. The projection expects the global population to reach 8.5 billion in 2030, 9.7 billion in 2050 and 10.9 billion in 2100. (UN, 2019)

Population projections carry a lot of uncertainty but assuming a constant growth rate may be far from being accurate. The scenario will represent a more realistic expectation of population growth in the basin established through changes in demographic trends. The projections are different for each country as they are based on historical data and present conditions of each one.

Chapter IV: Results and Discussion

4.1. Water Balance of the Yarmouk Watershed

Before analyzing different scenarios, it is important to establish the water balance. The soil moisture water balance of the watershed is shown in Table 20 where positive values represent inflows to the system while the negative ones represent the outflows. Runoff and interflow peaks in the 3 months of January, February and March.

Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Total
Precipitation	82.0	474.5	292.5	434.6	680.0	252.3	138.8	54.4	3.1	0.5	0.5	5.3	2418.3
Irrigation	12.3	4.0	8.2	4.1	1.1	19.9	39.6	50.0	45.6	39.8	37.0	32.1	293.6
Decrease in Soil Moisture	18.6	1.5	3.2	1.8	1.5	166.2	250.7	234.2	173.2	122.6	83.0	50.5	1107.1
Evapo-transpiration	-53.5	-91.1	-100.6	-124.9	-165.9	-294.9	-341.9	-287.8	-184.7	-134.7	-95.7	-57.6	-1933.3
Flow to Groundwater	-20.9	-38.4	-58.9	-80.5	-121.7	-115.0	-73.0	-44.3	-30.1	-23.1	-19.6	-19.1	-644.7
Increase in Soil Moisture	-36.2	-340.1	-131.2	-207.4	-326.6	-3.3	-1.2	-0.8	-4.5	-3.2	-3.5	-9.6	-1067.4
Interflow	-1.6	-3.5	-5.7	-8.4	-12.3	-10.7	-6.3	-3.4	-2.0	-1.4	-1.2	-1.3	-57.9
Surface Runoff	-0.6	-7.4	-7.6	-19.5	-56.6	-14.1	-5.9	-1.6	-0.3	-0.2	-0.2	-0.3	-114.5
Sum	0.0	-0.5	-0.1	-0.3	-0.6	0.5	0.8	0.7	0.4	0.2	0.1	0.0	1.2

Table 20: Soil moisture water balance of Yarmouk watershed

a) Runoff:

The runoff varied from one land class to another (Figure 15 and Figure 16). Bare areas produced the highest runoff in most sub-basins along with water bodies. Forest, olive, vine and fruit tress land classes have higher runoff resistance which slow down the runoff response. These LUC classes were found to produce the lowest runoff in the basin.

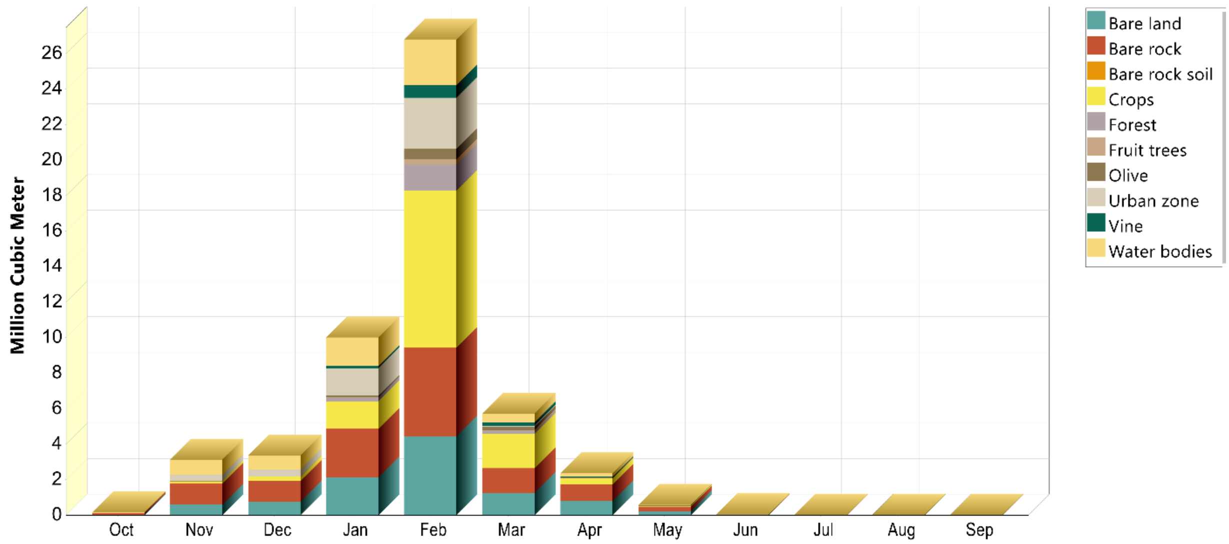

Figure 15: Runoff per LUC class in Raqqad sub-basin

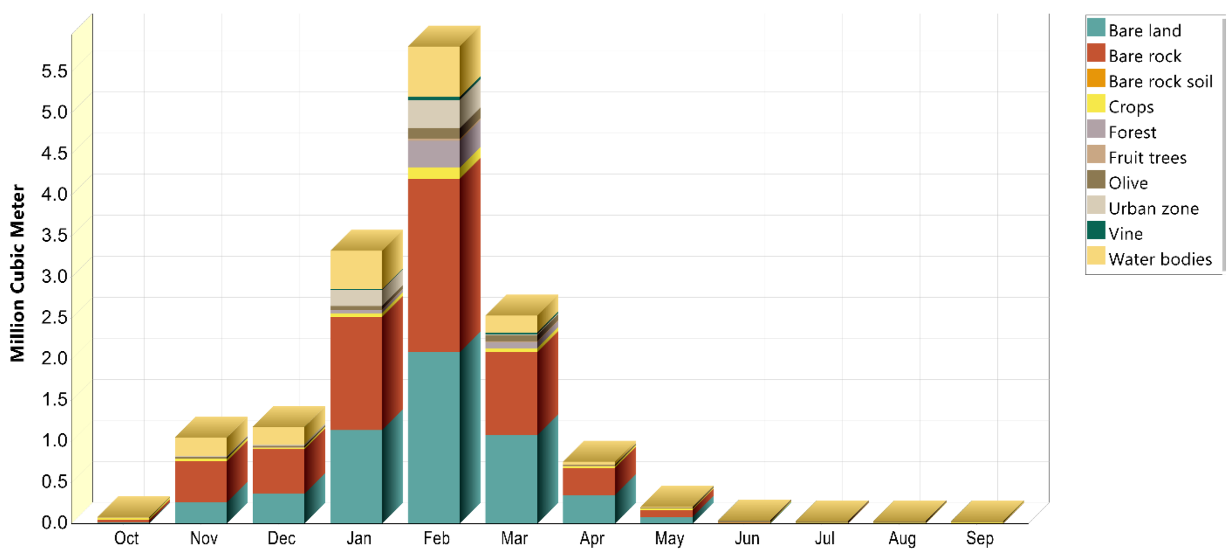

Figure 16: Runoff per LUC class in the Main Outlet sub-basin

The Raqqad and Main Outlet sub watersheds produced the highest amounts of surface water flow in the basin (Table 21). These two sub watersheds are characterized by higher precipitation levels compared to the rest of the sub watersheds. Al Hareer was another main source of runoff and interflow. The sub-watershed of Shallala produced the lowest flow of all sub-basins.

Catchment	Average Runoff + Interflow (MCM)
Al Hareer	27.98
Thahab	4.31
Allan	14.6
Main Outlet	43.76
Raqqad	38.18
Shallala	1.74
Zeidi	25.44

Table 21: Average total annual surface water per sub-basin

b) ET and GW infiltration:

Soils with good water conductivity are found in the eastern parts of the basin near Leja Pateau and at the northern fringes of the basin and in the south east. Al Hareer sub-basin is where most of the infiltration occurs especially in the bare areas in its eastern region (Figure 17).

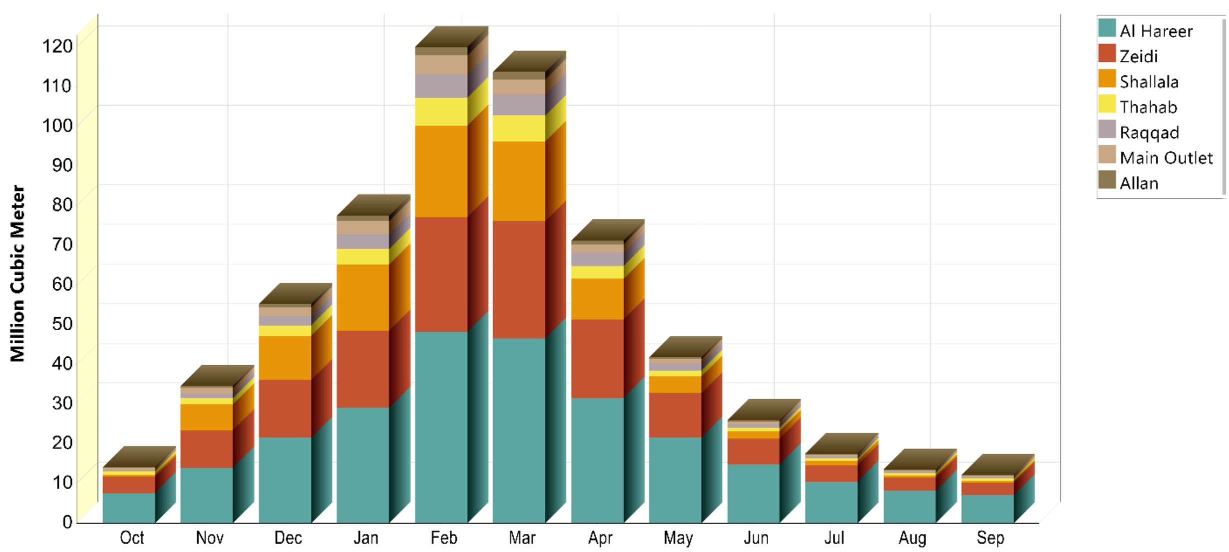

Figure 17: Monthly GW infiltration per sub-basin

Evapotranspiration is usually higher in bigger sub-basins where higher rainfall volumes occur. Al Hareer and Zeidi have the highest ET rates in the basin (Figure 18). Evapotranspiration also varies through different LUC classes. Crop areas were the highest source of ET in the basin. Bare areas allowed more infiltration and runoff and produced lower ET rates while forest and land covers of various trees and vines also produced high ET. Evapotranspiration from all LUC classes in al Hareer sub-basin are shown in Figure 19.

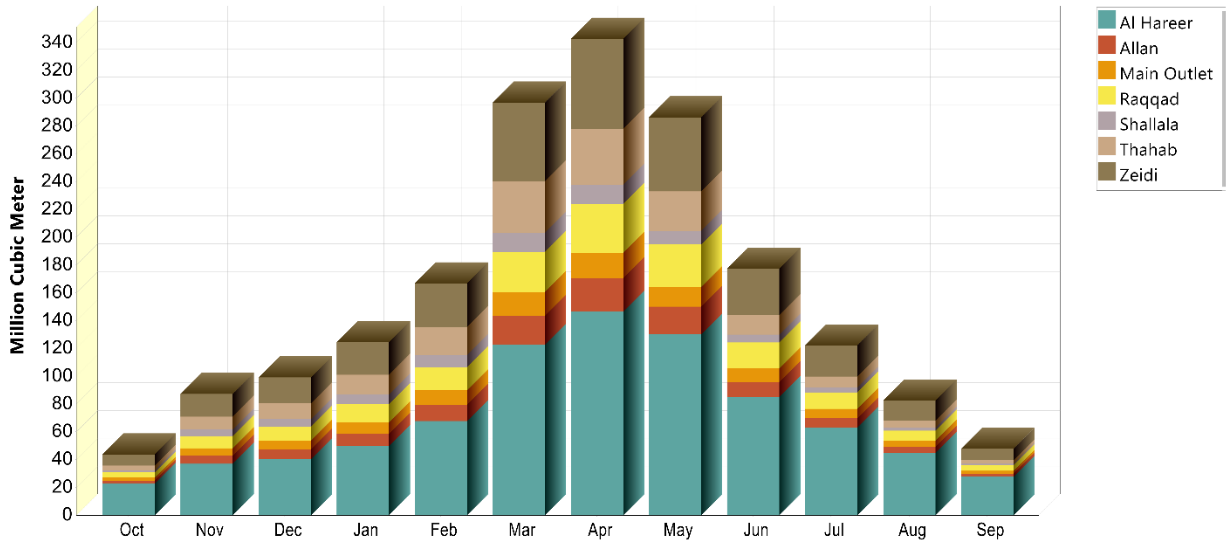

Figure 18: Monthly ET per sub-basin

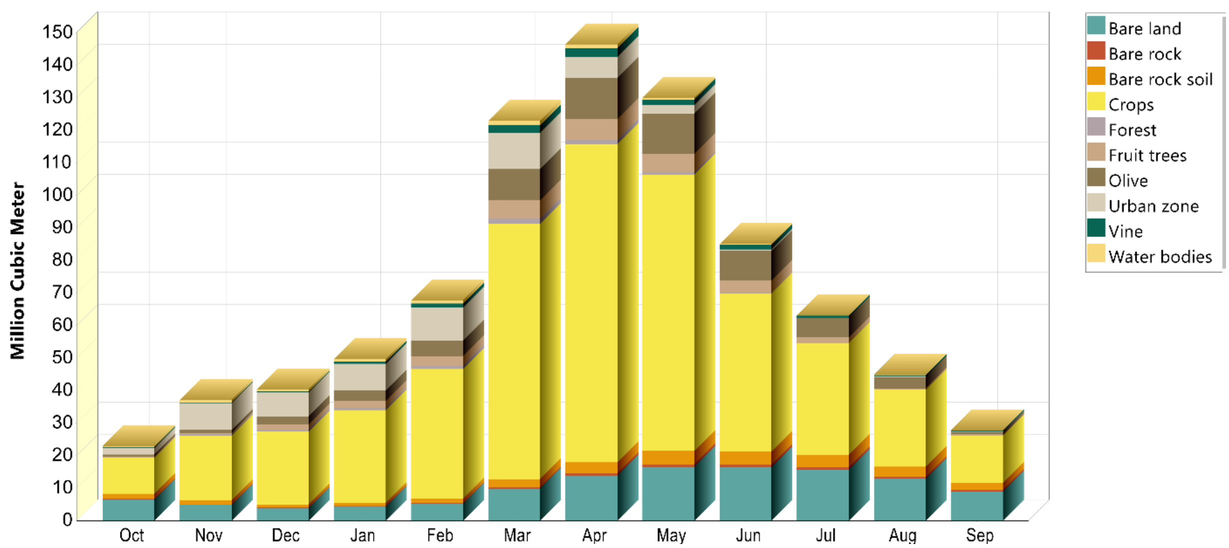

Figure 19: Monthly ET in Al Hareer sub-basin

c) Demands:

The total irrigation demand in the basin was 362.7 MCM divided as 71 MCM, 254 MCM and 37 MCM for trees and vines, crops in Syria and crops in Jordan respectively. The agricultural demand varied on a monthly basis and is very small during rainy season and high in late spring and summer seasons (Figure 20) when soil moisture is not enough to satisfy the crop water requirements.

Domestic demand was 111.2 MCM at the start of the reference scenario. The demand was split to 88.64 MCM in Syria and 22.52 MCM in Jordan.

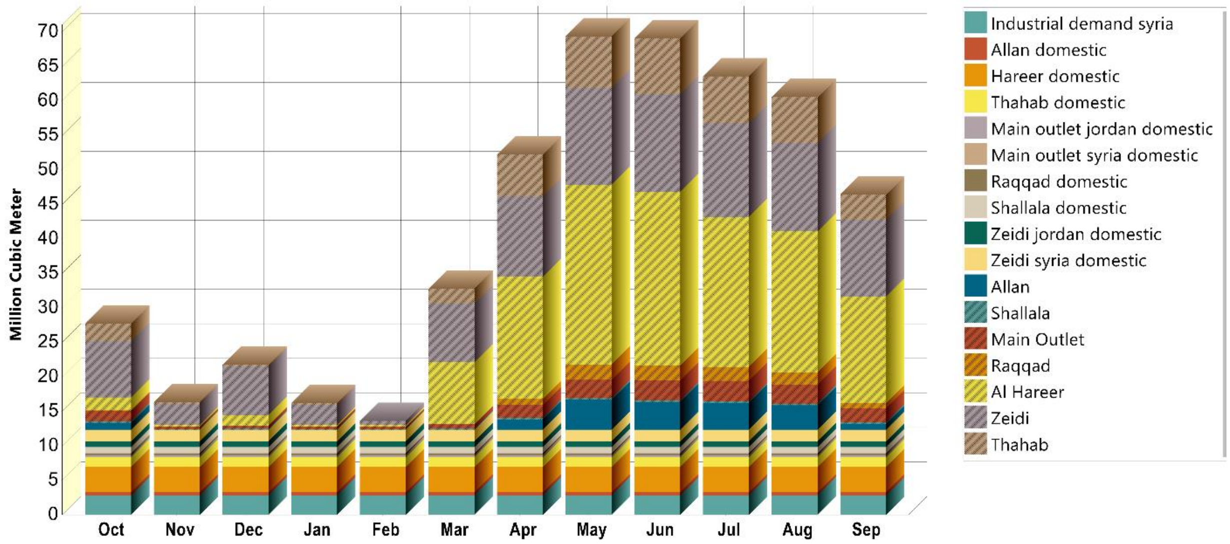

Figure 20: Monthly demands in Syria and Jordan

d) Return flows:

The total return flows of non-consumed water from domestic and industrial demands was equal to 66 MCM at the start of the simulations. Return flow from agriculture was equal to 5.5 MCM. These flows are directed to either agricultural catchments or river tributaries.

e) Unmet demand:

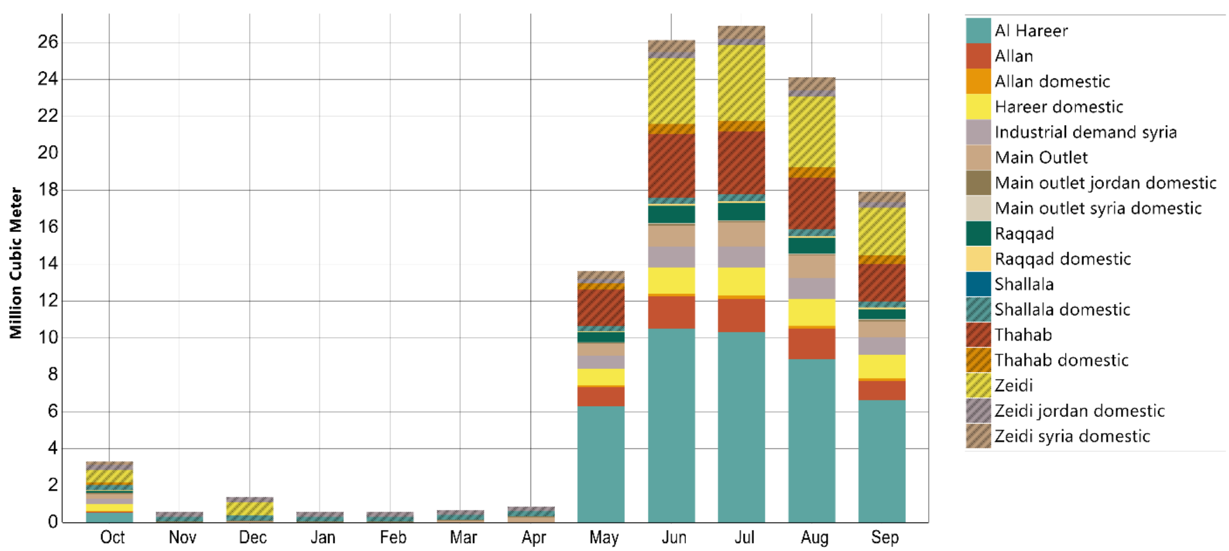

Figure 21: Monthly unmet demand

Water deficit was suffered in all demand sectors, however much is covered by over-exploitation of GW resources in the basin. The unmet demand at initial conditions before running simulations was equal to 115.7 MCM/year. The shortage is low in the winter months but increased in the summer season and peaked in June when it reached 26.5 MCM (Figure 21).

4.2. Scenario Results

4.2.1. Reference Scenario

At end of reference scenario:

Several changes occurred in the water balance at the end of BAU scenario. Irrigation inflow decreased considerably in addition to evapotranspiration and groundwater inflow. Also, runoff and interflow slightly decreased in the basin (Table 22).

Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Total
Precipitation	82.0	474.5	292.5	434.6	680.0	252.3	138.8	54.4	3.1	0.5	0.5	5.3	2418.3
Irrigation	11.3	6.1	4.9	3.2	2.3	17.1	31.3	33.0	27.8	24.5	22.5	20.8	204.8
Decrease in Soil Moisture	6.9	0.0	2.4	0.5	0.2	162.1	250.4	236.5	172.4	121.0	81.8	47.1	1081.3
Evapo-transpiration	-46.7	-87.0	-98.3	-122.9	-164.3	-292.5	-337.1	-277.7	-173.8	-124.2	-86.8	-52.7	-1864.0
Flow to Groundwater	-13.5	-32.9	-54.4	-76.7	-119.1	-112.7	-70.3	-40.9	-26.0	-18.6	-14.9	-13.4	-593.4
Increase in Soil Moisture	-38.7	-351.1	-134.5	-211.7	-331.2	-1.2	-0.5	-0.1	-1.6	-2.0	-2.1	-6.3	-1081.0
Interflow	-0.8	-2.9	-5.2	-8.0	-12.1	-10.5	-5.9	-2.9	-1.5	-1.0	-0.7	-0.7	-52.3
Surface Runoff	-0.6	-7.2	-7.4	-19.2	-56.3	-14.0	-5.9	-1.5	-0.1	-0.1	-0.1	-0.1	-112.5
Sum	-0.1	-0.5	-0.1	-0.3	-0.6	0.5	0.8	0.7	0.4	0.2	0.1	0.0	1.2

Table 22: Soil moisture water balance at end of BAU scenario

a) Dams:

The total retention in dams inside Jordan, Syria and occupied Golan reached 112 MCM under. Wehdeh dam maximum retention was 57 MCM in March. The total losses through evaporation from all dams was 5.6 MCM yearly. The retained volume in dams slightly increased by mid-century as a result of higher return water flow due to increased domestic water use.

The high growth in population caused more competition over water resources and given that domestic and irrigation are supplied simultaneously from GW wells or from springs, the share of domestic water increased while irrigation share decreased.

b) Demand:

The demands are projected to increase throughout the BAU scenario. In the baseline scenario the domestic demand increased from 111.2 MCM to 126.9 MCM in 2010 then decreased slightly throughout the war. The domestic demand then reaches 298.1 MCM by 2050 and reaches 1,009 MCM by 2100 under the assumption that the demand per capita and the annual population growth rate both remain constant by then.

Even though agricultural areas were set to remain constant, the agricultural demand increased because of the increased water shortage since the model considers any deficit from the month preceding any time-step calculation a part of the new demand. The demand increased 6.92% by 2050 and 17.78% by the end of the century.

c) Water shortage:

Increased demand with limited available water led to higher water shortage which increased from 115.7 MCM at the start of simulations to 317.1 MCM in 2050 and 1213.8 MCM in 2100 (Figure 22).

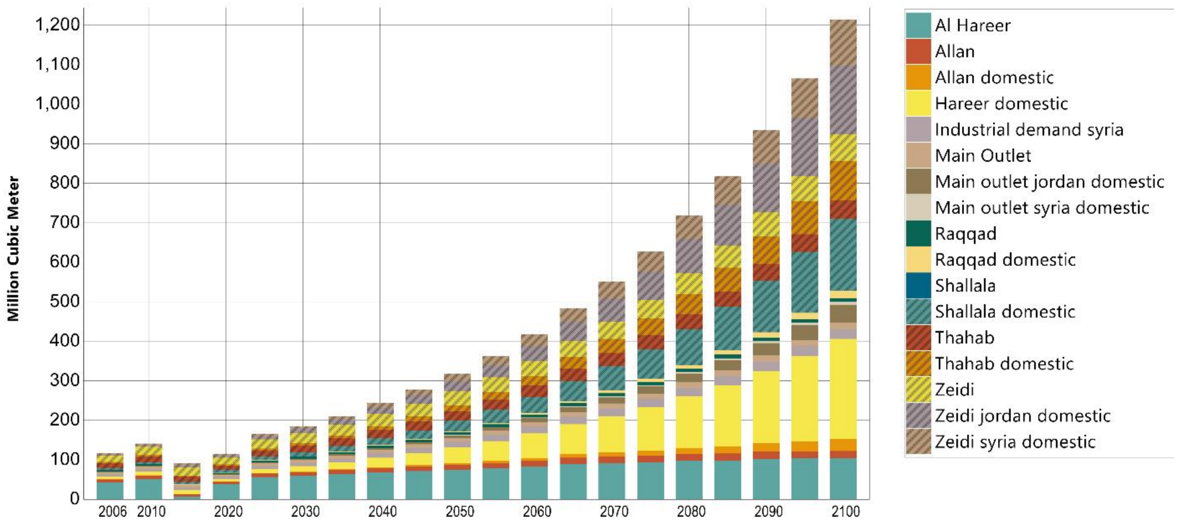

Figure 22: Unmet demand in BAU scenario

All water sectors were affected by water shortage that was suffered during winter and summer seasons by the end of the century, though higher deficit was recorded during the latter (Figure 23).

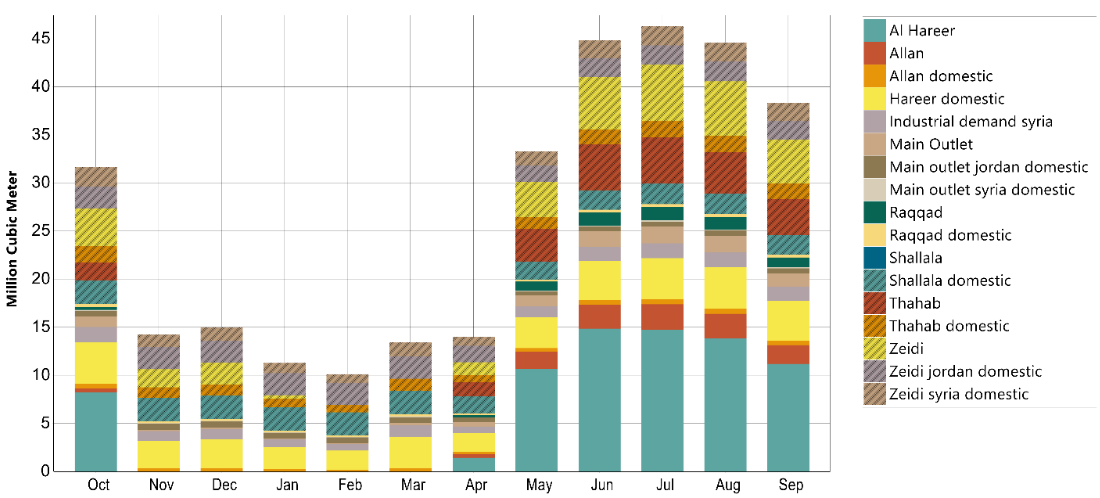

Figure 23: Monthly unmet demand at mid-century under reference scenario

WWTPs in Jordan supplied a maximum outflow for irrigation of 13.3 MCM in 2065. The total return flow from domestic and industrial demands in the basin was 94.8 MCM by the end of the century.

The Jordanian use of GW was divided as 80% for irrigation demands and 20% for domestic demands. At the end of the century more supply was delivered to the domestic sector which was supplied by 75% of the total GW abstraction. The use of water in Syria reached 155 m^3/capita by 2050 and went below 100 m^3/capita by 2068.

Lack of data on the distribution of water between sectors led to the assumption made that agricultural, industrial and domestic demands are simultaneously from their designated sources with limits being placed upon extraction of water from these sources.

4.2.2. Climate Change Scenarios RCP 4.5 and RCP 8.5

Climate change impacts much of the supply and demand in the basin. The decrease in rainfall accompanied with an increase in temperatures will lead to increased droughts and reduction in available renewable water.

The RCP scenarios showed decreased water supply and increased potential evapotranspiration. Increased pressure on all water sectors and higher shortages were also detected.

Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Total
Precipitation	76.2	441.3	272.0	404.1	632.4	234.6	129.1	50.6	2.9	0.4	0.4	4.9	2249.0
Irrigation	9.8	6.3	6.2	4.9	2.4	17.5	31.5	26.8	24.0	22.5	21.3	20.1	193.3
Decrease in Soil Moisture	6.2	0.0	1.2	0.2	0.4	156.1	236.7	224.1	160.7	111.9	75.3	43.5	1016.3
Evapo-transpiration	-44.1	-84.3	-96.2	-121.6	-163.8	-287.3	-324.1	-261.4	-162.0	-115.3	-80.7	-49.4	-1790.1
Flow to Groundwater	-11.7	-28.5	-47.3	-67.2	-105.0	-99.0	-61.7	-35.6	-22.4	-16.0	-12.8	-11.6	-518.9
Increase in Soil Moisture	-35.4	-327.0	-125.6	-198.8	-313.8	-1.0	-0.8	0.0	-1.4	-2.5	-2.8	-6.8	-1015.7
Interflow	-0.7	-2.5	-4.6	-7.1	-10.7	-9.3	-5.2	-2.6	-1.4	-0.8	-0.7	-0.6	-46.3
Surface Runoff	-0.4	-5.7	-5.8	-14.9	-42.4	-11.0	-4.8	-1.2	-0.1	-0.1	-0.1	-0.1	-86.5
Sum	-0.1	-0.5	-0.1	-0.3	-0.5	0.5	0.8	0.7	0.3	0.2	0.1	0.0	1.2

Table 23: Soil moisture water balance at end of RCP 4.5 scenario

Changes in the water balance are noticed under RCP 4.5 scenario when compared with the reference scenario. Actual ET decreased through the scenario in addition to the flow to groundwater that decreased by 12.55%. Runoff and Interflow were also changed (Table 23).

Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Total
Precipitation	71.3	412.8	254.5	378.1	591.6	219.5	120.8	47.3	2.7	0.4	0.4	4.6	2103.9
Irrigation	9.5	6.5	6.3	6.1	2.8	17.9	27.2	23.9	22.7	21.6	20.7	19.7	184.9
Decrease in Soil Moisture	5.5	0.0	1.2	0.0	0.1	153.4	227.3	208.4	148.0	102.5	68.8	39.8	954.8
Evapo-transpiration	-41.8	-83.0	-95.6	-122.2	-166.3	-286.4	-313.5	-245.8	-151.1	-107.1	-75.1	-46.3	-1734.2
Flow to Groundwater	-10.2	-24.6	-40.9	-58.3	-91.6	-85.9	-52.6	-30.0	-18.9	-13.6	-11.0	-10.1	-447.5
Increase in Soil Moisture	-33.4	-305.3	-116.9	-186.2	-295.7	-1.2	-0.2	0.0	-2.0	-2.9	-3.1	-7.0	-953.8
Interflow	-0.6	-2.2	-4.0	-6.2	-9.4	-8.1	-4.5	-2.2	-1.1	-0.7	-0.6	-0.6	-40.3
Surface Runoff	-0.3	-4.5	-4.6	-11.7	-32.0	-8.7	-3.6	-0.9	-0.1	0.0	0.0	-0.1	-66.7
Sum	-0.1	-0.5	-0.1	-0.3	-0.5	0.5	0.8	0.7	0.3	0.2	0.1	0.0	1.2

Table 24: Soil moisture water balance at end of RCP 8.5 scenario

Under RCP 8.5 scenario the precipitation decrease much more than the RCP 4.5 scenario. ET losses and GW recharge decreased significantly (Table 24). Supply to all demand sectors also changed considerably.

Change in runoff and reservoirs retention:

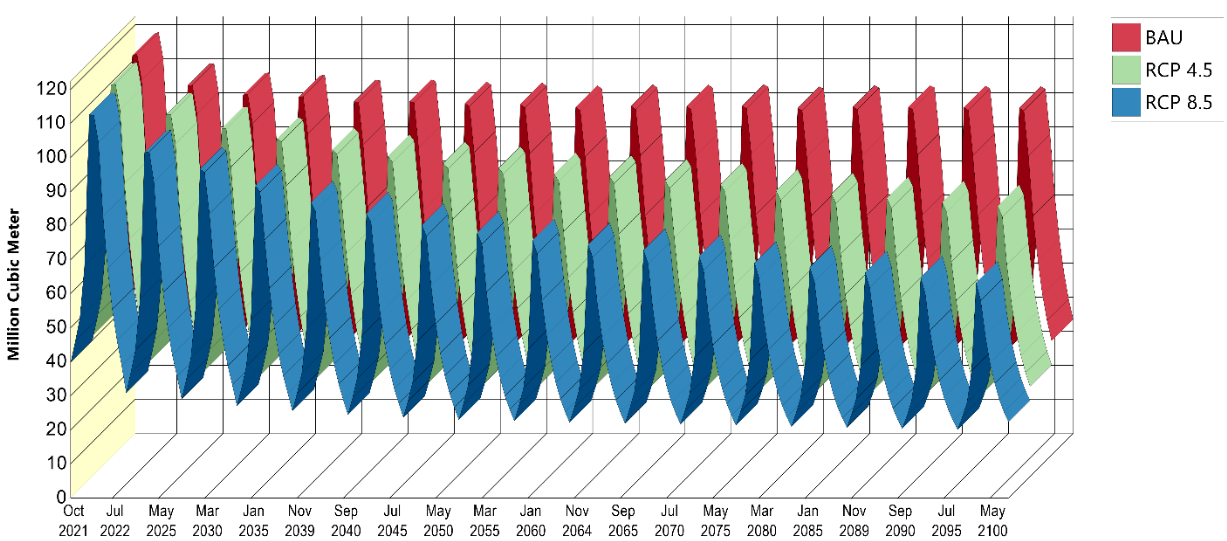

Figure 24: Retained volume in all dams except Wehdeh

The total runoff in the basin decreased by 11.8% by 2050 under the RCP 4.5 scenario and 24.4% by 2100. Interflow was reduced by 9.63% and 20.12% by mid and end century respectively.

RCP 8.5 scenario showed a higher reduction in runoff than RCP 4.5 scenario. Runoff decreased 24.2% by 2050 and 41.74% by 2100, the interflow on the other hand decreased by 17% and 30.4% by 2050 and 2100 respectively.

The decrease in runoff and interflow led to decreased retention in all dams (Figure 24). The lower retention volumes imply that most dams will not be utilized to their maximum storage capacities and many may only retain water in wet years. Wehdeh dam retention is also projected to gradually decrease (Figure 25) thus decreasing the shares of downstream countries. Compared to the maximum yearly retention in the reference scenario, the Wehdeh dam maximum retention decreased by 10.7% and 21.8% by 2050 and 2100 respectively under the RCP 8.5 scenario. Under the RCP 4.5 scenario the changes were more significant by the end of the century where the decrease reached 12.3%.

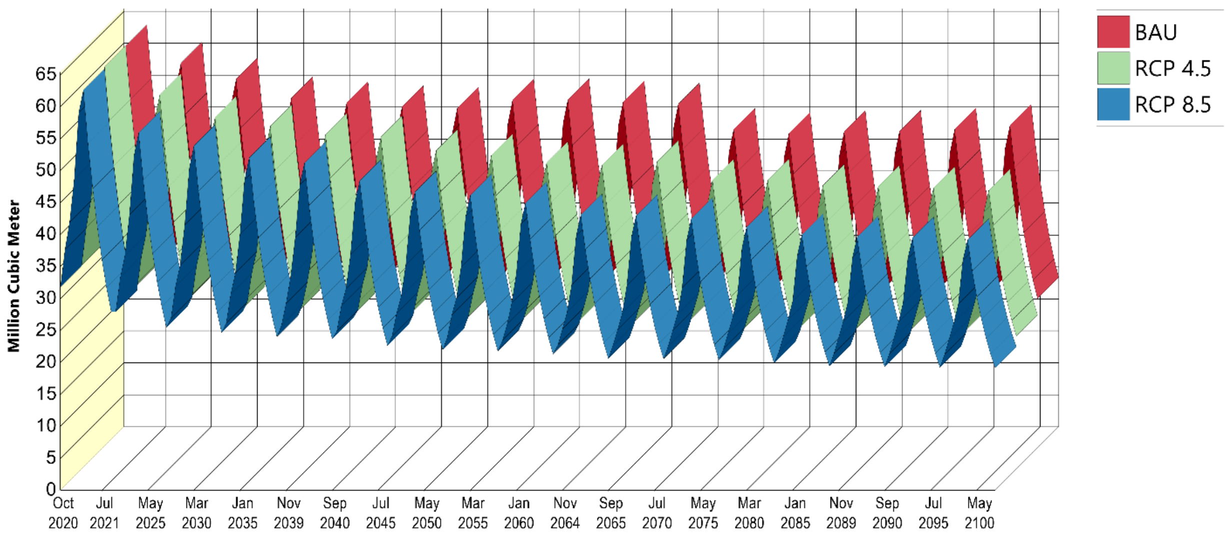

Figure 25: Retention volumes in Wehdeh dam

Decrease in shares:

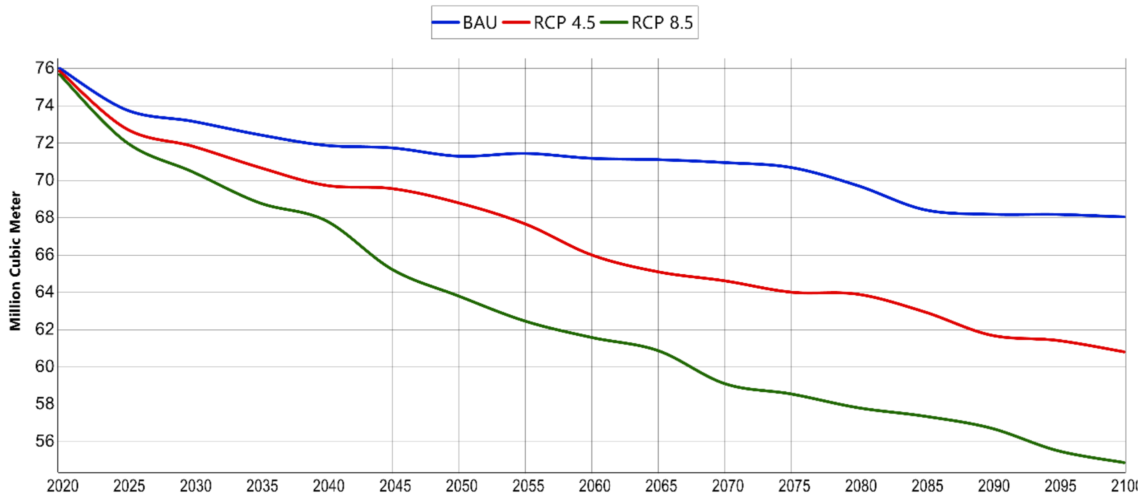

Figure 26: KAC diversion

Both Jordan and OSoI had their shares decreased; the reduction in flows diverted by Jordan and OSoI are shown in Figure 26 and Figure 27. RCP 8.5 scenario showed that Jordan's share will decrease by 16.18% by 2050 and 27.9% by 2100. OSoI share also decreased but to a lesser degree. The runoff flow bypassing Adassiyeh weir decreased by 13.4% in 2050 and 23.6% in 2100. RCP 4.5 showed a 9.6% and 20.1% decrease by 2050 and 2100 respectively in Jordan's diversion. For OSoI share from the river, the volume decreased by 7% in 2050 and 16.7% in 2100.

Jordan's flow is more vulnerable to climate change effects than OSoI due to the commitments in the treaty signed with OSoI that are evident in the current regime and operation of the constant flow of 1 m^3/s released to OSoI through the weir at Adassiyeh. This result indicate that Jordan will be the side that is benefitting less from the water arrangement with OSoI.

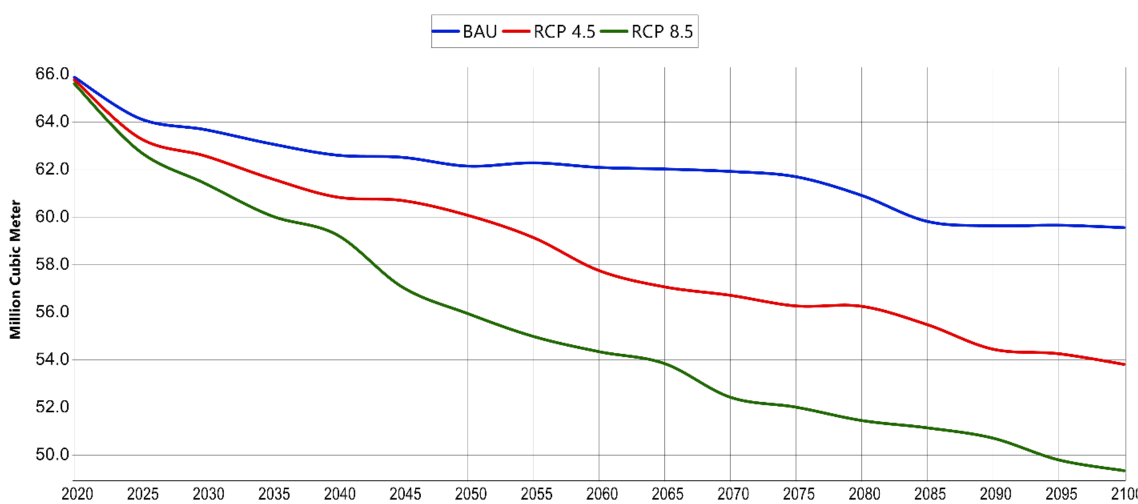

Figure 27: Flow bypassing Adassiyeh weir to OSoI

Increase in water shortage:

Deficit in the water budget is projected to increase in the climate change scenarios (Figure 28). RCP 4.5 scenario had the total unmet demand increasing to 324 MCM in 2050 while RCP 8.5 showed a 355 MCM deficit implying an increase in water shortage by 11.95% and 22.4% by each RCP scenario compared to the reference scenario.

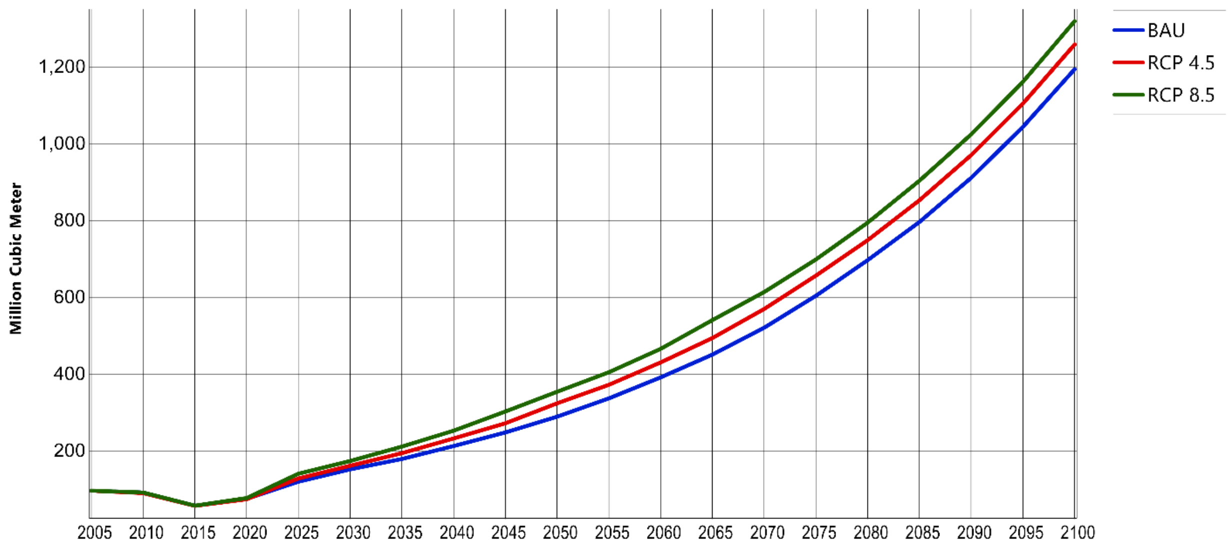

Figure 28: Unmet demand under climate change scenarios

4.2.3. Agricultural Intensification Scenario

Under this scenario, agricultural demand increased by 18.5% in 2050 and 54.6% by 2100. Moreover, an increase in supply for agricultural use was registered in the basin. By 2050 the irrigation supply increased by 4.2% and by 2100 it increased by 12.4%.

Coverage of all demand sectors dropped and the unmet irrigation demand reached 195 MCM by 2050 and 476 MCM at the end of the century. Runoff also decreased in the basin and flows into Maqarin dropped by 10.7% by 2060 and 9.3% by 2100. A change that can be attributed to the expansion of planted areas.

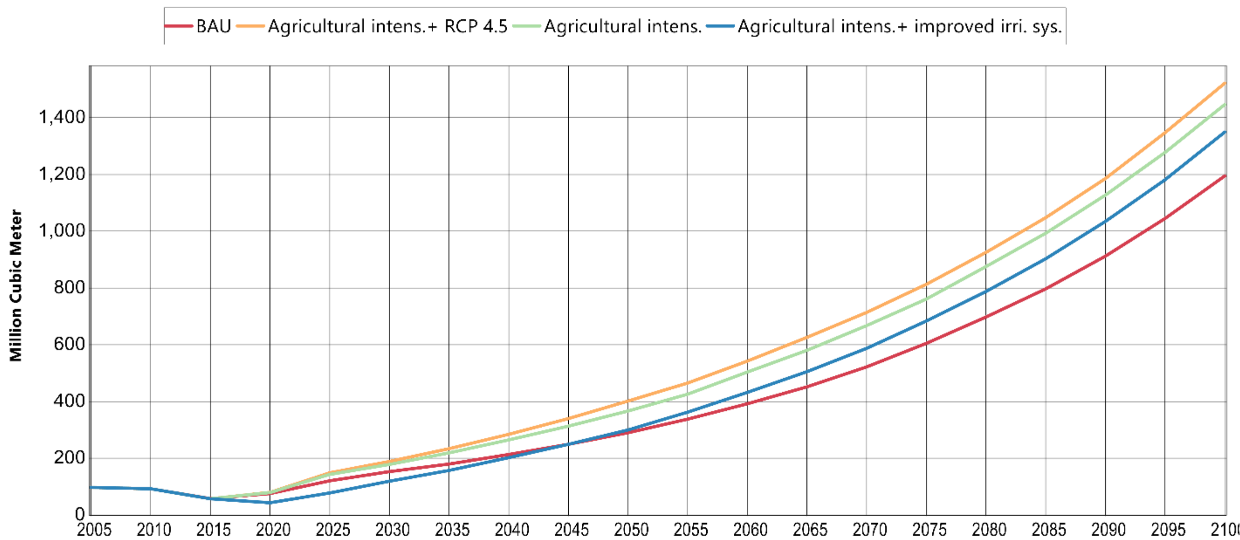

Figure 29: Comparison of unmet demand under a combination of scenarios

When combined with RCP 4.5 scenario, the unmet demand was at its highest compared to all scenarios (Figure 29). While when enhanced irrigation efficiency scenario was coupled with the agricultural intensification scenario, the unmet demand was lower than that in the reference scenario till year 2045 when it could no longer be considered an improvement over BAU scenario.

4.2.4. Irrigation Systems Enhancement Scenario

The enhancement in irrigation systems led to a decrease in irrigation water demands by 57.5 MCM by 2050 and 65 MCM by 2100. When combined with the RCP 4.5 scenario, the decrease reached 19.9 MCM at the end of the scenario (Figure 30).

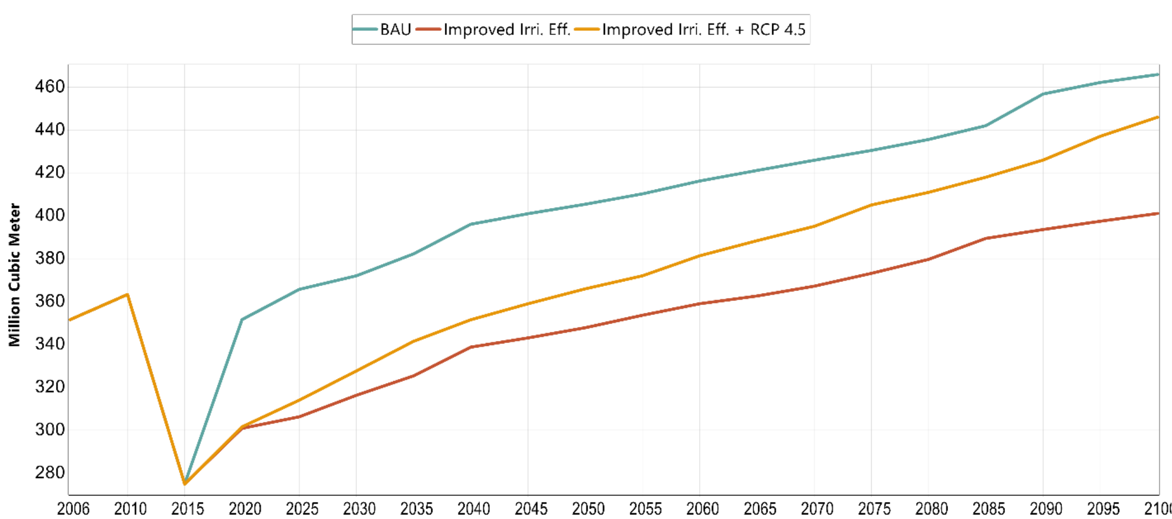

Figure 30: Irrigation water demand under improved irrigation efficiency scenario

Change in coverage/water shortage:

The change in irrigation systems and the improved efficiency led to better coverage of agricultural demands. The coverage increased during the shortage months at the mid and end of the summer season by 15% then decreased under increased pressure on other sectors. (Figure 31).

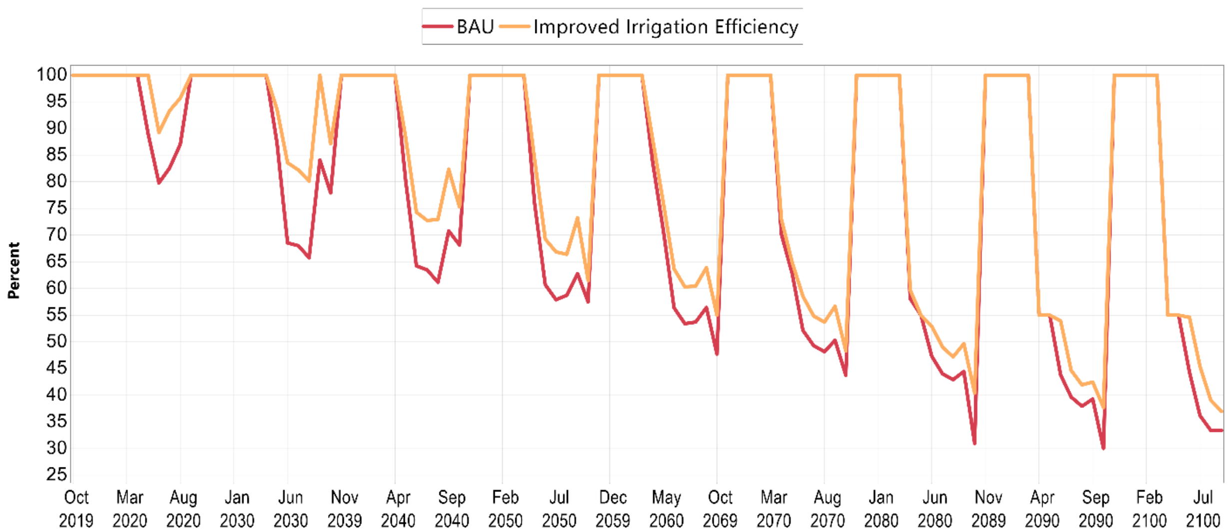

Figure 31: Demand coverage in Raqqad agricultural catchment

Combining the improved irrigation scenario with RCP 4.5 scenario still showed improvement in demand coverage until 2070 when all the improvements started to diminish due to climate change impacts (Figure 32).

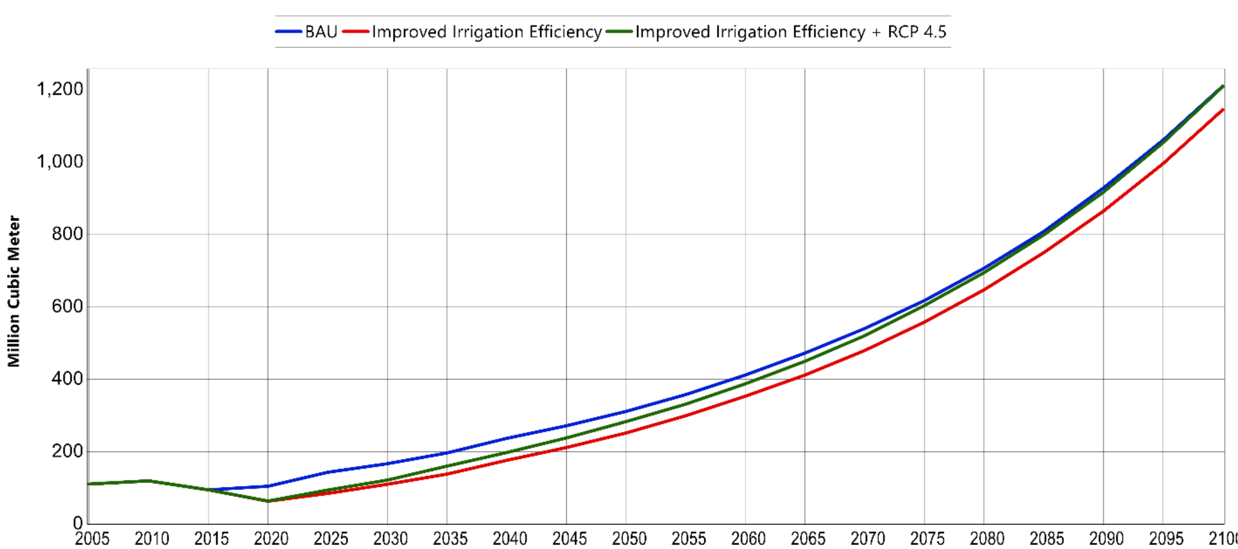

Figure 32: Unmet demand under improved irrigation efficiency scenarios

In the long term, the decrease in irrigation demands resulted in increased supply to domestic demands in the basin. The share of agriculture still decreased slightly by the end of the century to 180.6 MCM.

4.2.5. UN Medium Variant Population Projection Scenario

The UN medium variant population projection impacts the domestic demand in the basin. The projection showed that the population growth in Syria will remain high in the near future then starts to decrease gradually. The total number of inhabitants peaked and stabilized after 2060. Syria's population returned to pre-war levels by 2030 and continued growing to 1.74, 1.92 and 2.09 million by 2040, 2050 and 2100 respectively (Figure 33).

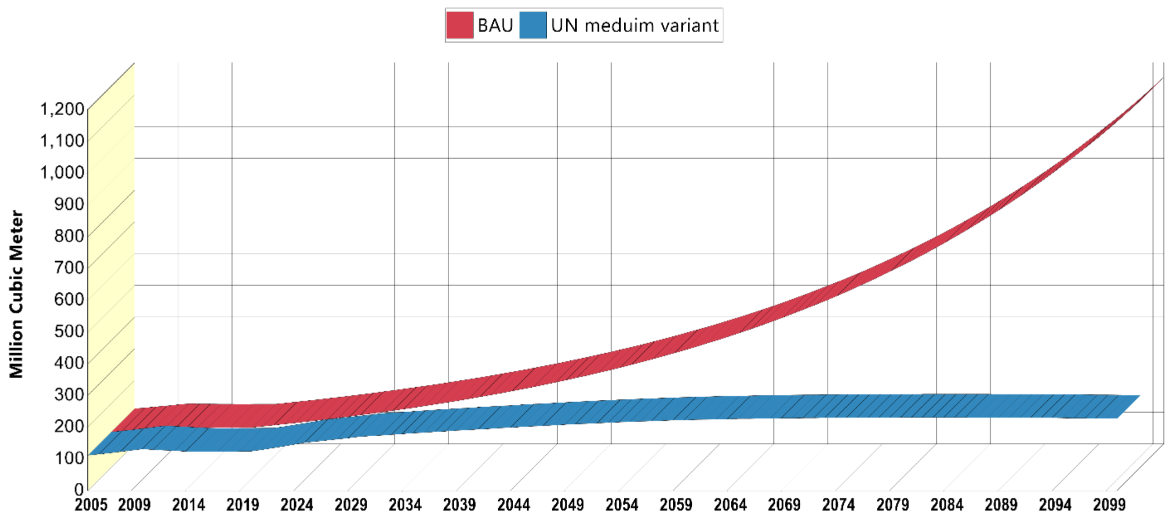

Figure 33: Change in domestic demand under BAU and UN medium variant population projections

The BAU scenario showed that the inhabitants of the Jordanian part of the basin will almost double and reach 2.2 million inhabitant by 2050 and 9.68 million by 2100 if the high population growth rate remains constant. The UN medium variant projection showed that the population in Jordan will stabilize quickly and will reach 1.08 million by 2050 and 1.14 million by 2100. Annual domestic water demand thus increased from 22.5 MCM at the start of the simulations to 41.38 MCM by 2030, 50.25 MCM in 2050 and 53.04 MCM in 2100.

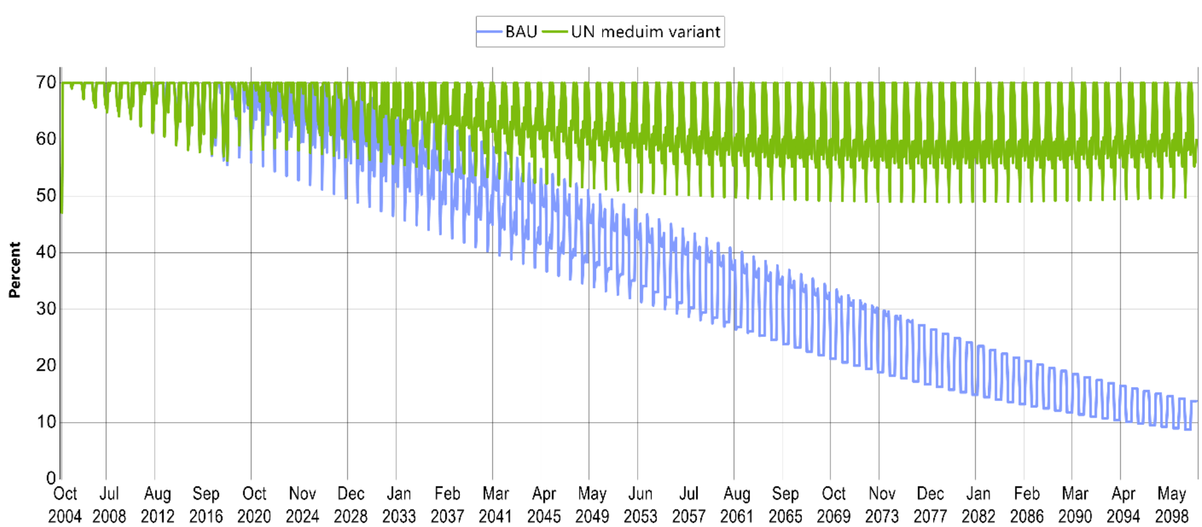

Figure 34: Domestic demand coverage in Jordan

The exponential growth assumed in the BAU scenario produced huge shortage in the domestic sector in Jordan. Assuming that the per capita demand will stay constant, the demand coverage, at the end of the century, will reach 60% on average under the UN projection while under the BAU scenario it will reach 44% on average in 2050 and 13.3% by the end of the century (Figure 34).

In Syria, the BAU scenario showed that the annual unmet domestic demand increased from 12.6 MCM at the start of the simulation to 69 MCM in 2050, then jumped to 499 MCM by 2100. In comparison, the unmet demand was 44.3 MCM by 2050 and 53.8 MCM by 2100 under the medium variant scenario (Figure 35). Stabilization of population caused the irrigation supply to also stabilize at 247.6 MCM by the end of the century.

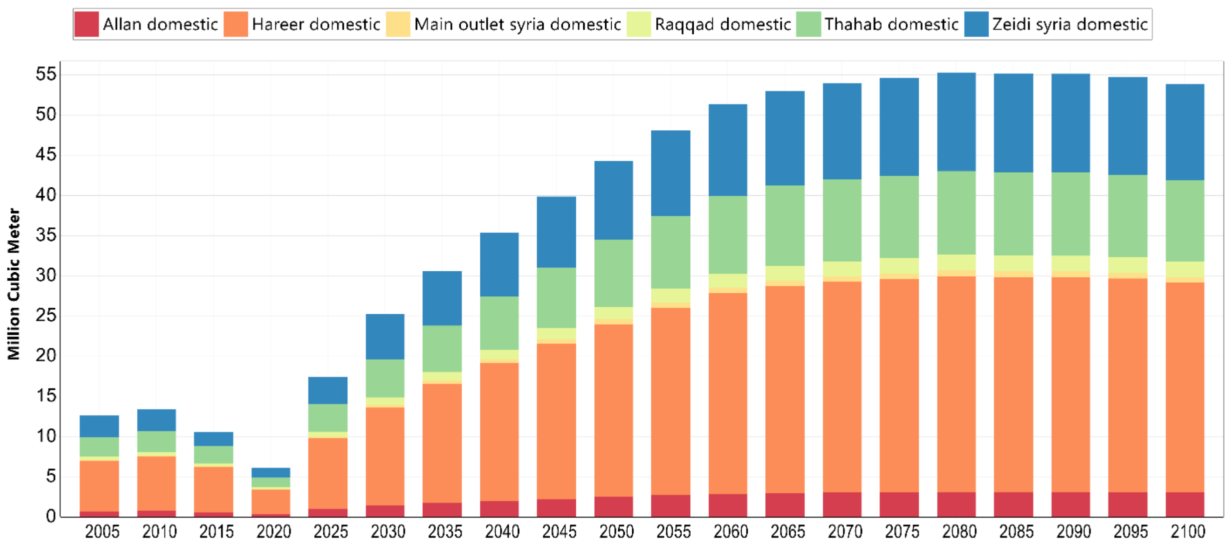

Figure 35: Unmet domestic demand in Syria under UN medium variant population projection

Results of the UN medium variant projection scenario indicate that both Syria and Jordan would benefit greatly from a lower population growth by decreasing the pressure on water resources. Decreased water supply per capita is a certain expectation in the basin but in the case of population stabilization, water saving methods and reduction of losses in supply networks may compensate the decreased supply.

Combined with Irrigation systems enhancement scenario:

When combined with the improved irrigation systems efficiency scenario, the new combination scenario showed increase in irrigation supply in addition to improved coverage on all scenarios in domestic, industrial and agricultural demands (Figure 36). Unmet domestic demand was the lowest compared to the rest of scenarios. In Syria, unmet demand reached 35.4 MCM by 2050 and 44.4 MCM by 2100. In Jordan this value reached 16.6 MCM by 2050 and 18.9 MCM by 2100. Unmet agricultural demand in both Syria and Jordan decreased to 82.4 MCM by 2050 compared to 150.5 MCM in the BAU scenario and 103.9 MCM in the UN medium variant population projection.

The total water shortage in Jordanian demands reached 31.9 MCM and 129.1 MCM at the end of the century in Jordan and Syria respectively.

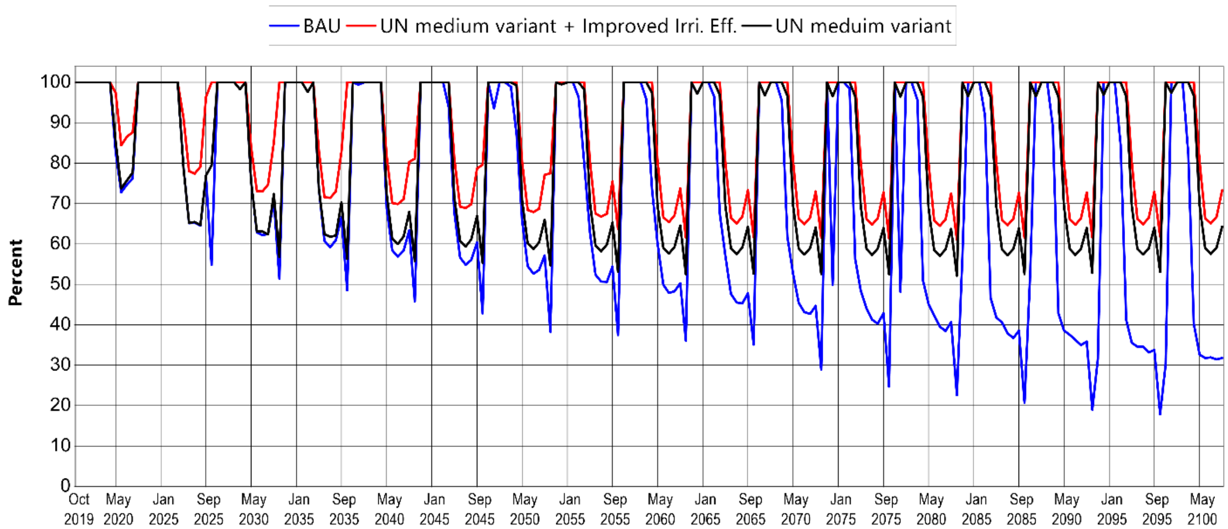

Figure 36: Demand coverage in Thahab agricultural catchment

4.3. Limitations:

Some limitations can be found in the study such as the changes in natural groundwater discharge under non-sustainable groundwater abstraction. The constant headflow of Yarmouk River assumed to be constant at 0.8 m^3/s in the current account year could decrease as a result of the impact of over-pumping of GW from wells. However, the model could not represent the changes in baseflow as a result of increased GW over-abstraction or decreased GW recharge as a result of both the lack of accurate data on GW pumping in Syria and the inability to draw water out of the second bucket in the original two-bucket model. Moreover, the modelled allocation system does not take into consideration the inequality of flows going into each dam within the same sub-catchment since dams of each sub-catchment were dealt with as one dam node. Also, climatic data were assigned to each catchment thus the spatial variability of these data within each catchment were not fully captured.

Summary, Conclusion and Recommendations

Water availability can be a daily concern in countries where water is not sufficient to fulfill demands. Management of these resources is a necessary step to accommodate and develop water coverage. Human development and the increasing living standards along with the climate change trends are both increasing the gap between supply and demand. In this study a water balance for the transboundary Yarmouk watershed was established based on the current account year 2005 and scenarios were simulated till the end of the century. A WEAP model was built and optimized by adjusting several input parameters.

The total water resources available inside the basin was found to be around 440 MCM while the total internal demand was equal to 512.2 MCM. The flow of Yarmouk River in addition to discharge from Mukheibeh wells of approximately 128 MCM are diverted to outside the basin's boundary by Jordan and OSoI.

The reference scenario indicated that the current situation is far from being sustainable and that any further developments in the same manner as before the armed conflict in Syria will create a huge imbalance between supply and demand. Under the business as usual scenario, unmet demand rose to 290.1 MCM in 2050 and 1195 MCM in 2100. Water withdrawal per capita in Syria decreased from 400 m^3 at the start of the scenario to 178 m^3 by 2050. In Jordan this value was at critical levels and initially below 100 m^3.

Under agricultural growth scenario, more supply was delivered for irrigation but unmet demand increased hugely in all sectors indicating that any increase in demand cannot be sustained under the current water use in Syria and Jordan. The unmet irrigation demand increased to 195 MCM by 2050.

Climate change scenarios RCP 4.5 and RCP 8.5 showed that surface water will be the most affected due to climate change. Runoff decreased and thus hindered surface water resources and led to more dependency on groundwater what may cause consequently, more over-abstraction. Flows diverted to Jordan reduced more than the flows bypassing Adassiyeh weir to OSoI under both scenarios.

Enhancing irrigation efficiency improved coverage of all demands in the basin and initially increased irrigation coverage by 15%. When coupled with the RCP 4.5 scenario, the new combination scenario showed higher decrease in unmet demand compared to BAU scenario until 2070.

Under the UN medium variant population projection, the coverage of domestic demand stabilized at 60% in Jordan and the unmet demand in Syria stabilized at 37.7 MCM/year by 2070. The lower population growth coupled with irrigation efficiency enhancement led to a 45.5% decrease in total unmet agricultural demand compared to the reference scenario.

All results provided evidence that the increase in water shortage is a certain expectation in the future. The Continuation with the same regime of water use and allocation in the basin accompanied with the same growth of population led to a large unmet demand in the basin. Embracing new measures taken to reduce demands and a decreasing population growth helped reduce the impact of these changes. Water management in an urgent necessity to sustain growth in the Yarmouk basin.

Syria's adaptation in the upcoming years will play a role in shaping the future of water in the basin. The changes made in water utilization during the armed conflict and the increased abstraction of GW may persist under the little present monitoring and regulations.

The dependency of Jordan on the flows from Yarmouk River while diverting it to areas further away from the basin means that it will suffer much more than Syria and OSoI. The supply to the areas within Jordan in the basin can be much better but will require solutions to be implemented in areas outside of the basin that are fed from KAC. Using the water of Wehdeh dam locally instead of releasing them to be diverted at Adassiyeh would improve the allocation of Jordan.

Lack of data and info is the major complication in the modelling process of the Yarmouk watershed especially when accompanied with complex changes in a basin that is over-developed with water infrastructure.

Improving data availability especially from the Syrian side in the basin can reduce much of the uncertainty around evapotranspiration and GW recharge rates. Also, additional data on flow in tributaries and GW use in Syria could further improve the optimization and validation process of the model. A more detailed model can be attained when scrutinizing each sub-catchment while considering the operation and use from each reservoir within. A groundwater model must be coupled with WEAP to better understand the recharge patterns and to represent the exchanges between different aquifers and thus allowing for an accurate GW balance to be developed. Moreover, the increased wastewater returns and the subsequent risk of pollution of dams should be addressed as it could further decrease the availability of surface water.

Last but not least, it is important to mention that the increased water shortage under the current non-cooperation between the riparian states in the basin could push for more confinement of water sources and more exploitation of any leverage over them. Taking into account the geo-politics of the region in addition to the continued occupation of Golan Heights which Syria have every right to its land and water resources, true cooperation between the three countries and consequently any improvement in water sharing and management may not be easily achieved.

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Annex

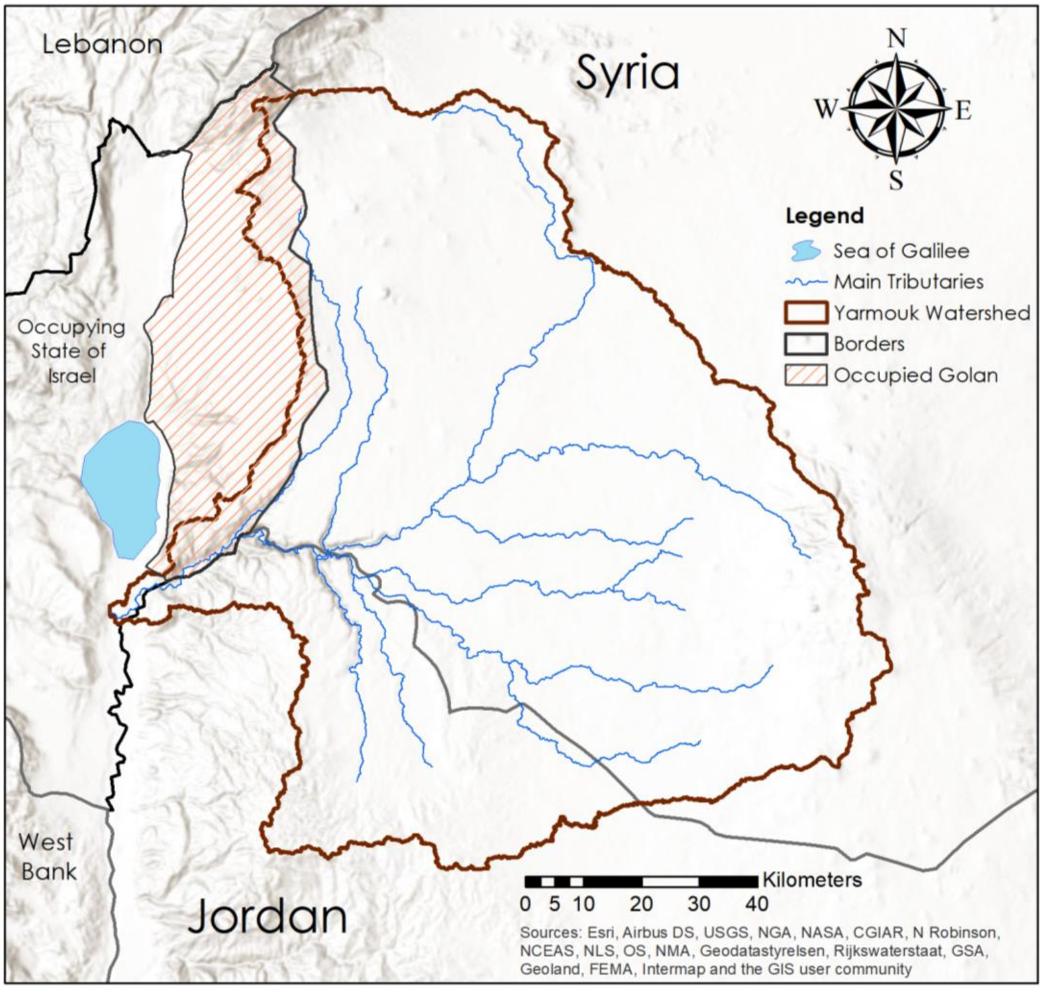

Figure 37: Boundaries of occupied Golan Heights and riparian countries in Yarmouk basin

Dam name	Storage capacity (MCM)	Country	Tributary	Storage capacity of WEAP reservoir node (MCM)
Al Allan	5.25	Syria	Al Allan	32.728
Al Hujah	0.85	Syria		
Saham al Golan	20	Syria		
Taseel	6.628	Syria		
Abta' al Kabeer	3.5	Syria	Al Hareer	39.95
Abta' al Sagheer	0.5	Syria		
Adwan	5.85	Syria		
Al Rom	6.4	Syria		
Al Sheikh Maskin	15	Syria		
Gharbi Tafs	2.1	Syria		
Jowayleen	0.5	Syria		
Qanawat	6.1	Syria		
Al Butmeih	0.3	Occupied Golan	Raqqad	102.43
Kheital	5	Occupied Golan		
Meitsar	0.6	Occupied Golan		
Bental	4.2	Occupied Golan		
Al Mantara	40.2	Syria		
Al Raqad	9.2	Syria		
Burayqah	1.1	Syria		
Ghadir al Bustan	10.8	Syria		
Kudnah	30	Syria		
Ruwayhaniyah	1.03	Syria		
Al Asleha	0.04	Syria	Thahab	4.78
Al Ghariyah al Sharqiyah	2.45	Syria		
Al Raha	0.45	Syria		
Ghadir al Suf	0.16	Syria		
Rasas	0.03	Syria		
Sahwet al Blata	1	Syria		
Uthman	0.65	Syria		
Al Ain	1.35	Syria	Zeidi	33.29
Al Batm	2.14	Syria		
Al Muta'iyah	1	Syria		
Dar'a al Sharqi	15	Syria		
Hebran	1.95	Syria		
Sahwet al Khoder	8.75	Syria		
Al Bouwayda	0.7	Jordan		
Ghadir al Abyad	0.7	Jordan		
Sama al Sarhan	1.7	Jordan		
Abedeen	5.561	Syria	Yarmouk MainOutlet	115.561
Al Wahdah	110	Syria/Jordan		

Table 25: Name and storage capacity of dams in Yamrouk basin

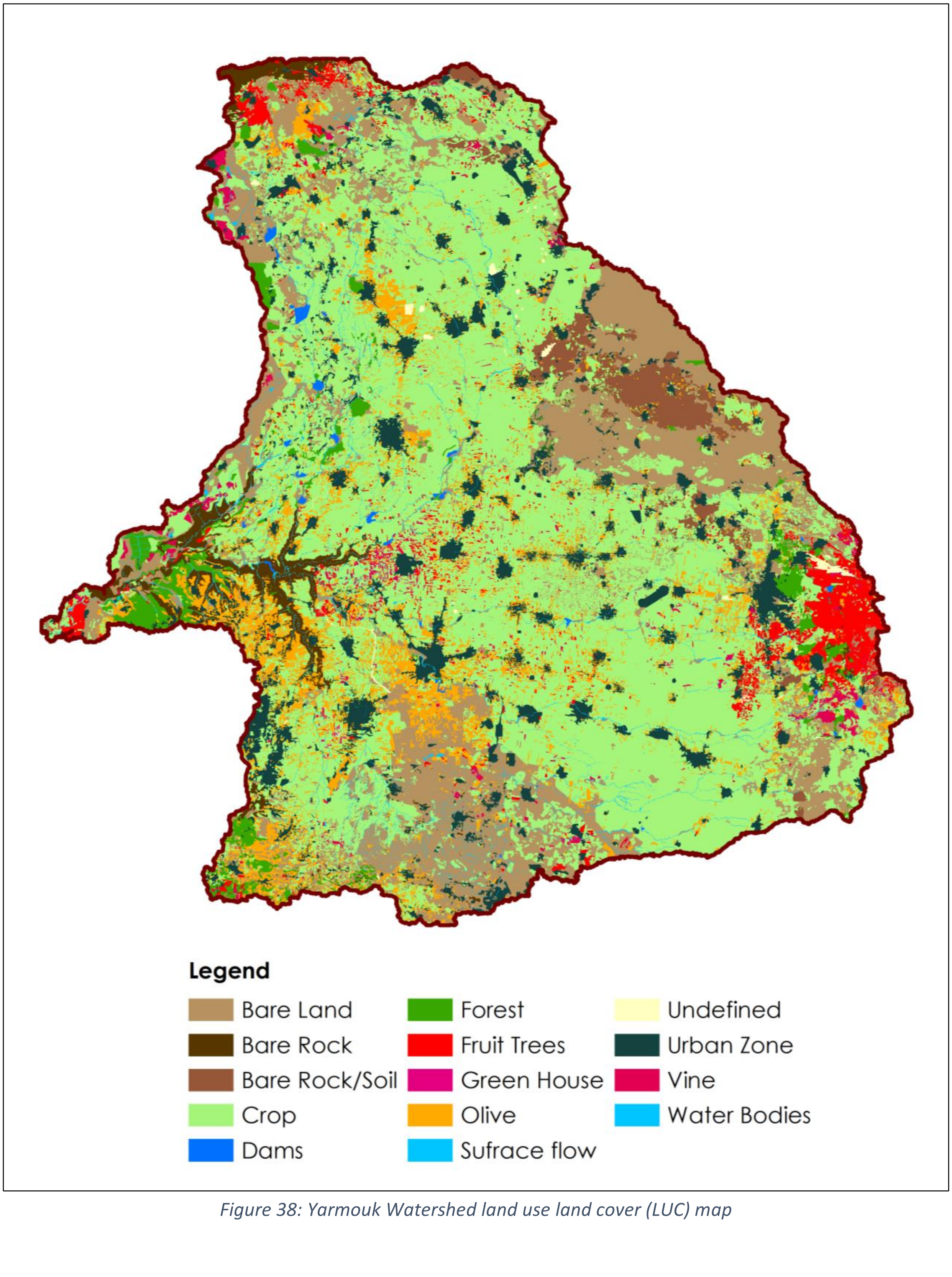

Figure 38: Yarmouk Watershed land use land cover (LUC) map

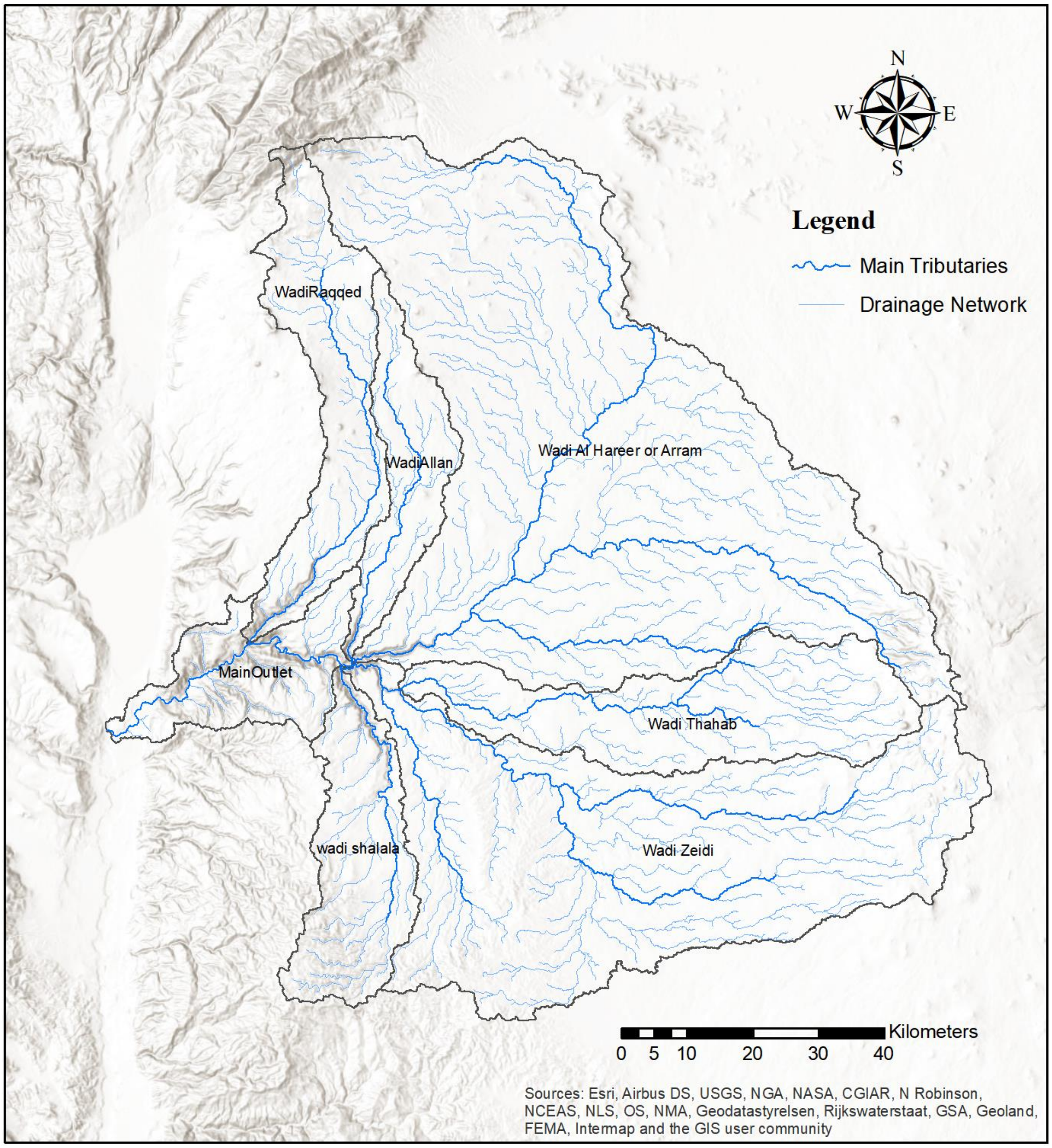

Figure 39: Yarmouk sub-basins and drainage network