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RESEARCH PAPER

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Scenario simulation and analysis in the transboundary Yarmouk River basin using a WEAP model

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ABSTRACT
Water is a finite resource but an essential one. The continuously increasing demand leads to competition and conflict over limited resources. Syria, Jordan, and Israel compete over the water resources in the transboundary Yarmouk River basin where two water agreements dictate the allocation of water. The two arrangements are far from being efficient and fair while little cooperation is being made over sharing the resources that are being over-exploited. In this study, water sustainability was investigated under projected developments and trends based on the current use and allocation regime in the watershed using several scenarios. A one bucket soil moisture model was adopted and optimized in order to fully represent the ever-changing hydrology of the basin using the 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. The growth of both agriculture and population produced huge water shortages in all demand sectors. Under climate change scenarios RCP 4.5 and RCP 8.5, surface water availability and the retention of dams reduced significantly. The share of Jordan from the Yarmouk River was the most vulnerable to climate change impacts. Enhancing irrigation efficiency and a more stable population growth based on the UN medium variant population projection showed improvements in water coverage within all demand sectors. Analysis of future scenarios suggests that water shortage is expected in all riparian states of the basin but can be mitigated by reducing demands.

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Yarmouk; river; basin; Syria; Jordan; Israel; transboundary; WEAP; scenario; water resource management

1. Introduction

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 freshwater has been increasingly threatened by pollution and climate change. Accompanied with the increase in population and the huge expansion of agricultural lands since the start of the past century, the rapid rise of water demand has led in many cases to the over exploitation of water resources. This is certainly true in water stressed environments such as the Mediterranean climate where the combined effect of climate and land cover changes has led to an overall decrease in water resource availability (García-Ruiz et al., 2011). Furthermore, a global study on organic pollution of rivers concluded that by 2050, more than 2.5 billion people will be affected by organic pollution as compared to 1.1 billion in 2017 (Wen et al., 2017). Hence, the proper management of these vulnerable resources has become a necessity for achieving water security for various countries, especially in semi-arid areas.

Many countries are continuously trying to secure their rightful water resources whether they come from internal or external origins. Water bodies, rivers, and aquifers may traverse international borders and sometimes the allocation and sharing of these waters could turn into a competitiveness that may develop into a conflict between several countries. Such water is referred to as 'Transboundary waters' which are defined as any surface or ground waters that mark, cross, or are located on boundaries between two or more States (UNECE, 1992)). About 153 countries across the world share rivers, lakes, and aquifers accounting for an estimated 60 percent of global freshwater flow (UN, 2018b).

Most parties initially seek to keep their control over water resources for their important economic and political value (ASCE, 2013). The contest for fresh water has often led to the deterrence of relations between neighboring nations and has pushed some countries to threaten their counterparts. Nonetheless, many countries have ended such contests through mutual water agreements and treaties. However, such agreements are not always equitable (Zeitoun & Warner, 2006). This is indeed the case of the Yarmouk River basin. A transboundary river shared between three countries, Syria, Jordan, and Israel, is located in one of the most water-stressed environments in the world (Bar & Stang, 2017). An agreement on water sharing does exist between the various riparian states, however, it is considered by some to be unfair, especially for Jordan (Hussein, 2017).

Despite the vitality of a permanent water course such as Yarmouk in a region with severe water scarcity problems, few studies exist on the current and future water management strategies in the basin and their possible impact on water availability for the various stakeholders. Previous studies in the area focus more on the hydro-chemical characteristics of surface and groundwater (e.g. Howari & Banat, 2001, 2002; Rosenthal et al., 2020 among others) and groundwater contamination (Awawdeh & Jaradat, 2010) while very

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few studies deal with the hydrology of the river and the impact of current management strategies and water policies on the river flow. A recent study by Shentsis et al. (2019) on water consumption in the basin concluded that during the period 1997–2009, water consumption was estimated as 76% of the natural flow (82% for surface water and 67% for groundwater). This rate increased to more than 95% for the period 2006–2009. These findings highlight the severe pressure put on the water resources of the Yarmouk basin and underline the importance of implementing better management strategies for a sustainable use of water in the region.

Water sharing of the Yarmoukhas been directly related to the geopolitical situation in the region during the past century. Starting with the fall of the Ottoman Empire and the recognition of the river as the boundary between French Syria and British Transjordan, the history of the basin was filled with conflict rather than cooperation. Land control in the basin changed after the occupation of Palestine in 1948 and the occupation of the Golan Heights in 1967. The three involved states developed their own plans independently with the help of international backers, however, the conflict peaked when military intervention was used to halt the plans of different sides, especially in the 1960s. Nowadays, two water agreements govern the allocation in the basin. The first is the 1987 Syria-Jordan water agreement while the second is the 1994 peace treaty between Jordan and Israel.

The aim of the study is to investigate the long term impact of different changes that may occur in the Yarmouk river basin and assess the compatibility of current water policies in the future. The study also intends to establish a system that represents the current water allocation mechanism between the riparian states in addition to the exploitation and use of each. Such a resulting model will present a new tool to analyze water resources and their management in an understudied area of conflict at a country and sub-basin level. Several scenarios that incorporate variations in agriculture, population, and climate are simulated till the end of the century and analyzed against a baseline reference of projected historical data. The study shall provide further insight into the future of the basin in light of the various transformations that could be managed or not.

2. Literature review

2.1. Study area

The Yarmouk River is one of the main tributaries of the Jordan River. The river meets the lower Jordan River south of Lake Tiberias at Baqura. The River is transboundary by definition as it marks the borders of three riparian states: Syria, Jordan, and Israel. The watershed is located in the southern part of Syria and the northern part of Jordan, it extends to Jabal al Arab to the east, Jabal al sheikh (Mount Hermon) to the northwest, and Ajloun Mountains to the south. The basin includes the Hauran plain and areas from the eastern and southern parts of the Golan Heights.

The area of the basin is estimated to be 7386 Km^2 with 80% being in Syria (Occupied Golan Heights represents 4.5%), 19.7% in Jordan, and 0.3% in Israel (Figure 1(a)) (UEA, 2019). The basin has a low slope except in the areas near Jabal al Arab, Jabal al Sheikh and in the Yarmouk valley. There are 6 main tributaries feeding the mainstream river: Raqqad, Allan, al Hareer, Thahab, Zeidi, and Shallala (Figure 1(b)). All but Raqqad meet near Maqarin on the Syrian – Jordanian border.

Yarmouk is located in a region with severe water scarcity problems. Indeed, the main riparian state in this basin, Syria, is under water stressed conditions with a total water withdrawal per capita equal to 853.7 m^3/year (Aquastat, 2016). Jordan on the other hand is ranked the second poorest country in water resources where less than 100 m^3 of renewable water is available annually per capita (MWI, 2017). The country suffers from water scarcity and is exploiting its non-renewable resources at high rates. The Jordanian authorities have constructed dams and wastewater treatment plants to maximize their water resources. Water shortage is a reality in Jordan and with the very limited internal water availability accompanied with high population growth and huge refugee influx, more pressure is being placed on water resources. The last portion of the basin is under 'Israel's' control and includes the occupied Golan Heights. In Israel, water withdrawal per capita is around 282 m^3/year (Aquastat, 2016) placing it in a better position compared to Jordan. Israel, similar to Syria and Jordan, relies on external sources of water and already uses more than its legal share from the transboundary Jordan river (Zeitoun et al., 2019a), especially from the headwaters within the Golan heights.

The climate in the Yarmouk basin is Mediterranean with cold rainy winters and hot dry summers. The annual precipitation varies between 200 and 775 mm in the basin and is around 300 mm on average. The rainfall is higher near Jabal al sheikh, Jabal al Arab, and Yarmouk gorge areas and lower near Mafraq in Jordan (UEA, 2019). The basin is mainly covered by crops (49%) and bare areas (24%). The main soil cover is vertic cambisols which are mostly abundant in the Hauran plain. Regarding groundwater, two main aquifers are present in the basin: the basalt aquifer and the A7/B2 aquifer (Figure 2). The former outcrops primarily in the Syrian side where it is mostly exploited while the latter outcrops on the Jordanian side and is the main source of groundwater there.

In March 2011 the Syrian war started, the war that expanded to most regions in the country. The armed conflict inside the Yarmouk basin was effectively put to an end in July 2018 but left 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 (Müller et al., 2016) and many of the existing infrastructures were damaged or destroyed.

2.2. Infrastructure

The Yarmouk River is heavily dammed with about 40 dams located on various tributaries throughout the basin (UEA, 2019). The majority of these dams are in Syria with a total of 32 dams alongside 4 more dams in the occupied Golan Heights. 3 dams are in Jordan whereas the Wehdeh dam exists on the border between Syria and Jordan. Moreover, a concrete weir is constructed at Adassiyeh at the border between Jordan and Israel. Water diverted by this weir is carried to Jordan using the King Abdullah canal. Figure 3(a) shows the location of the reservoirs in the basin while Figure 3(b) shows the main allocation infrastructure on the mainstream river. More details on the basin infrastructure and reservoir capacities are presented below.

- **Dams in Syria:** the 32 dams exist over all the main tributaries within. The total capacity of these dams is 205.54 million cubic meters (MCM). The largest two dams Al-Mantara and Kudnah with respective capacities of 40.2 and 30 MCM are located on the Raqqad tributary. Several dams are polluted and some are out of service.
- **Dams in Jordan:** the 3 dams are located 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. (UEA, 2019)
- **Dams in Golan Heights:** the 4 dams are located in the Raqqad sub-basin with a maximum capacity of 10.1 MCM.
- **Wehdeh dam:** finished in 2006, the dam is located near Maqarin and is the largest in the basin with a 110 MCM capacity.

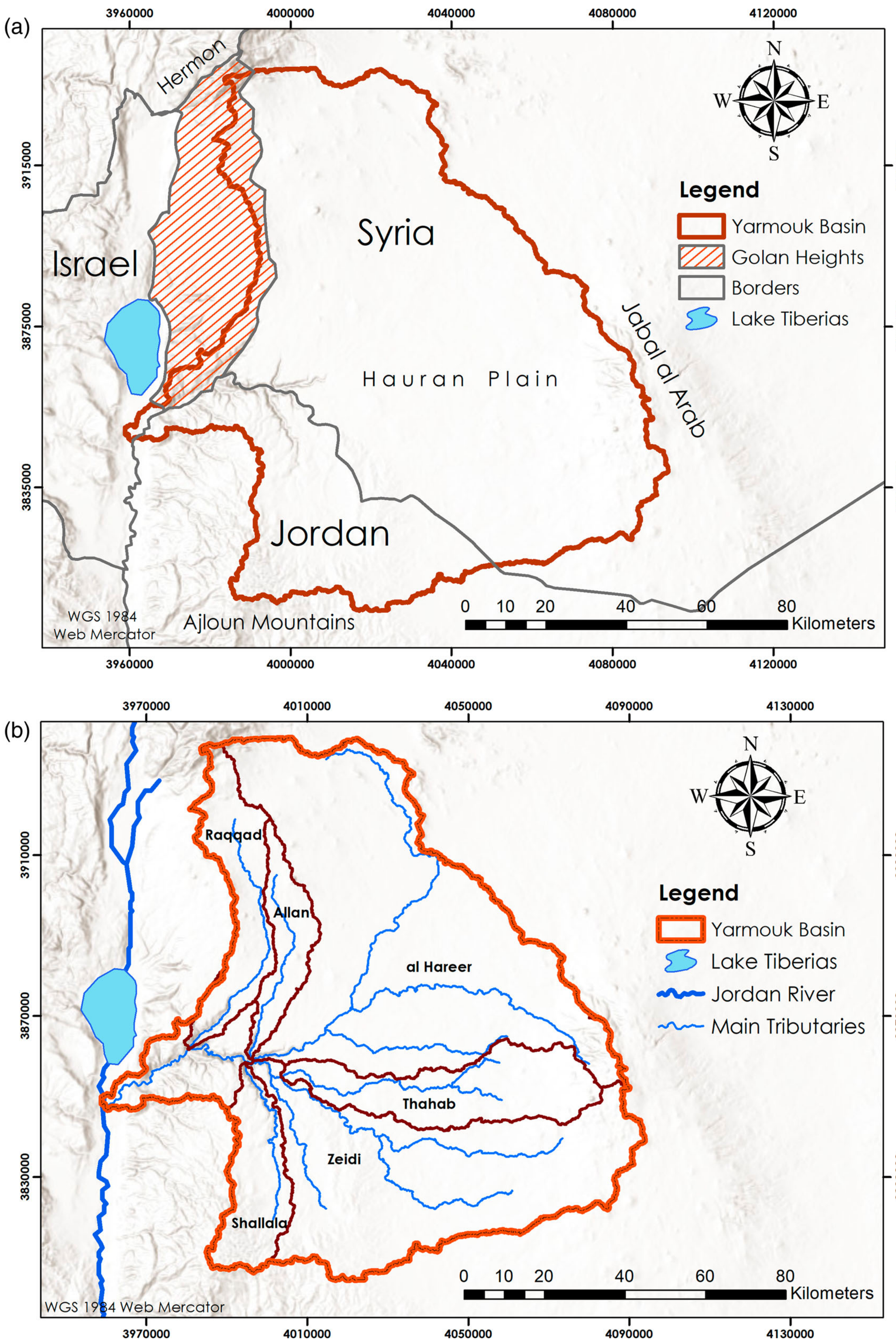

Figure 1. (a) Hydrological and administrative boundaries in the Yarmouk basin. (b): Yarmouk River and its main tributaries.

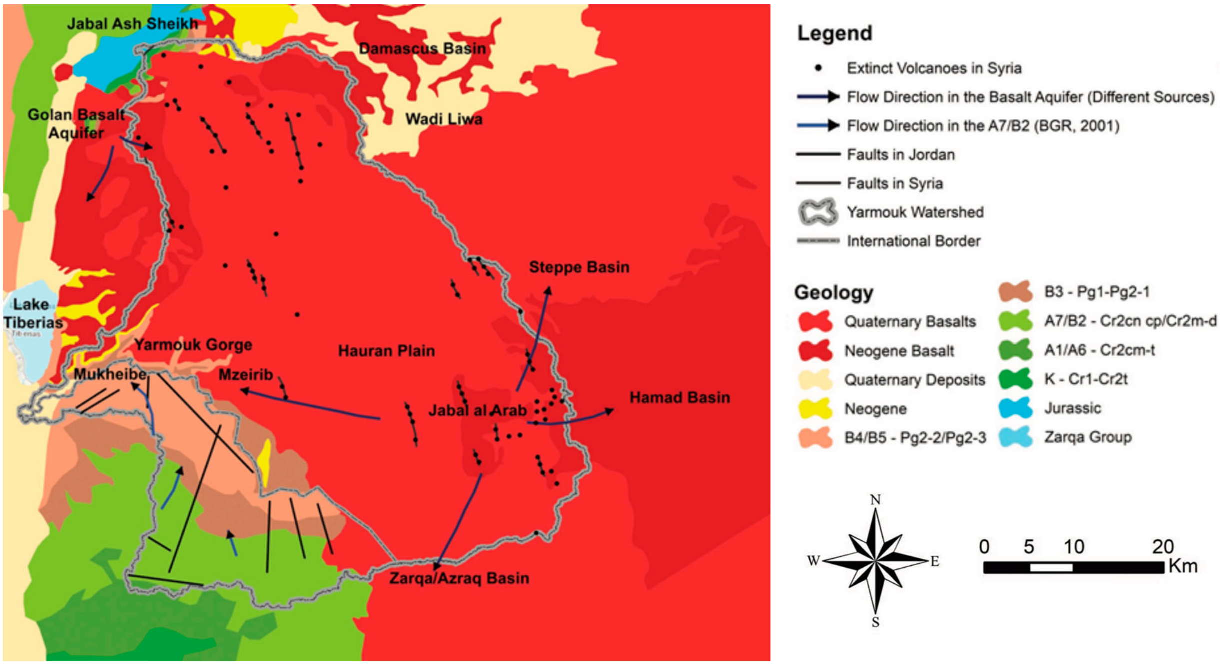

Figure 2. Geology of the Yarmouk basin (UEA, 2019).

- **Adassiyeh weir:** completed in 1999, the concrete weir is used to divert flows away from the river into Jordan.
- **King Abdullah canal (KAC):** the canal is parallel to the Jordan River and is used to carry the diverted flows into Jordan.
- **Yarmoukim reservoir:** located upstream of the Yarmouk confluence inside Israel, the reservoir has a capacity of 750,000 m^3 and is used to store the flow of the river (Zeitoun et al., 2019a).

2.3. Water agreements

Key points from the agreement between Syria and Jordan (1987) on the utilization of Yarmouk waters include:

- Agreement to build Wehdeh dam on the border near Maqarin to be used for power generation and irrigation (completed in 2006 without the power generation part)
- Wehdeh dam is to be filled after the filling of 26 dams in Syria with a total capacity of 134.17 MCM in which Syria has full right to
- Syria retains the right to use all springs except those welling above the dam and below 250 meters above sea level (which include the majority of the springs in Syria)
- Jordan has the right to use the overflow of the Wehdeh dam

The treaty between Jordan and Israel (1994) included clauses on water sharing; some important clauses regarding Yarmouk are:

- Israel gets to pump 25 MCM from the Yarmouk river (12 MCM in summer and 13 MCM in winter)
- Jordan is entitled to the rest of the river flow but Israel is to store an additional 20 MCM in Lake Tiberias during winter to be then returned to Jordan during summer
- Agreement to build diversion dam at Adassiyeh (completed in 1999)
- Both countries may use excess flood water downstream Adassiyeh

2.4. Water allocation

The allocation of surface water in the Yarmouk is dictated by the structures along the river and its tributaries. Despite the two water agreements, the actual water allocation in the basin occurs as seen in the flow chart (Figure 4). The total flow captured by dams in Syria, Jordan, or Golan heights along the tributaries is used locally by each state. It is worth noting that the Syrians have built 6 more dams than those specified in the 1987 agreement, these dams however rarely retain to their full capacity and only retain on average 40% of this capacity (UEA, 2019). The total allocation of Syria is completed by adding their exploitation of local springs and from groundwater through the thousands of drilled wells.

The lack of cooperation between Syria and Jordan is evident by the absence of any type of release or exchange from upstream dams toward the mainstream river. Hence, the flow reaching Maqarin at the Syrian /Jordanian border can be traced to three sources: surface runoff originating downstream from the dams in the two states, the rare overflowing of these dams, and spring discharge not exploited by Syria. These flows are stored in Wehdeh dam then released during the dry season.

Just upstream from the Yarmouk confluence, the flow of the river is shared between Jordan and Israel at Adassiyeh. This flow originates from three sources: the natural flow of the river, releases from Wehdeh dam and the discharge of Mukheibeh wells. Mukheibeh is located in northern Jordan where a number of highly productive wells are found. The discharge of these wells is diverted into the Yarmouk riverbed (Zeitoun et al., 2019b). The sharing mechanism is ensured by the Adassiyeh weir where the flow of the river either overflow the weir or is diverted away. The Jordanian operators of the weir allow a constant flow of 1 m^3/s from

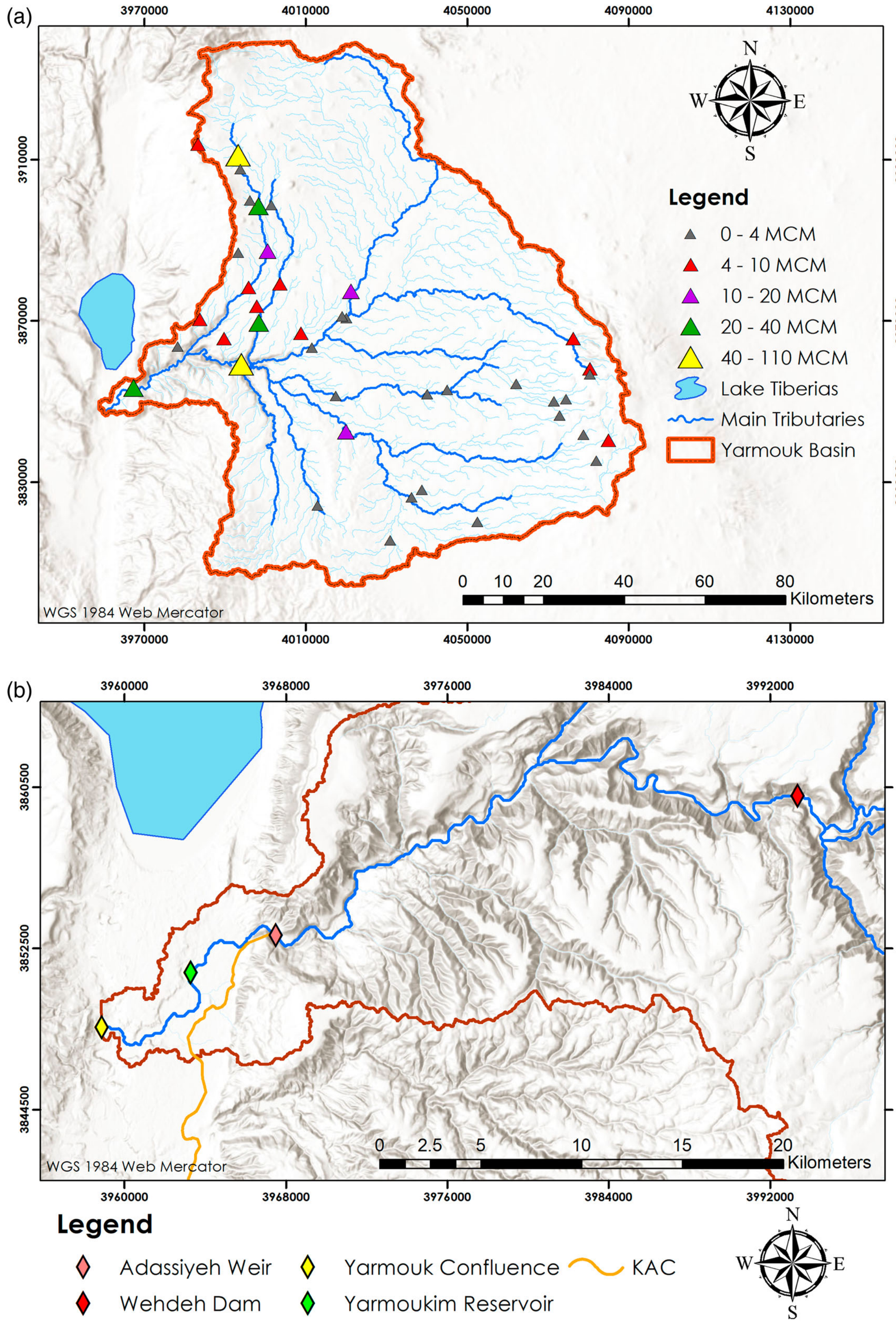

Figure 3. (a) Capacity and location of dams inside Yarmouk basin. (b) Main allocation infrastructure in the Yarmouk basin.

the diverted water to be returned through special gates to the riverbed downstream (Zeitoun et al., 2019b). This flow guarantees the 25 MCM conceded by Jordan to Israel as per the 1994 treaty. The conceded flow in addition to the flow that bypass the Adassiyeh weir by overspilling its crest eventually reach Yarmoukim reservoir where water is pumped for local use in Israel or sent to Lake Tiberias.

The rest of the diverted flow is carried through KAC into Jordan. Further flows are sent from Lake Tiberias into KAC as part of the exchange agreed on in the 1994 treaty. The surplus flow sent from the lake include concession for the additional flows bypassing the weir through the gates and purchased water.

2.5. Hydrology

The Yarmouk River has witnessed drastic changes within the past two decades years in terms of hydrology. Analysis of the

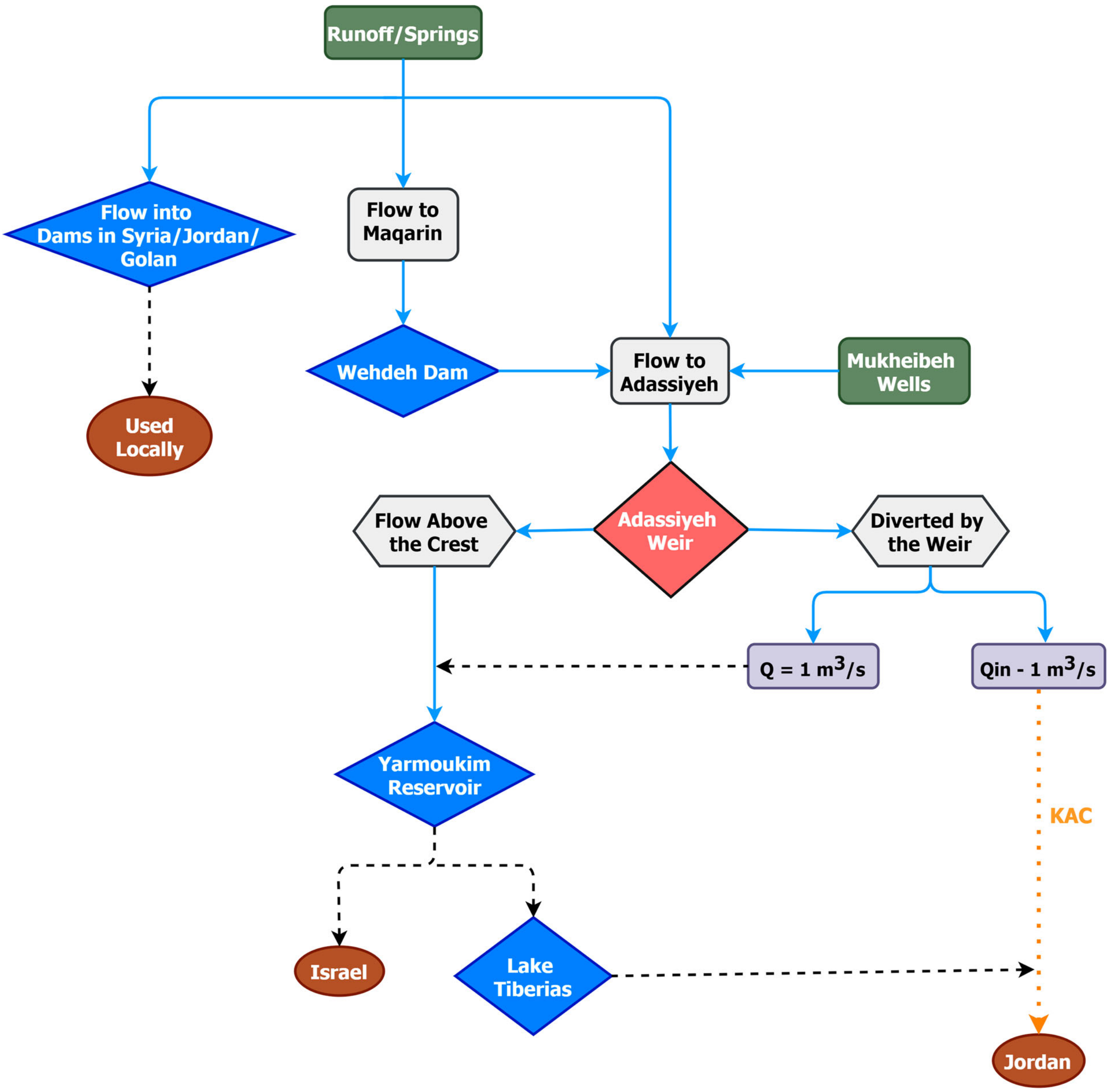

Figure 4. Water allocation diagram in the Yarmouk basin.

stream flow showed a significant decline in the baseflow of the Yarmouk river after the year 2000 that almost disappeared by 2006. Available data on the annual discharge of the main springs within the Syrian part of the basin showed a remarkable reduction especially after 2006 (CBS, n.d.). During the Syrian crisis and especially after 2013, the runoff reaching Maqarin increased considerably. This is attributed to the damage of dams, wells and pump stations, mismanagement of water resources and the decrease in irrigated areas in Syria. Nevertheless, the lack of supervision and regulation resulted in an increase in unlicensed wells causing many of them to dry up as a result of water table deepening (Etana, 2015). The over-reliance on groundwater was evident by the drying up of Muzayrib lake near Daraa which is supplied from spring discharge (Cooke, 2017).

Climate change and the frequent droughts are often considered the culprits behind hydrological variations. The impact of local water management policies especially in Syria has had a great role in the changing hydrology of the river. (Avisse et al., 2020) and (Shentsis et al., 2019) state that groundwater over-abstraction is the main driver behind the change in the flow regime despite the impact of climate change and the lack of transboundary water sharing mechanisms. This indicates an influence from local water management policies on the transboundary water allocation in the basin.

3. Materials and methods

3.1. Data sources

The availability and reliability of data is a major obstacle in the Yarmouk basin. Little data is available from the Syrian side where needed information are considered part of the national security. No data were available on Syrian dams except the storage capacities and the elevation and maximum surface area of some. Data from Jordan are not reliable and contain many gaps. Table 1 shows the sources of acquired data.

Climatic data were extracted from satellite observations. The acquired rainfall data were generated by coupling data from remote sensing (CHIRPS) and from ground gauging stations that showed moderate to good fit (UEA, 2019). The monthly averages for temperature were extracted

Table 1. Description and sources of data used to build the WEAP model.

Data	Description	Source	
Climate data	Precipitation (2000–2015)	Monthly precipitation on subbasin level	UEA (2019)
	Temperature (2000–2015)	Monthly averages downscaled per subbasin	NASA FLDAS Noah Global data products (0.1°)
	Wind speed; Relative humidity (2000–2015)	Monthly point average at 2 m elevation	MERRA-2 products from NASA Power meteorological data sets (0.5°)
Population	Capita	2004 population consensus in Syria and Jordan	Syrian Central Bureau of Statistics (CBS); Jordanian department of statistics (DoS)
	Growth rate	Annual growth rate in Jordanian governorates Annual growth rate estimates in Syria	Jordanian department of statistics (DoS) UN World population prospects 2019
Gauged flow	Daily flow at Maqarin, Adassiyeh (Alpha, Beta, Mukheibeh Wells, Return from Tiberias), Shallala and Shummar Wadis; Inflow and Outflow of Wehdeh dam	Jordan Valley Authority (JVA)	
Soil	World soil map based on FAO-UNESCO soil classification (1:5,000,000 scale)	FAO digital soil map	
Land Use/Cover	Land cover/use with 13 classes (scale 1:20,000; 50 cm resolution)	UEA (2019) based on ESRI GEOEYE 2011 basemap	

using ArcGIS and calculated for each sub basin using Thiessen polygon method. The collected data for wind speed and relative humidity are point monthly averages taken at the latitude 32.68° and the longitude 36.13° for a 2 m above ground elevation. Regarding stream flow, the only available gauged data are from the Jordanian side (Figure 5) and are recorded by the Jordanian Valley Authority (JVA), however they were not adequate and contained gaps. The available flow at Adassiyeh is divided into alpha and beta flows. 'Alpha' flows are the flow diverted by the weir at Adassiyeh and continue to Jordan. They are recorded separately by JVA from three sources: natural Yarmouk flow, Wehdeh dam releases and Mukheibeh wells discharge. The measured 'Beta' flows represent the flow that bypass the weir. The flows sent from Israel to KAC from Lake Tiberias are also available. Moreover, data on the wastewater treatment plants were acquired from literature (MWI, 2015). The treatment plants allocate 3.8 MCM that are used for irrigation in Jordan (Al-Bakri et al., 2016).

3.2. Estimation of retention in dams

The initial storage of the reservoir nodes was estimated with the help of remote sensing methods. The storage of 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. The near infrared bands were used to detect the surface area of the major dams in the basin. The areas

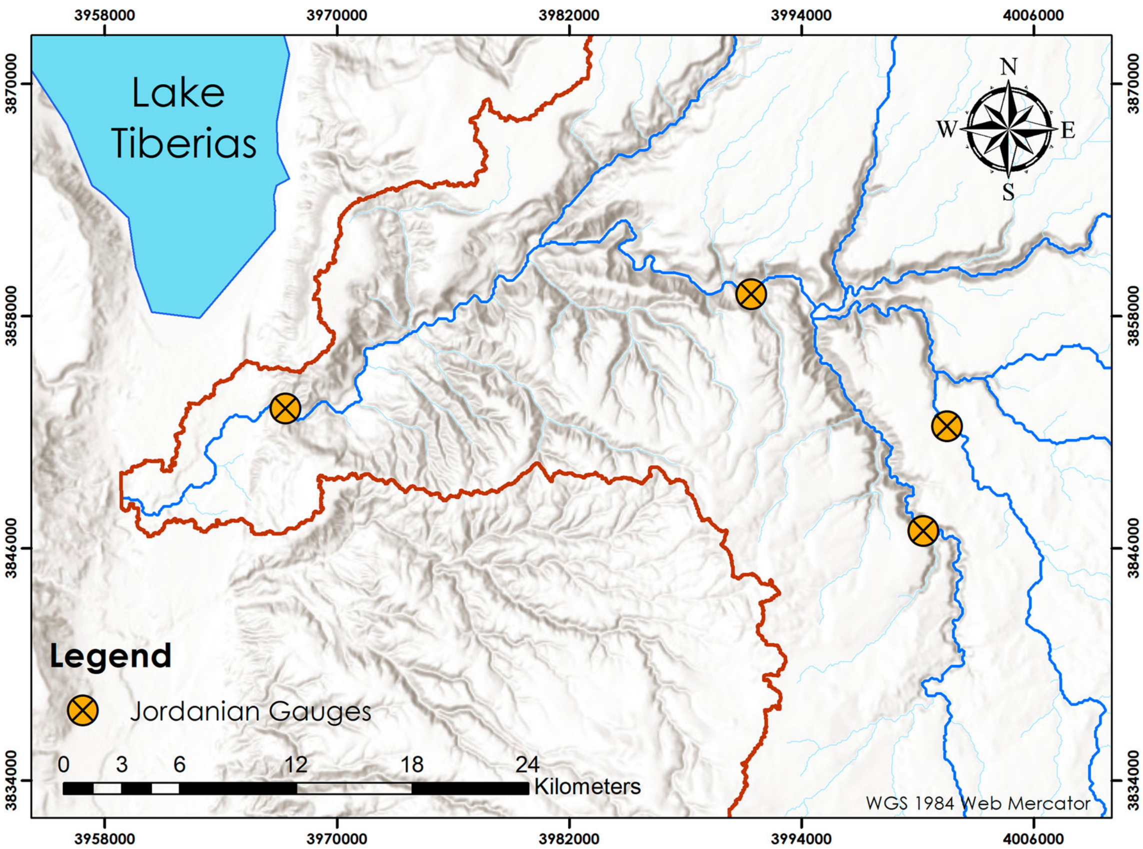

Figure 5. Location of Jordanian gauges.

were then delimited and measured then a linear volume-area relationship was used to calculate the storage of each dam. This method was validated by comparing the maximum retention of some dams with the maximum retention found in literature. Comparison showed an 80% accuracy and thus this method was considered valid (UEA, 2019).

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.

3.3. Water evaluation and planning (WEAP)

Developed by Stockholm environmental institute (SEI), WEAP is a platform to model watersheds with all its components and characteristics. The software is a decision support system (DSS) that 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 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, limits and supply preferences. The tool is mainly used to develop and evaluate scenarios incorporating future changes and transformations in various aspects of the water sector. WEAP has been successfully used previously to assess transboundary basins in North Africa (Rajosoa et al., 2021), the Middle East (Avarideh et al., 2017; Hoff et al., 2011) and North America (Sandolas-Solis et al., 2013).

Five methods for catchment modelling are incorporated in WEAP. The soil moisture rainfall-runoff method was chosen to model the rainfall-runoff relation in the catchments of the WEAP model.

3.3.1. Soil moisture method

The method is a two-bucket soil moisture accounting scheme. The upper bucket represents the root zone layer while the bottom one represents the deep soil layer and the aquifer storage. In each timestep, WEAP calculates the soil moisture level in each layer based on the inflow and outflow. Runoff, interflow, evapotranspiration and deep percolation are then calculated based on the parameters of the top layer. Baseflow discharge from the deep layer is dictated by its soil moisture level and the controlling parameters of the bottom layer. This scheme however, does not allow any abstraction from the deep layer and thus the baseflow is never impacted by over-exploitation of groundwater. The two-bucket model may be a better fit in a watershed where groundwater discharges at a consistent rate and is not an important source for local use (Yi, 2016). In the Yarmouk basin, the aquifer discharge is affected by groundwater withdrawals which are above sustainable limits (Shentsis et al., 2019). To overcome this issue, the bottom layer is neglected and substituted by an external groundwater node that is accessible by demand sites. The adopted model therefore became a one bucket soil moisture scheme (Figure 6) where the baseflow and interflow are estimated adjointly.

A watershed unit can be divided into N fractional areas representing different land uses/soil types, and a water

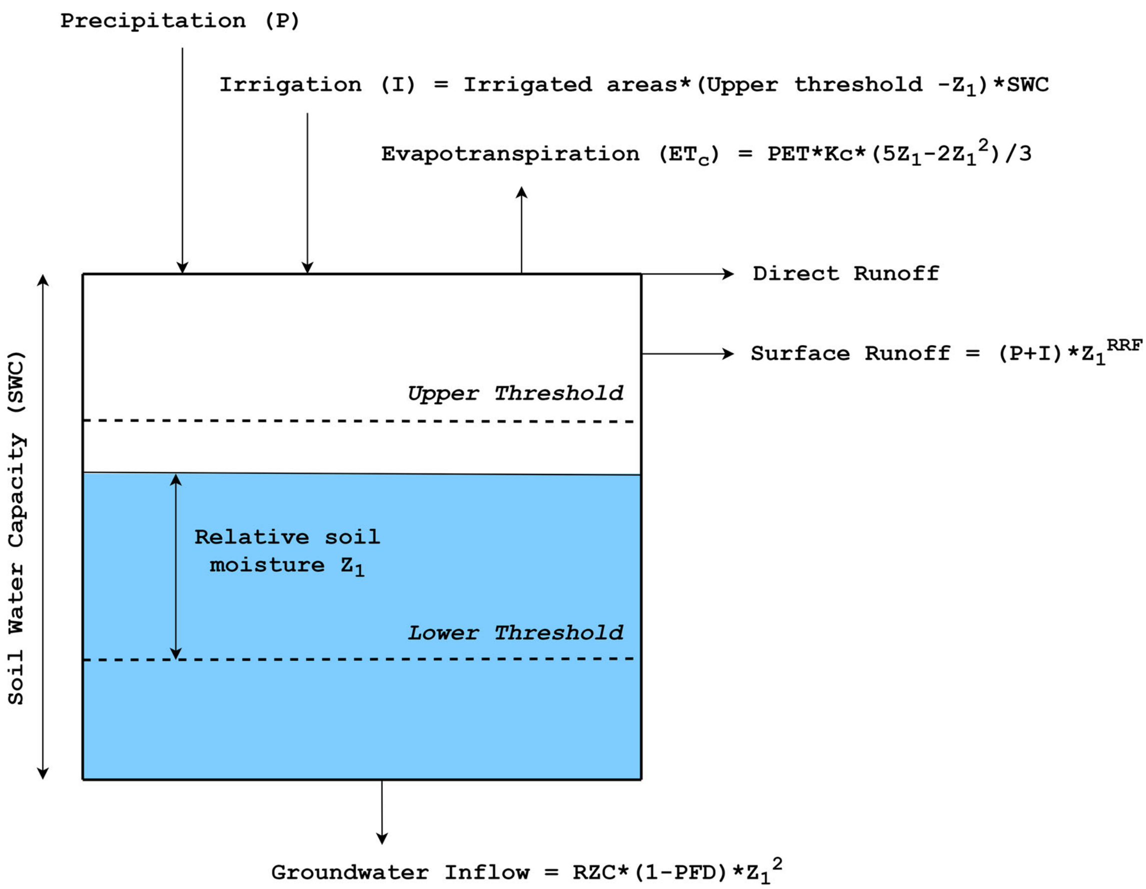

Figure 6. Conceptual diagram of the one-bucket soil moisture method (adapted from SEI, 2011).

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 $Z_{1,\,j}$ 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 is the reference potential evapotranspiration calculated using a modified Penman-Monteith equation. $K_{c,j}$ is the crop coefficient for each fractional land cover and RRF_j is the runoff resistance factor of the land cover. $K_{z,j}$ is an estimate of the root zone saturated conductivity (mm/time) and f_j is the preferred flow direction; a coefficient used to partition the flow out of the first bucket into interflow and deep percolation.

3.3.2. Demands

WEAP calculates domestic and industrial demands based on three parameters: the annual activity level, the annual water use rate and the monthly variation. The annual activity level represents the number of demand units such as population. The water use rate is the usage rate according to the type of demand while the monthly variation is the proportion of the annual demand in each month. The monthly demand is then calculated by multiplying the three values.

Agricultural demands are calculated according to the used catchment method. In the soil moisture method, the irrigation demand is triggered based on the value of the relative soil moisture of the irrigated area. When the relative soil moisture goes below the lower irrigation threshold, irrigation is applied till the relative soil moisture reaches the upper threshold level. The rate in which irrigation is applied is therefore mainly dictated by the crop evapotranspiration, deep percolation and the two irrigation thresholds.

Demands in WEAP are supplied based on a priority value. Demands with higher priorities are supplied before demands with lower ones. Whereas equal priorities mean water is supplied equally until no more water is available for allocation. Supply limits can be also applied to restrict the supply form a water source.

3.3.3. Reservoirs

The management of the reservoirs in WEAP is based on four defined zones within its storage (Figure 7). The flood control zone is kept empty for flood protection purposes whereas the conservation zone is used to freely allocate water to the different demands. If the water level reach the buffer zone, the releases are restricted by a buffer coefficient that defines the monthly fraction that can be released. Water releases are eventually halted if the water level drops into the inactive zone.

3.4. Model setup

The model was set to have a monthly time-step and the water year was set to begin in October and end in September. Due to the huge impacts of the Syrian war on the water sector, 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 (2018–2100). To fully capture the pre-war dynamics the water year 2005 was chosen as the current account year. The last year of simulations was set to 2100. The first two periods were characterized by the general trends and developments that occurred in the basin during them while the last period was used to explore the future scenarios. The built model (Figure 8) included:

- 7 catchments: were used for each sub-basin. The catchments included irrigated areas and thus act as an agricultural demand node as well as a watershed unit.
- 16 demand nodes: 3 nodes representing Israel's demand from Yarmouk flow, groundwater and dams. 6 demand nodes for Syrian domestic demand in each sub-basin and one node for the Syrian industrial demand. 4 nodes were used in Jordan, 3 for domestic demands per sub-basin and one for their use from Yarmouk River.
- 7 dam nodes (Wehdeh dam, Yarmoukim reservoir and one on each of the Hareer, Raqqad, Allan, Thahab and

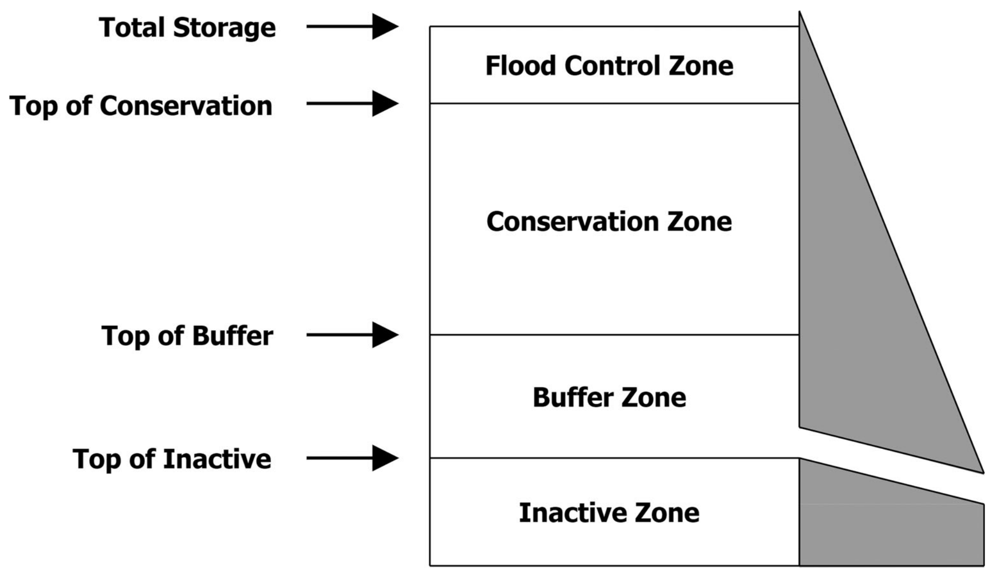

Figure 7. Reservoir zones in WEAP (SEI, 2011).

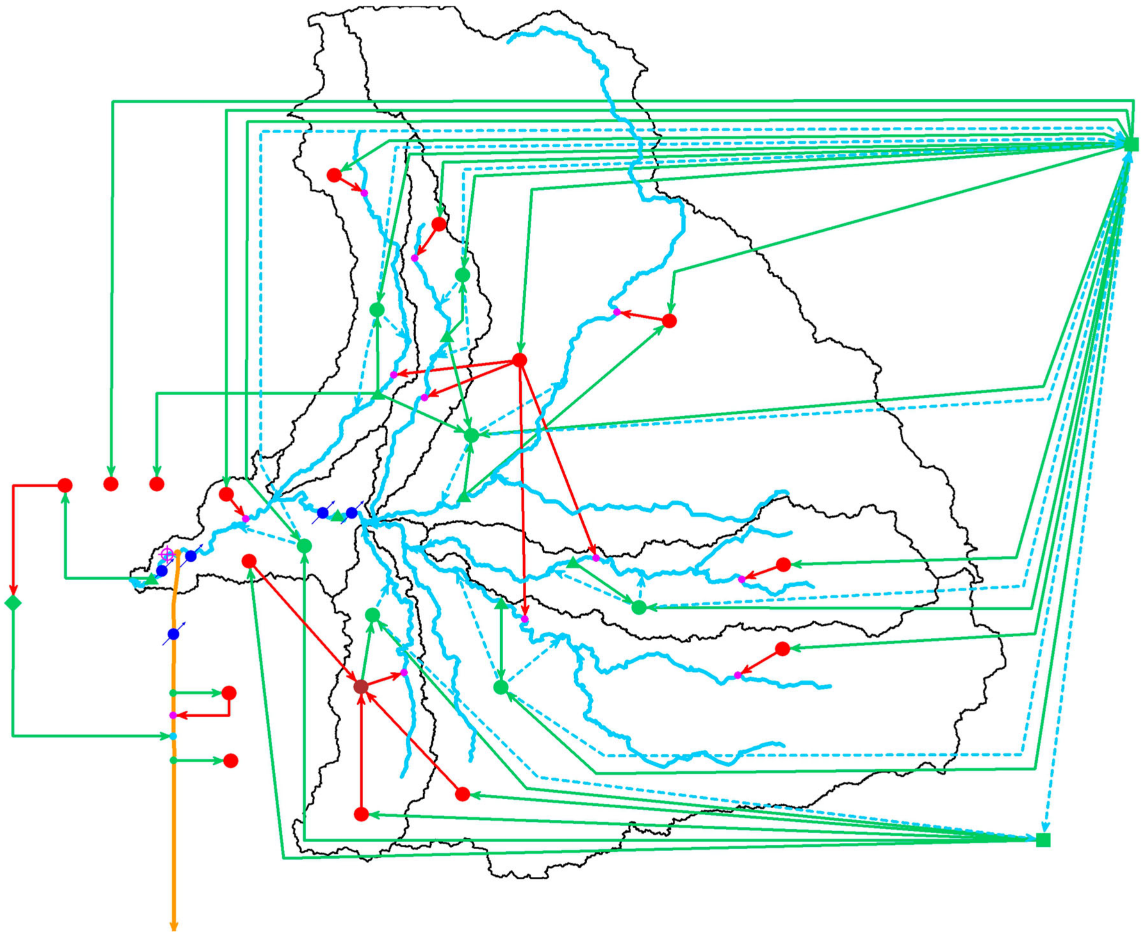

Figure 8. WEAP schematic of the Yarmouk basin.

Zeidi tributaries where each node represented the set of dams on the tributary).

- 1 flow requirement placed on the mainstream river just downstream of the KAC diversion and assigned a minimum flow of 1 m^3/s.
- Diversion at Adassiyeh (King Abdullah canal).
- 20 runoff/infiltration links.
- 16 return flow links.
- 7 rivers (6 tributaries and the mainstream Yarmouk River).
- 33 transmission links.
- 2 aquifer nodes (Basalt aquifer and A7/B2 aquifer system).
- 1 wastewater treatment plant in Jordan representing the 4 identified plants there.
- 1 other supply node representing the flow from Lake Tiberias.

The model was assembled and refined in order to represent both the supply-demand system that is established in the basin and the allocation between the riparian countries. After drawing the river reaches and King Abdullah Canal, demand, wastewater treatment plant, other supply, flow requirement, groundwater and catchment nodes were added. Dams and gauges were then placed at their respective locations. The demand nodes were then connected according to their supply source using a transmission link and to their respective river using a return flow link. Catchments were connected to the river reaches and to groundwater nodes. Area, climate and irrigation data were then entered within each catchment. Annual activity and use rate in addition to consumption and monthly variation rates were added to the demand nodes. Groundwater data including maximum withdrawal and initial storage were entered as well as the data of dams. Finally, observed measurements were added at the different gauge stations.

Local demands in Syria, Jordan and Golan Heights were assumed to be supplied simultaneously, while priorities were assigned based on the actual allocation order and the operation of infrastructure in the basin. No supply was allowed to be withdrawn during winter from dams. Also, the flow requirement at Adassiyeh was ensured before any diversion.

Domestic demands in Syria and Jordan were considered to be supplied solely from groundwater whereas agriculture was supplied simultaneously from dams and groundwater. Supply limits were applied to irrigation transmissions in Syria with a 55% maximum supply from surface water sources and 45% from groundwater sources. The inter-dam hydraulic connection between Syrian dams on Raqqad, Allan and Al Hareer tributaries was also integrated. In Jordan supply to domestic demands from internal sources was set to a maximum of 70% based on the current actual supply.

Some modifications within the model were necessary in order to accommodate the availability of data. Due to the lack of data on Syrian dams, all dams within the same sub-basin were considered as one reservoir unit. Additionally, the minimum flow in the Yarmouk River for each year was entered as the headflow of the river in order to compensate for the complex changes in base flow throughout the years.

A series of assumptions on the operation of dams 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%. The buffer coefficient was initially given a value of 0.2. The volume-elevation relations were set for each dam node using a linear relationship between the maximum height and surface area of the dams in Syria. Monthly evaporation rates were derived from FAO water productivity open access portal database (FAO, n.d.).

3.5. Initial parameters

3.5.1. Land use parameters

a. **Area**

Crop areas were divided within each catchment by three criteria: country, type of crop and irrigation status. The total irrigated areas is around 35,000 hectares in Syria and 6000 hectares in Jordan. 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 and irrigated areas in the Yarmouk basin were identified by comparing the agricultural statistics in Syria (CBS, n.d.) and Jordan (DoS, 2018) with the crop LUC map area and their distribution over the Jordanian and Syrian governorates. The identified irrigated crop areas were consistent with that found in literature. For fruit trees, vine and olive, the irrigated areas were based on identified areas within the agro-climatic zones in the basin (UEA, 2019).

a. **Crop Coefficients**

Values of crop coefficients for various crops and trees were adopted from FAO irrigation and drainage paper no. 56 (Allen et al., 1998). These values were assigned based on the growth stages of a crop or tree. For other land use/cover classifications crop coefficients were adapted based on values from Nistor (2018) and Amato et al., (2006).

b. **Runoff Resistance Factor**

The runoff resistance factor (RRF) 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 were based on LAI estimates for different land covers adopted from Scurlock et al. (2001) and Amato et al. (2006).

3.5.2. Soil parameters

a. **Soil water capacity**

This parameter characterize the capacity of the upper soil layer to withhold water and is represented as depth of water (mm). 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 and permanent wilting point were estimated based on the dominant soil classes in the basin using Soil Water Characteristics software based on the clay, sand, silt and organic matter contents of the topsoil layer. Initial values of the soil water capacity (SWC) were derived based on the soil and the average rooting depth of each LUC class. The rooting depth values were adapted from Dickinson et al. (1993) and Liu & Smedt (2004). Each LUC class was then partitioned based on the soil types and each area was thus assigned a SWC value.

b. **Root zone conductivity**

The root zone conductivity (RZC) 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 through 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 texture of the topsoil layer of each soil class. Similarly, each LUC class was partitioned to several categories based on the intersection between the soil map and LUC map. Each category was then assigned an initial RZC value.

It is important to note that the soil water capacity and root zone conductivities do not exactly represent measurable physical values of the soil but are WEAP-specific items (Droubi et al., 2008). This difference can be justified by the soil-water interaction mechanisms used in the WEAP model and by the adopted monthly time-step.

c. **Preferred flow direction**

This parameter partitions the soil moisture of the top bucket into interflow and infiltration. The factor is a unitless coefficient that ranges between 0 and 1. All preferred flow direction values were initially set to 0, implying that water leaving the upper layer is only infiltrated to the aquifers.

3.6. Optimization

The model was optimized using a historical model having the same setup as the scenario model. Running the model using initial values of soil and land class parameters yielded very low ET values and high runoff. Thus, the parameters of the soil moisture method were in need for optimization to fit the available observations.

Inconsistencies and gaps found in the gauged flows during many years in addition to the complex changes in stream flow restricted the ability to calibrate and validate the model. The impact of the armed conflict in Syria and the lack of accurate data on retention of dams in addition to the changes due to overexploitation of water also played a role in increasing uncertainty. Out of the four available gauges in Jordan, only the Maqarin and Adassiyeh ones measure perennial flow of the Yarmouk river. The rest measure the flow in mostly dry tributaries. Some years in the Adassiyeh gauge measurements were dismissed from the calibration process due to found discrepancies.

The model was calibrated for the period between 2004 and 2011 using the gauged flow at Maqarin, Adassiyeh and Shallala tributary mouth in addition to the estimated retained volumes in dams by manually adjusting the variables using specific step adjustments. The trial and error method was used until a good fit between the observed and simulated streamflow was achieved. Comparisons were then made with the observed and estimated values and assessed using the Nash Sutcliffe efficiency index:

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n} \left(Q_i^{\mathrm{sim}} - Q_i^{\mathrm{obs}}\right)^2}{\sum_{i=1}^{n} \left(Q_i^{\mathrm{obs}} - \bar{Q}^{\mathrm{obs}}\right)^2}$$

where Q_i^{obs} is the observed flow at ith time-step; Q_i^{sim} is the simulated flow at ith time-step and $\bar{Q}^{\mathrm{obs}}$ is the mean observed flow discharge of n total time-steps.

The main parameters controlling soil moisture and runoff generation were mainly scrutinized during calibration (2004–2011) including runoff resistance factor (RRF), soil water capacity (SWC) and root zone conductivity (RZC). To initiate the calibration process, the SWC and RZC parameters were alternated until a general agreement with the observed flow was reached. The calibration proceeded from upstream to downstream starting with the SWC, RZC and RRF parameters of the land and soil covers that were calibrated using the flow at Maqarin. Irrigation thresholds of crops and trees were then modified to capture their estimated irrigation water demand. The PFD in Hareer, Zeidi, Allan and Thahab subbasins in addition to the buffer coefficients of the dams were then calibrated based on the estimates of peak retention in the dams of each. The top of buffer and buffer coefficient of the Wehdeh dam were adjusted based on its observed retention. Additionally, the PFD of Shallala subbasin was adjusted based on the gauged flow in its tributary. Finally, the PFD of the Main Outlet subbasin was calibrated against the gauged flow at Adassiyeh. The initial and final parameter range and their step adjustments are shown in Table 2.

3.7. Scenarios

The pre-war period was characterized by a normal growth in population and constant irrigated areas. The war-period was characterized by negative population growth in Syria and an increased one in Jordan. Agriculture was set to decrease by 30% and the capacity of dams were modified based on the estimated volumes during the war.

a. Reference Scenario

The reference scenario will assume a business as usual (BAU) trend in the post-war period. This scenario will thus inherit the general trends from the pre-war period. Additionally, no change in land use/cover was 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. Furthermore, the scenario will also assume that the current allocation regime remains the same as well as the domestic, agricultural and industrial water demand rates.

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 (115 and 128.1 MCM respectively, excluding Wehdeh dam). Backed by reports of the rehabilitation of dams, irrigation networks and pump stations in the basin (GCWR, 2020a, 2020b), it was assumed that all Syrian dams returned to their normal capacity and that Syria's exploitation of surface water resumed as pre-war levels.

b. Climate Change Scenarios RCP 4.5 and RCP 8.5

Representative Concentration Pathways (RCP) 4.5 and 8.5 are scenarios that assume an increase in greenhouse emissions that is equivalent to a radiative forcing of 4.5 and 8.5 W/m^2 in 2100 respectively (Thomson et al., 2011). The former 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, while the latter, which is the worst case scenario, shows a 1.5°C increase in mean temperature and 7% decrease in rainfall by 2050 and a 3.2°C temperature increase and 13% rainfall decrease by 2100 (ESCWA et al., 2017). Our climate change scenarios were developed by projecting monthly changes in temperature and rainfall levels based on the ensemble of three CMIP5 global climate models (EC-EARTH, CNRM-CM5, GFDL-ESM2M) downscaled by Rossby Centre regional atmospheric model (RCA4) with a 50 km grid resolution. Both RCP scenarios are based on the Intergovernmental Panel on Climate Change IPCC fifth assessment report database.

c. Irrigation Systems Enhancement Scenario

Based on available data on irrigation systems in Syria, the scenario will assume an increased use of more efficient field application systems such that drip, sprinkler and surface watering methods usage will reach 70%, 20% and 10% respectively. In addition, an improved utilization and conveyance of surface and ground water is also assumed. Field application efficiencies of 90%, 75% and 60% were used for drip, sprinkler and surface irrigation methods respectively (Brouwer et al., 1989).

d. Agricultural Intensification Scenario

This scenario will assume an increase in both rainfed and irrigated agriculture at a rate of 0.5% per year in Syria and Jordan.

e. UN Medium Variant Population Projection

Table 2. Ranges of main initial and calibrated parameters in WEAP.

Parameter	Unit	Model Range	Initial Range	Step Adjustment	Calibration Range
Soil Water Capacity	mm	0–higher	680–1500	50	50–1000
Root Zone Conductivity	mm/month	0–higher	480–19,400	20	15–650
Runoff Resistance Factor	–	0–1000	0.1–8.2	0.1	1.1–9.52
Preferred Flow Direction	–	0–1	0	0.05	0–0.65

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). 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 in each one.

4. Results and discussion

4.1. Model performance

Simulated retained volume in Wehdeh dam (Figure 9) showed decent results relative to the observed retention during the period from 2007–2015 with a nash-sutcliffe index of 0.65. This value can be considered satisfactory according to Moriasi et al. (2007).

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. The model produced acceptable results in most years (Figures 10 and 11) with a NSE value of 0.51 during the calibration period (2004–2011) regarding the flow at Maqarin. The first two years of the Syrian conflict (2012–2013) were used for validation purposes at the Maqarin gauge station and showed satisfactory results with a NSE = 0.54. The period after 2013 was dismissed for validation when several dams went out of service and the impacts of the conflict became manifest. The model also produced decent results on a monthly basis (Figures 12 and 13). Peak flows were not very well captured in the years 2003 and 2004. The year 2003 was an exceptionally wet year in the basin when flooding occurred.

4.2. Water balance

The monthly water balance of the Yarmouk basin showed a peak in surface flow during the three months of January, February and March. Bare areas produced the highest runoff while crop areas produced the highest evapotranspiration. Evapotranspiration was higher in the months of March, April and May. Al Hareer sub-basin was found to be where most of the infiltration occurs especially in the bare areas in the north-eastern region near Leja Plateau.

a. Reference Scenario:

Several changes occurred in the water balance at the end of the BAU scenario. Precipitation levels remained constant but irrigation supply decreased by 30%. Furthermore, groundwater inflow slightly decreased similar to the runoff and interflow as a result of less irrigation return flows. Moreover, evapotranspiration decreased to 77% of total precipitation. No considerable change occurred on a monthly timescale during this scenario. Table 3 shows the annual soil moisture water balance at the start of the simulation and at the end of the reference and climate change scenarios.

b. RCP 4.5 and RCP 8.5 Scenarios:

The RCP climate change scenarios showed a decrease in water supply and an increase in potential evapotranspiration. Changes in the water balance were noticed under RCP 4.5 scenario when compared with the reference scenario. Actual ET increased to 79.6% of total precipitation while the flow to groundwater decreased by 12.55%. Under RCP 8.5 scenario the precipitation decreased much more than under the RCP 4.5 scenario but the evapotranspiration increased to 82.4% of total precipitation while groundwater recharge decreased by 24.6%.

The total runoff in the basin decreased 11.8% by 2050 and 24.4% by 2100 under the RCP 4.5 scenario. Interflow declined by 9.63% and 20.12% by mid and end of 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 17% and 30.4% by 2050 and 2100 respectively.

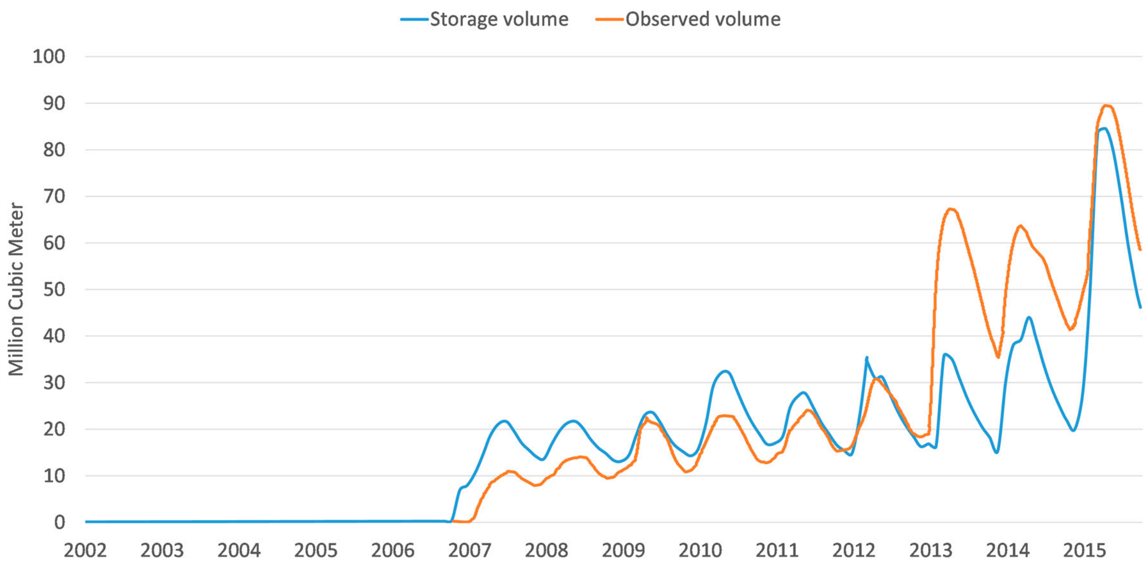

Figure 9. Observed vs. simulated retention of Wehdeh dam.

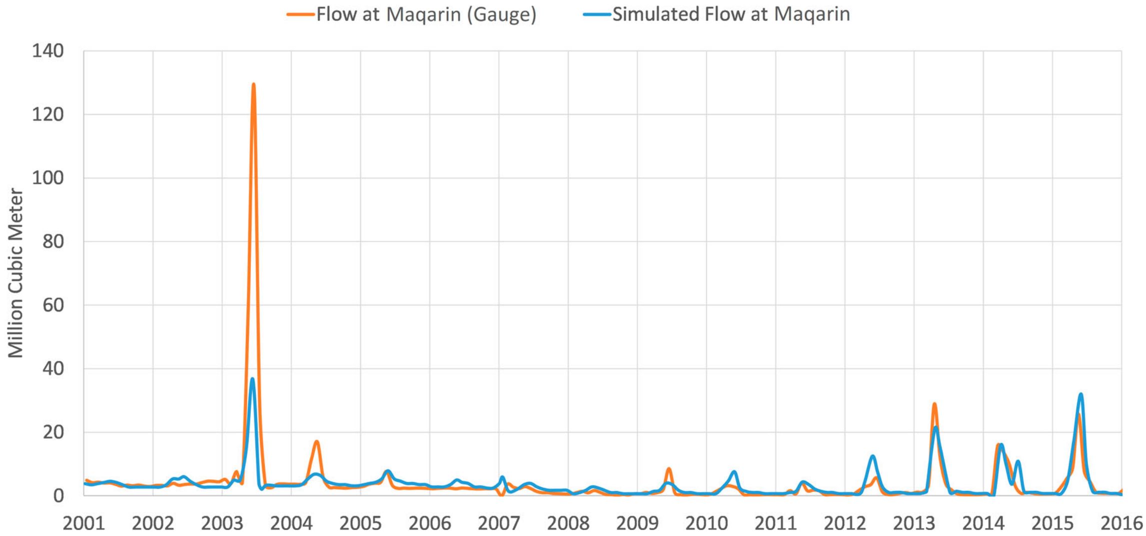

Figure 10. Observed vs. simulated flow at Maqarin.

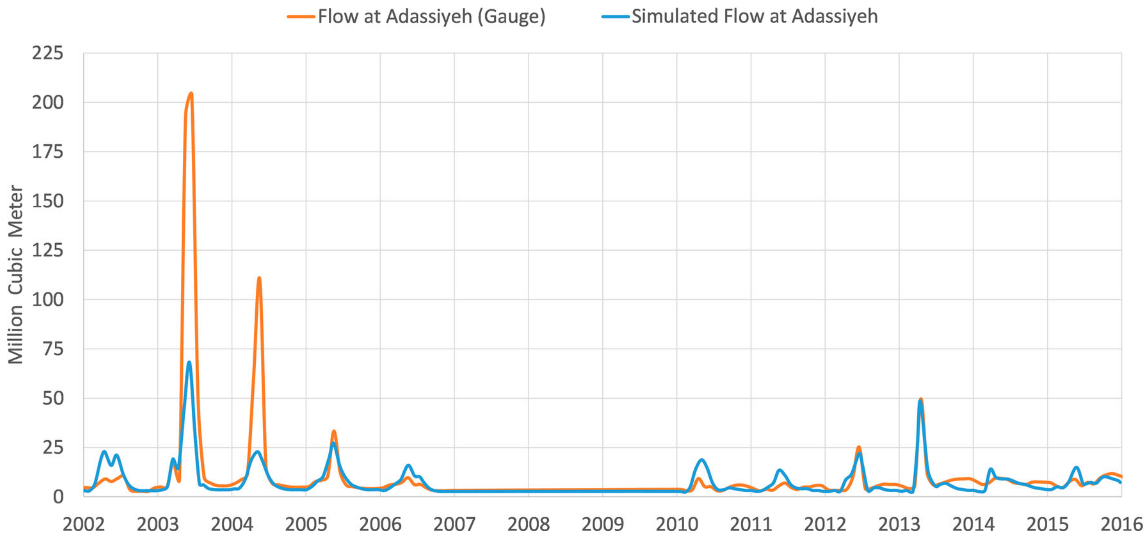

Figure 11. Observed vs. simulated flow at Adassiyeh.

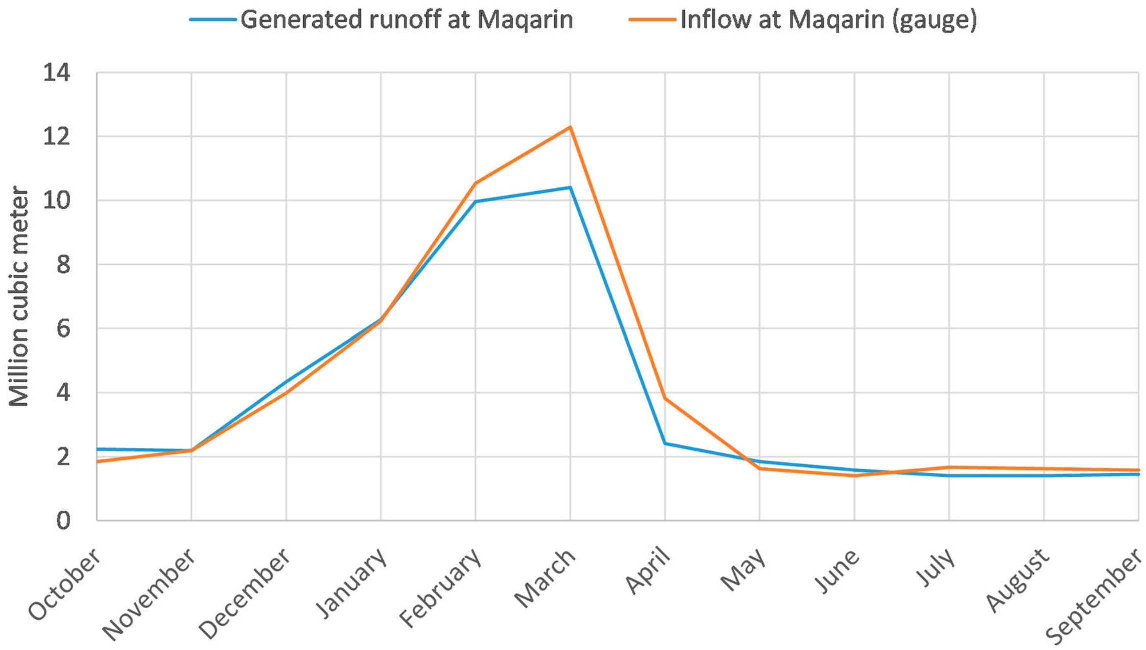

Figure 12. Monthly average flow at Maqarin (2003 excluded).

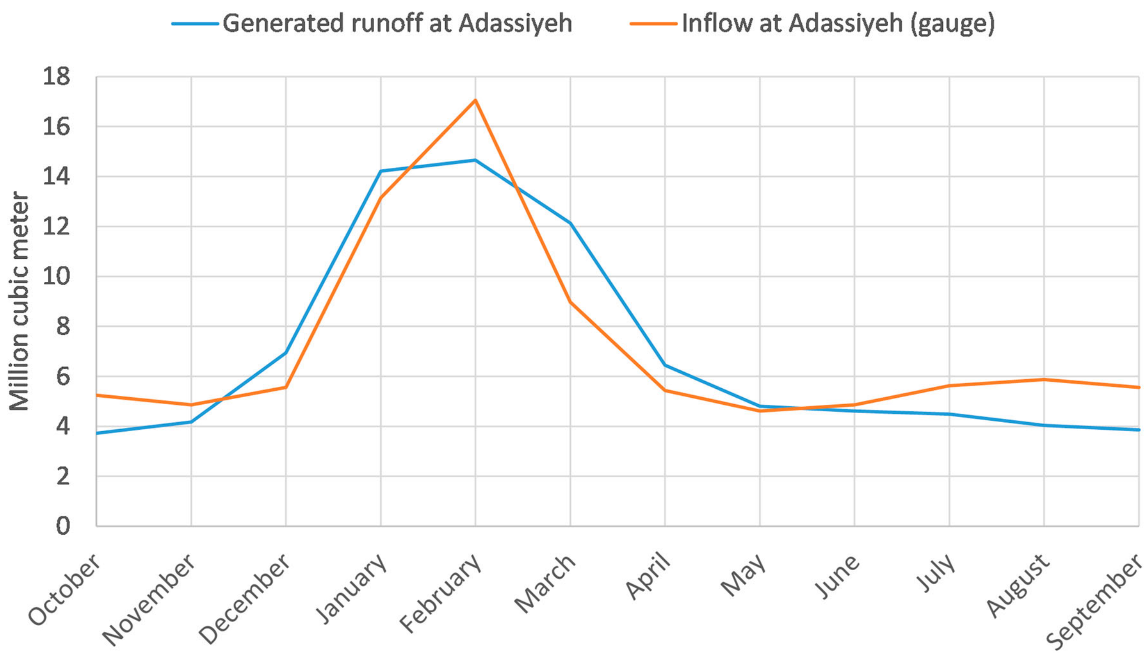

Figure 13. Monthly average flow at Adassiyeh (2003 excluded).

Table 3. Initial and final soil moisture water balance under climate change and BAU scenarios.

Inflows and Outflows (MCM)	Initial Water Balance	End of BAU Scenario	End of RCP 4.5 Scenario	End of RCP 8.5 Scenario
Precipitation	2418.3	2418.3	2249	2103.9
Irrigation	293.6	204.8	193.3	184.9
Evapotranspiration	−1900.7	−1864	−1790.1	−1734.2
Flow to Groundwater	−631.8	−593.4	−518.9	−447.5
Interflow	−57.9	−52.3	−46.3	−40.3
Surface Runoff	−114.5	−112.5	−86.5	−66.7

Table 4. Total surface water flow per sub-basin.

Catchment	Total surface flow (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 5. Maximum withdrawal from groundwater.

Aquifer system	Maximum annual withdrawal (MCM)
Basalt	250
A7/B2	50

The dry season is when runoff and interflow are mostly reduced. This finding indicates that surface flow will reach critical levels during the months from June to October thus causing many perennial streams to dry.

4.3. Supply

Surface flow varied from one sub-basin to another with Raqqad and main outlet producing the highest and Shallala sub-basin the lowest (Table 4). The total volume of return flows from all sectors in the basin was initially 71.5 MCM. Irrigation annual supply was 293.6 MCM per year. The maximum retention of dams inside the basin excluding Wehdeh was 112 MCM at the start of the simulations. Wehdeh dam maximum retention was 57 MCM in March.

Also, it is important to note that groundwater was the main source of internal consumption in the basin measuring up to two thirds of water use. All agricultural nodes were supplied simultaneously from groundwater with a general limit on each aquifer system and no specific limit on each sub-basin due to the huge uncertainty in the number of wells in the basin, their distribution and the volume of withdrawal. The maximum annual withdrawal of groundwater from the basalt and A7/B2 aquifer systems is shown in Table 5.

a. Reference Scenario:

The high growth in population caused more competition over water resources and given that the domestic and agricultural sectors are supplied simultaneously from groundwater, the share of the domestic sector increased while irrigation's share which consumed more than half of groundwater supply gradually decreased. The supply from groundwater reached its maximum limit within 10 years from the start of the scenario. Moreover, the retained volume in dams increased 2% by mid-century due to the higher return water flow resulting from the increase in domestic supply.

b. RCP 4.5 and RCP 8.5 Scenarios:

The decrease in runoff and interflow led to a lower retention in all dams (Figure 14). Wehdeh dam retention decreased gradually thus affecting the shares of Jordan and Israel. Compared to the maximum annual retention in the reference scenario, Wehdeh dam maximum retention decreased 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 less significant where the decrease reached 12.3% by the end of the century.

The shares of both Jordan (Figure 15) and Israel decreased. RCP 8.5 scenario showed that Jordan's share will decrease 16.18% by 2050 and 27.9% by 2100. Israel's

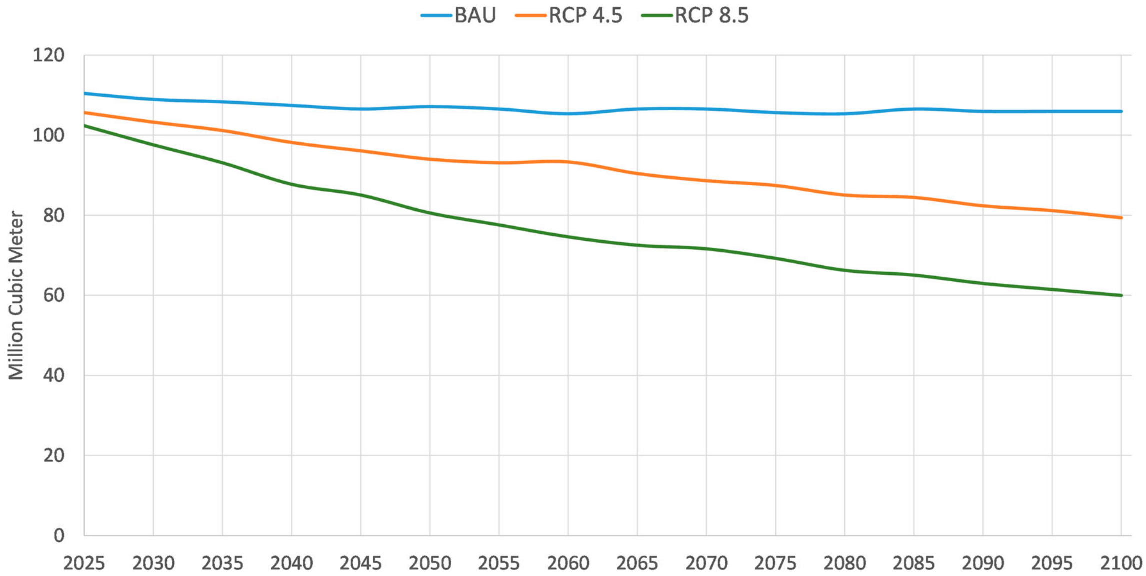

Figure 14. Change in peak retention in all dams excluding Wehdeh.

share also decreased but to a lesser degree. The flow bypassing Adassiyeh weir decreased 13.4% by 2050 and 23.6% by 2100. RCP 4.5 showed a 9.6% and 20.1% decrease by 2050 and 2100 respectively in Jordan's diversion. For Israel's share from the river, the volume decreased by 7% in 2050 and 16.7% in 2100.

At the end of the century, Thahab sub-basin was the most affected by climate change where surface flow decreased by 27.9% and 47.3% under RCP 4.5 and RCP 8.5 scenarios followed by Al Hareer sub-basin with a decrease of 25.4% in the former scenario and 45% in the latter.

Regarding groundwater supply, the maximum withdrawal from the aquifers did not change with the decline of groundwater recharge as they are independent in WEAP.

4.4. Demand and shortage

The highest total annual water demand was found in Syria with 426.3 MCM (Table 6). In Jordan the internal demand was 64.6 MCM with a further 74.4 MCM diverted away based on the current account year. In Israel the demand was 21 MCM internally and 63 MCM as the share from the mainstream river flow also based on the current account year.

The agricultural demand was the main consumer of water inside the basin measuring up to 70% of the internal demand in Syria and Jordan. The demand was higher in the Hareer and Zeidi Sub-basins which are the largest in area (Table 7).

At the start of simulation, water deficit was suffered in all demand sectors, however much could have been covered by the over-exploitation of groundwater resources in the basin. The total unmet demand at initial conditions was equal to 115.7 MCM/year. The shortage was negligible in the winter months but increased in the summer season and peaked in July when it reached 26.4 MCM (Figure 16).

a. Reference Scenario:

In the baseline scenario the domestic demand increased from 111.2 MCM to 126.9 MCM in 2010 then decreased throughout the war then increased to 298.1 MCM by 2050

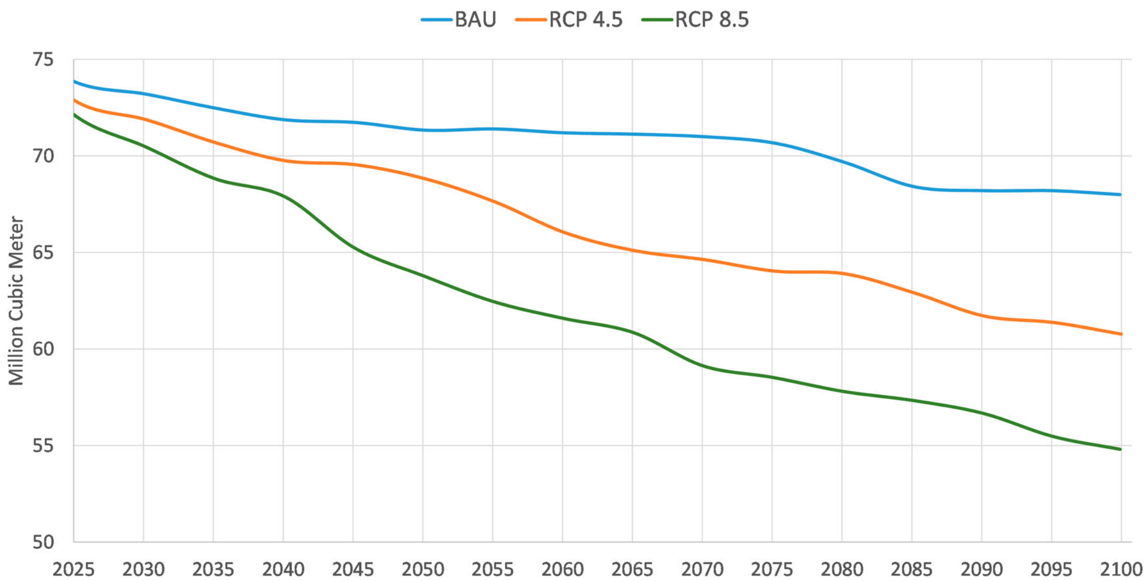

Figure 15. Change of annual volume entering King Abdullah Canal under climate change scenarios.

Table 6. Annual demand per country.

Country	Demand	Yearly volume (MCM)
Syria	Domestic	88.6
	Agricultural	303.7
	Industrial	34
Jordan	Domestic	22.5
	Agricultural	42.1
	KAC diversion	74.4
Israel	From dams	5
	From groundwater/springs	16
	Pumping from Yarmoukim	63

Table 7. Domestic and agricultural demand per sub-basin.

Catchment	Domestic + agricultural demand (MCM)
Al Hareer	189.3
Thahab	61.1
Allan	26.2
Main Outlet	23.4
Raqqad	14.1
Shallala	12.6
Zeidi	132.5

under the assumption that the demand per capita would remain constant by then. Water shortage increased from 115.7 MCM at the start of simulations to 291.6 MCM in 2050 and 1213.8 MCM in 2100 (Figure 17). The shortage was suffered in all demand sectors. Moreover, the total return flow in the basin reached 95 MCM by the end of the scenario.

By the end of the BAU scenario, the shortage was the lowest in Raqqad and Allan and the highest in Zeidi and al Hareer sub-basins representing 32.3% and 30.2% of the total shortage of the basin. In addition, Shallala was the most water stressed sub-basin followed by Zeidi and Main Outlet sub-basins. The three sub-basins extend to areas in Jordan indicating that Jordan would be the most water stressed country.

b. RCP 4.5 and RCP 8.5 Scenarios:

Deficit in the water budget increased under the climate change scenarios (Figure 18). Total unmet demand reached 324 MCM in 2050 under the RCP 4.5 scenario while under the RCP 8.5 scenario the deficit reached 355 MCM implying an increase in water shortage by 11.1% and 21.7% under each RCP scenario relative to the reference scenario.

By mid-century, the total shortage reached 234 MCM in Syria and 88.1 MCM in Jordan under the RCP 4.5 scenario. Under the RCP 8.5 scenario the shortage reached 265.6 and 89 MCM in Syria and Jordan respectively. Climate change led to an increase in water shortage throughout all months of the year but the shortage was higher in Syria during the months of May and June when the irrigation demand peaks.

c. Enhancement of Irrigation Systems Scenario:

The enhancement of irrigation systems led to a decrease in irrigation water demands by around 60 MCM. When combined with the RCP 4.5 scenario, the reduction only reached 19.9 MCM by the end of the scenario. The change in irrigation systems and the improved efficiency led to better coverage of agricultural demands that increased during the shortage months by 15% then gradually decreased under increased pressure from other demand sectors.

The sub-basins that benefitted the most from the increase in irrigation efficiency were al Hareer, Allan and Raqqad where the shortage decreased by 30.3%, 27.13% and 26.7%, respectively by 2050. The scenario impacted the Syrian part of the basin mainly during the irrigation season from April to September whereas in the Jordanian part most months were impacted because shortage appears in the winter season. This can be attributed to the crop and irrigation patterns and the lower rainfall levels there.

Combining the scenario with the RCP 4.5 scenario still showed improvement on the reference scenario regarding water deficit until 2070 when all the improvements started to diminish due to climate change impacts (Figure 19).

d. Agricultural Intensification Scenario:

Under this scenario, agricultural demand increased 18.5% by 2050 and 54.6% by 2100. Moreover, agricultural supply in the basin increased 4.2% by 2050 and 12.4% by 2100.

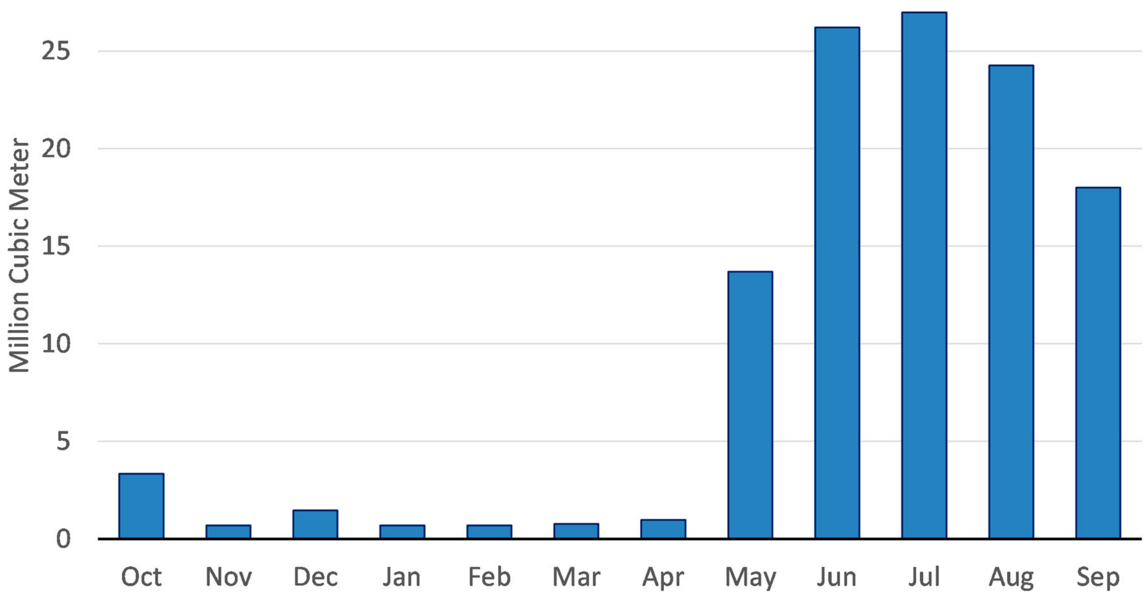

Figure 16. Total monthly water shortage at start of simulations.

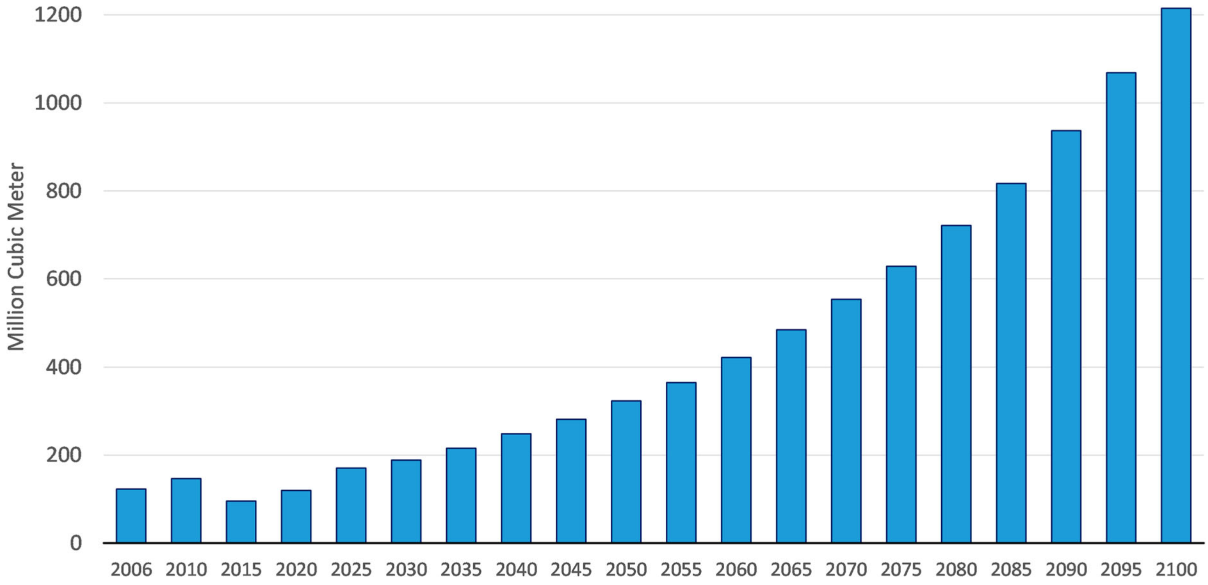

Figure 17. Total annual water shortage in Syria and Jordan.

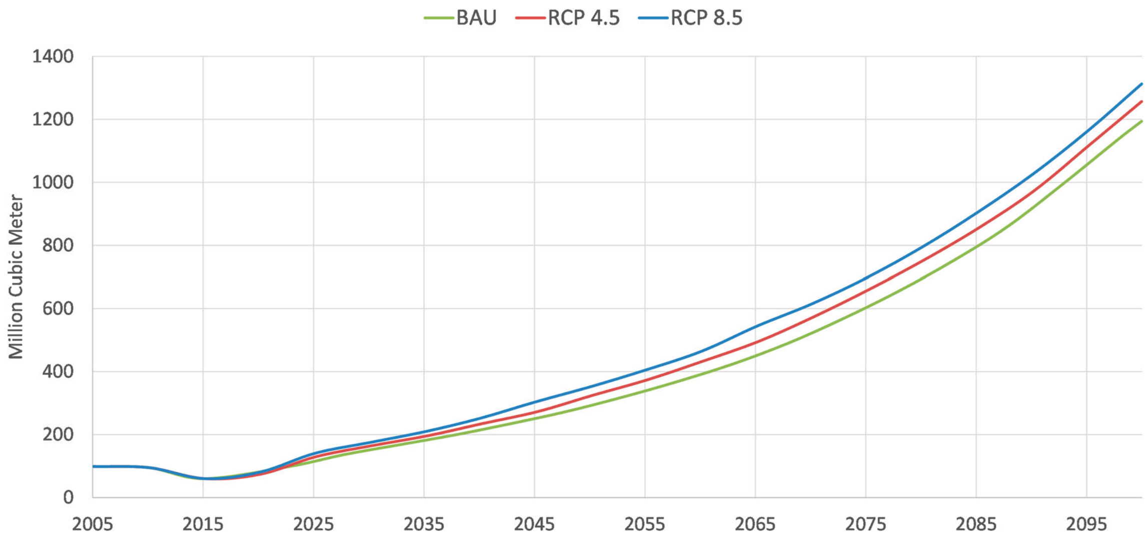

Figure 18. Water shortage under climate change scenarios.

Coverage of all demand sectors declined and the unmet irrigation demand reached 195 MCM by 2050. Runoff also decreased in the basin and flows into Maqarin dropped 9.3% by 2100; a change that can be related to the expansion of planted areas. Moreover, Raqqad and Main Outlet agricultural sub-catchments registered the lowest decrease in supply reliability indicating their ability to sustain some agricultural growth.

When the agricultural intensification scenario was combined with RCP 4.5 scenario, water shortage was at its highest compared to all scenarios (Figure 20). While when the enhanced irrigation efficiency scenario was coupled, the unmet demand was lower than that in the reference scenario till year 2045.

e. UN Medium Variant Population Projection Scenario:

Under the medium variant projection, the total number of inhabitants in Syria peaked and stabilized after 2060. The total Syrian population reached 1.74 and 2.09 million by 2050 and 2100. In Jordan the population stabilized quickly and reached 1.08 and 1.14 million inhabitants by 2050 and 2100 respectively. This growth led to a more stable domestic demand in the future (Figure 21).

Assuming that the per capita demand will remain constant, the Jordanian domestic demand coverage, at the end of the century, reached 60% on average under the UN projection compared to 13.3% under the BAU scenario (Figure 22).

In Syria the unmet domestic demand reached 44.3 MCM by 2050 and 53.8 MCM by 2100 under the medium variant scenario (Figure 23). The total shortage thus reached 38.8 MCM in Jordan and 177 MCM in Syria. The stabilization of population helped in stabilizing the irrigation supply at 247.6 MCM by the end of the century.

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.

Combining the medium variant projection with the enhanced irrigation systems scenario showed an increase in irrigation supply in addition to better coverage compared to all scenarios in domestic, industrial and agricultural sectors (Figure 24). In Syria, total unmet domestic demand

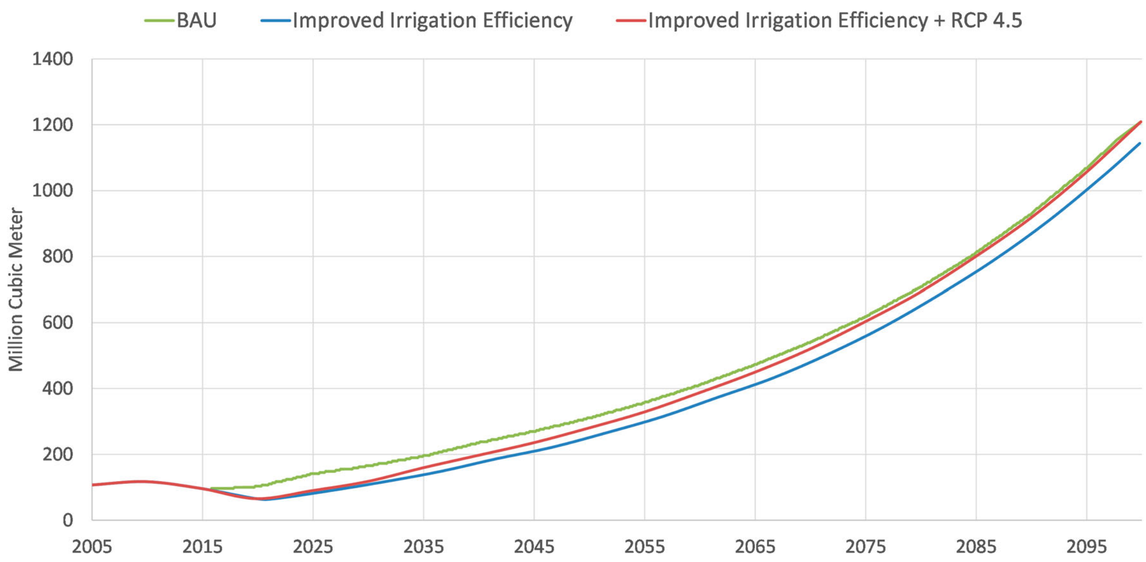

Figure 19. Unmet demand under improved irrigation efficiency scenarios.

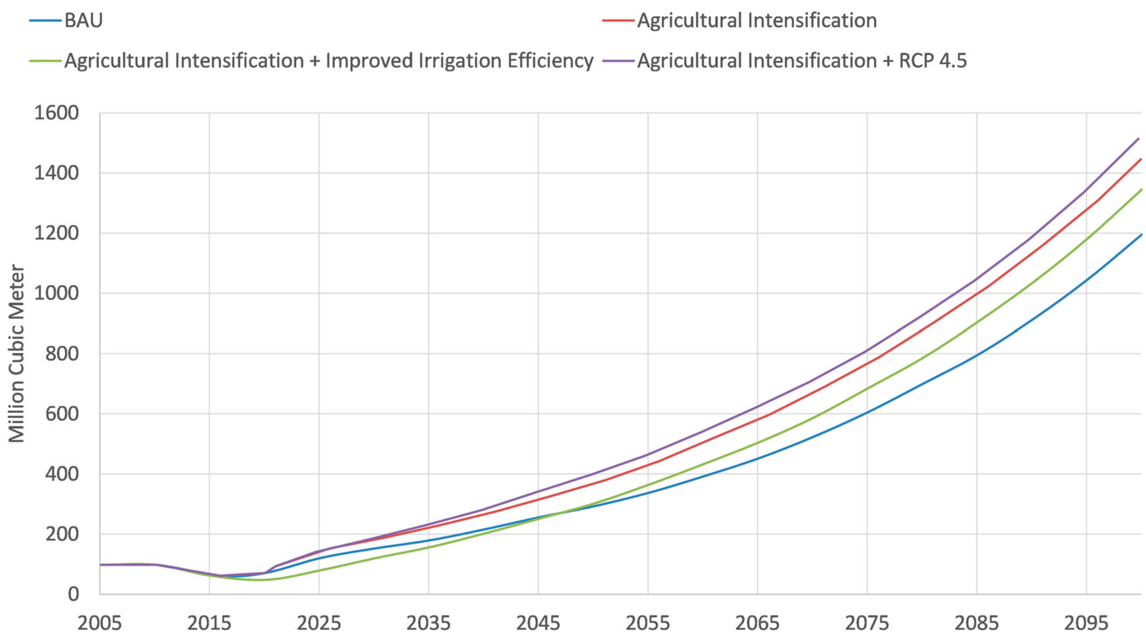

Figure 20. Comparison of unmet demand under a combination of scenarios.

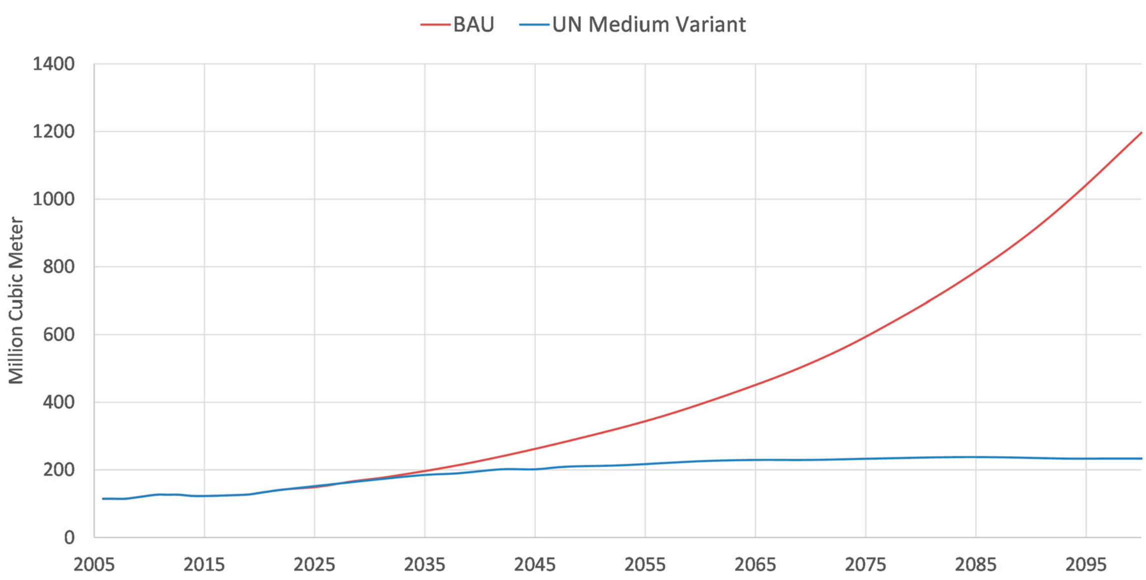

Figure 21. Change in domestic demand under BAU and UN medium variant population projections.

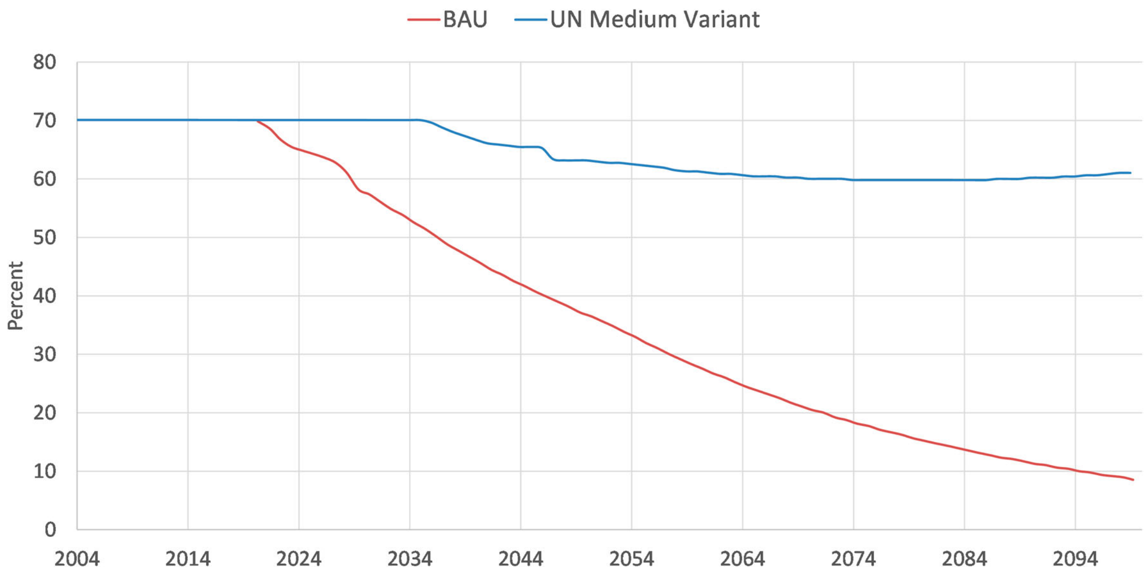

Figure 22. Domestic demand coverage in Jordan.

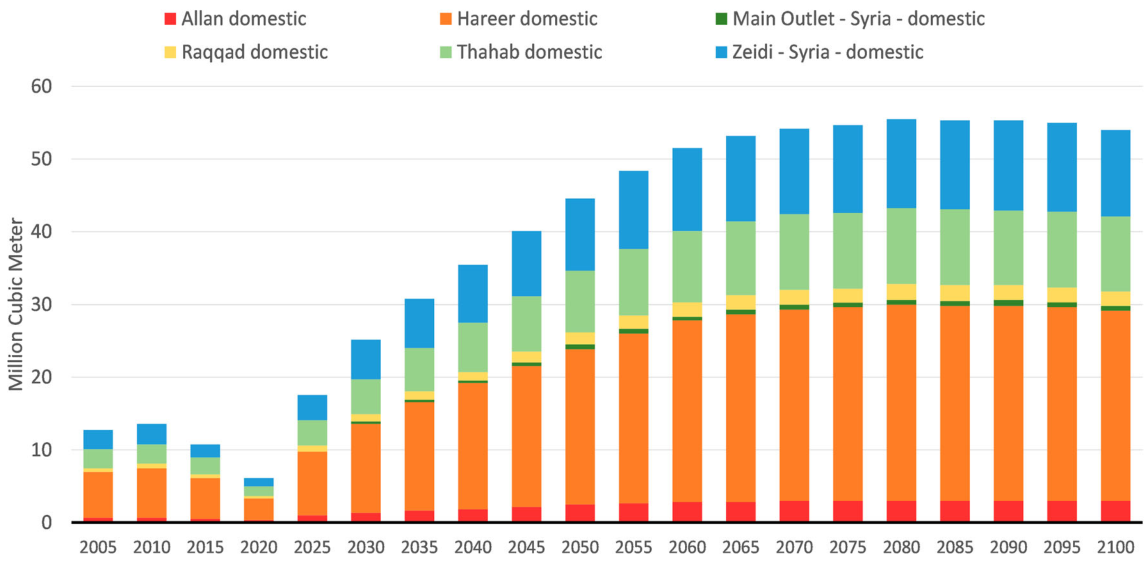

Figure 23. Unmet domestic demand in Syria under UN medium variant population projection.

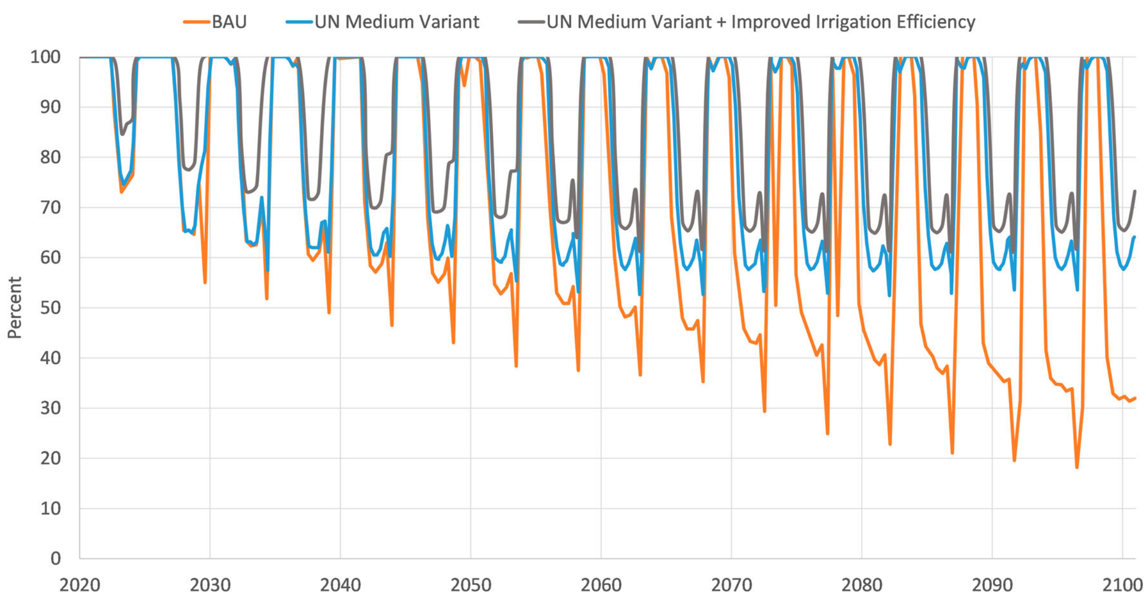

Figure 24. Demand coverage in Thahab agricultural catchment.

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 under the BAU scenario and 103.9 MCM under the UN medium variant population projection alone. The agricultural shortage was divided into 70 MCM in Syria and 12.4 MCM in Jordan.

5. Conclusion

The purpose of this work is to assess the impact of current water strategies in the transboundary Yarmouk River basin on water availability for all riparian states using various scenarios. It aims at evaluating the future (till the year 2100) of water resources availability in a region that is already water stressed taking into account climate change and land cover change, population growth and shifting in agricultural and water management strategies. The analysis was done using the Water Evaluation and Planning (WEAP) system of the SEI.

All demand and supplies in the basin were taken into consideration in this model. The year 2005 was chosen at the current account year and the modelling was made at a monthly time step using a one bucket soil moisture method. Despite the lack of data that was a major challenge in the modelling process, the simulated river flow and reservoir storage gave fair results in comparison with the observed values with a NSE of 0.51 and 0.65 respectively. The simulation suggests that current conditions in the basin are far from being sustainable. Water management is an urgent necessity to sustain growth in the Yarmouk basin. Indeed, a business as usual scenario will increase the gap between supply and demand. Water withdrawal per capita in Syria will decrease from 400 m^3 at the start of the simulation to 155 m^3 by 2050 while in Jordan this value was initially at critical levels below 100 m^3/capita. Climate change will further hinder surface water resources thus rendering many dams useless. Water shortage at mid-century increased by 11.1% and 21.7% under RCP 4.5 and RCP 8.5 scenarios respectively. All riparian states were affected by climate change but Jordan was the one affected most under the current operation of Adassiyeh weir. Moreover, irrigation growth inside the basin led to huge unmet demand in all sectors. Improving irrigation systems accompanied with agricultural growth still showed improvement in water coverage compared to the reference scenario for the following two and a half decades. Nevertheless, continued water shortage is a certain expectation in the future under all scenarios. The best case scenario was attained when irrigation systems were enhanced under the UN medium variant population projection. Total unmet demand reached by the end of the century 31.9 and 129.1 MCM in Jordan and Syria respectively.

Finally, embracing new measures to reduce demands and a decreased population growth will help reduce the impact of future developments. Only by decreasing the water demand in the basin, sustainability can be achieved. Moreover, Syria's adaptation after the end of the armed conflict will play a role in shaping the future of water in the basin. Additionally, the dependency of Jordan on the flows of Yarmouk River while diverting it to areas further away from the basin means that it will suffer much more than Syria and Israel. The supply to the areas in the Jordanian part of the basin can be much higher but will require solutions to be implemented in the areas located outside of the basin that are fed from KAC. Using the water of Wehdeh dam locally instead of diverting it at Adassiyeh would improve the allocation of Jordan.

In the end, one must say that the current non-cooperation between the riparian states in the basin could push for more confinement and more unregulated exploitation of water sources. The geo-politics of the region may further impede any true cooperation and sharing of water resources in the basin.

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