QUANTITATIVE ASSESSMENT OF CONTESTED WATER USES AND MANAGEMENT IN THE CONFLICT-TORN YARMOUK BASIN

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ABSTRACT

The Yarmouk River basin is shared between Syria, Jordan, and Israel. Since the 1960s, Yarmouk River flows have declined more than 85% despite the signature of bilateral agreements. Syria and Jordan blame each other for the decline and have both developed their own explanatory narratives: Jordan considers that Syria violated their 1987 agreement by building more dams than what was agreed on, while Syria blames climate change. In fact, as the two countries do not share information, neither on hydrological flows nor on water management, it is increasingly difficult to distinguish between natural and anthropogenic factors affecting the flow regime. Remote sensing and multi-agent simulation are combined to carry out an independent, quantitative, analysis of Jordanian and Syrian competing narratives and show that a third cause for which there is no provision in the bilateral agreements actually explains much of the changes in the flow regime: groundwater over-abstraction by Syrian highland farmers.

INTRODUCTION

The Yarmouk River basin (YRB) is shared by three countries: Syria, Jordan, and Israel (Fig. 1). Since the 1960s, development in the basin has increased and the historical annual flow of 450-500 hm^3/year (million cubic meter per year; Burdon 1954; Salameh and Bannayan 1993; Hof 1998; UN-ESCWA and BGR 2013) has dropped by more than 85% to reach 60 hm^3/year in 2010 indicating river basin closure. In 2013, river discharges rose to 120 hm^3/year during the Syrian civil war (Fig. 2).

The collapse of the Yarmouk flow occurred despite the signature of two bilateral agreements. The first one was signed in 1953 between Syria and Jordan (1953) and updated in 1987 (Syria and Jordan 1987) essentially to recognize water uses and dams already built in Syria (Rosenberg 2006; Hussein 2017). The 1987 version gives the right to Syria to retain water in 28 dams on the Yarmouk basin for a cumulative capacity of 164.64 hm^3, and allows Jordan to use water in the Wahda reservoir (a major reservoir that had yet to be built on the Yarmouk River; see Fig. 1) to irrigate crops in the Jordan Valley along the King Abdullah Canal (KAC) and to supply Amman with freshwater. No explicit limitation regarding groundwater withdrawals is mentioned in the document. The second agreement is the Treaty of Peace signed between Israel and Jordan (1994), which gives the two countries specific water rights on the Yarmouk waters: (*i*) Israel is entitled to a 25 hm^3 annual *allocation* while Jordan gets the rest of the flow; and (*ii*) Jordan has the possibility to store up to 20 hm^3 each year in Lake Tiberias during the Winter Period, and get it back at the entrance of the KAC in the Summer Period (*concession*). Technically, the sharing of water is operated at Adasiya (outlet of the YRB; see Fig. 1).

After considering surface water flow depletion caused by the Syrian reservoirs listed in the 1987 agreement, reduced groundwater triggered by irrigation from springs and projected wells in Syria, and irrigation return flows, the Jordanian Ministry of Water and Irrigation/Jordan Valley Authority (MWI/JVA 2002) expected inflows to the Wahda dam to attain 117.6 hm^3/year. Yet, the flow monitored by MWI/JVA has never reached such a level before the Syrian civil war, and Jordan has been the first affected by the river decline due to (*i*) its downstream position as most springs and wadis (intermittent rivers) feeding the Yarmouk are located in Syria and the Israel-controlled Golan Heights, and (*ii*) the fact that it bears the brunt of the hydrological risk as per the Israel–Jordan Treaty (no matter the flow reaching Wahda, Jordan has to send the 25 hm^3/year *allocation* to Israel).

The in situ measurements of the Yarmouk River flow by MWI/JVA at the Wahda dam, or Maqarin station before the dam's construction, and Adasiya are actually the only publicly available ground data in the basin. Even before the civil war, the Syrian regime never published water resources data or shared it with neighboring basin states. It is unknown what data the Syrian government collected or its quality. The data available are aggregated country- or basin-wide estimates from international donor organizations like the FAO or World Bank (Salman and Mualla 2008). For years following the 1960s, three stages can be observed in the WAJ/JVA data (Fig. 2): (*i*) a stationary regime before 1999; (*ii*) a sharp decrease of both the base flow and the runoff during the period 1999-2012; and (*iii*) the return of the runoff from 2013, when many Syrian refugees fled the civil war (Müller et al. 2016).

Jordan and Syria have both developed their own, competing, narratives to explain the decrease in Yarmouk flows: downstream Jordan considers that Syria violated their 1987 bilateral agreement by building more dams than what was agreed on, while upstream Syria blames climate change and particularly precipitation decrease (Hussein 2017). Each perspective is fostered by a few studies. Regarding the Syrian narrative, Salameh and Bannayan (1993) estimate that rainfall dropped by 30% in the second half of the 20th century. Moreover, after comparing two periods, 1927-1954 versus 1968-1987, Beaumont (1997) comes to the conclusion that natural runoffs were, on average, 25% lower in the second period. The fact that three of the four most severe multi-year droughts in the region since 1901 occurred after 1990 is also attributed to climate change according to Kelley et al. (2015). Other analyses overlook such natural aspects and rather adopt the Jordanian narrative that Yarmouk flows declined because of excessive water abstractions and uncoordinated construction of dams in the Syrian part of the YRB (FAO 2009; Yorke 2016).

Actually, Syria's role in the closure of the Yarmouk River basin is controversial, but not the significant extension of irrigated agriculture in that part of the basin (Shentsis et al. 2019).

Before the 1960s, the Yarmouk and upstream wadis waters were primarily exploited for subsistence agriculture (Courcier et al. 2005), but it changed with the first agrarian reform in 1958 and the following agricultural policies (Ababsa 2013; Ibrahim et al. 2014), which were implemented at the expense of water resources sustainability (Barnes 2009). In 1997, irrigation accounted for more than 80% of water use in the Syrian part of the YRB (World Bank 2001). Aw-Hassan et al. (2014) distinguish three phases in the development of irrigation in Syria. In the first one, between 1966 and 1984, irrigation systems expanded. The country started building numerous dams and canals on the Yarmouk tributaries in the upper part of the YRB to increase surface water availability. However, these investments were not sufficient to enable the agricultural production to meet the ever-growing population needs. In the middle of the 1980s, Syria still had to import a large share of basic food supplies (Ababsa 2013). In the second phase (1985-2000), irrigated crops area kept expanding with the Government's objective to increase food security and ensure self-sufficiency (Salman and Mualla 2008). Groundwater-irrigated area particularly grew – nationwide, its share rose from 49% in 1985 to 58% in 2000 (Kaisi and Yasser 2004) – as farmers could get low interest loans, well licenses were more easily delivered and fuel was strongly subsidized (Gül et al. 2005). But some of these incentives also fostered the growth of illegal groundwater pumping: 50% of wells were unlicensed at the end of the century (World Bank 2001; Salman and Mualla 2008). The third and last phase defined by Aw-Hassan et al. (2014), from 2001 to 2010, can then be described as a challenging management period for Syria. The Government tried to address groundwater depletion while liberalizing the economy to stimulate investments in the agricultural sector (Ababsa 2010; Kelley et al. 2015) and ensure food security. As a result, the decrease in the water table level could only be slowed down. To these development stages followed the civil war in March 2011. This conflict and the 2013 Syrian refugees migration led to destruction of reservoirs and reduction in reservoir storage in the Syrian part of the YRB (Müller et al. 2016). The impact on irrigation land area and operational wells remains uncertain (Etana Syria 2015).

Work to clarify the causes of the flow decrease has become nearly impossible since the start of the civil war in Syria. To the best of our knowledge, the study conducted by Al-Bakri et al. (2016)

on the Jordanian part of the YRB is the only analysis that provides local information on land use and water withdrawals. However, detailed information on reservoir operation, canal diversions, irrigation requirements, and groundwater withdrawals – all within Syria – is lacking and crucial to identify with precision the causes to flow regime changes, and to distinguish consistent study results from politically biased narratives.

Associating remote sensing with river basin modeling has been largely used to deal with remote, ungauged or conflict-torn areas. For example, Pereira-Cardenal et al. (2011) process remote sensing data in real-time and use them as input to a simulation-based hydro-economic model of the Syr Darya River basin. Rougé et al. (2018) present a modeling framework that relies on both land data assimilation and river basin modeling to identify key water resources vulnerabilities in transboundary river basins where data on both hydrological fluxes and on the management of reservoirs are either absent or incomplete. In that work, however, the authors ignore the institutional complexity by assuming that water allocation decisions are taken by a single organization (or agent) overlooking the entire river basin. In developed river basins, the impacts of hydrological and anthropogenic changes are often intertwined. Assessing their relative contribution is often a prerequisite towards the development of effective policies. For instance, Lei et al. (2019) use a coupled agent-hydrologic model to compare various water management policies based on environmental and economic criteria in the Heihe River basin in China. Biglarbeigi et al. (2018) analyze climate change uncertainty in the Dez and Karoun River basins in Iran to identify the dominant natural factors to focus on in the future when designing new infrastructure and monitoring systems.

We combine remote sensing and multi-agent simulation (MAS) to validate and apply the modeling approach in a river basin (the Yarmouk) where one country (Syria) is experiencing a civil war and limited ground data is available for use. We further use the validated model to test competing hypotheses and country narratives about the causes of a 60-year decline in stream flows, as well as possible future trajectories for flows after the civil war winds down and the roles riparian countries can play in post-war recovery efforts. Our working hypothesis is that the outflows of this highly-developed river basin are the synthesis of policies developed more or less independently by several institutions in the riparian countries.

This paper is organized as follows: the next section presents the river basin MAS modeling framework based on remote sensing and its application to the Yarmouk River basin. The remaining sections discuss the simulation results, present a sensitivity analysis, and provide concluding remarks.

MATERIALS AND METHODS

To analyze the two contested claims regarding the collapse of YRB outflows, we need a modeling framework that can (*i*) retrieve both hydrological and anthropogenic data and (*ii*) handle multi-scale interactions among diverse institutions, both with limited on-the-ground data. This is achieved by combining remote sensing with multi-agent simulation.

Remote Sensing

Remote sensing is used to retrieve hydrological and anthropogenic data for the river basin MAS model without any detailed on-the-ground measurement, observation, survey or interaction with water resources managers.

Physical network

We use the method developed by Avisse et al. (2017) to locate reservoirs, assess their maximal storage capacities, and monitor their storage levels from Landsat satellite images and digital elevation models (DEMs) only. The basic idea behind the method is to statistically correct the vertical errors of the DEM using the information on water surface areas derived from Landsat images: pixels more frequently immersed are likely to be lower than their neighbors which are less often covered with water. After this correction, the storage–area relationship can be determined and combined with Landsat images available at regular time intervals to obtain the storage trajectory of the reservoir without any direct measurements (storage variations are used in the section Validation for confirming our hypothesis on reservoirs operation policy). We then detect 37 reservoirs in the YRB (Fig. 1): 25 are Syrian and listed in the agreement between Syria and Jordan (1987), 1 is listed in the agreement but under Israeli control in the Golan Heights, 1 is the Wahda dam, and the remaining 10 have been unilaterally built by the three countries in the basin. These last 10 dams have a cumulative storage capacity of 34.5 hm^3 in Syria, less than 0.1 hm^3 in Jordan, and 2.9 hm^3 in the Israel-occupied Golan Heights (Fig. 3). Many detected reservoirs are very small as they are found to have not stored more than 1 hm^3 in 30 years. 2 dams among the 28 listed in the agreement are not detected because they are too small or rarely filled with water.

We choose to model 20 reservoirs with capacity greater than 1 hm^3 and naturalized incremental runoffs greater than 0.3 hm^3/year that we expect will most affect Yarmouk River flow (Table 1).

At the YRB outlet, the exchange system at Adasiya (see Fig. 3) separates the flow between *alpha* (diversion to the KAC) and *beta* (natural route), and the Israeli system at the Yarmoukeem Pool (YP; 3.5 km downstream from Adasiya along *beta*) sends up to 4.5 m^3/s to Lake Tiberias, essentially to supply the *allocation* and *concession*. This *concession* is eventually sent back to the KAC from Lake Tiberias as per the treaty between Israel and Jordan (1994). Flows above 4.5 m^3/s go to the Jordan River.

Rivers, pipes and canals connecting reservoirs and irrigated crop areas are obtained using DigitalGlobe and CNES/Airbus high resolution (~1 m) imagery available via Google Earth and elevation from a DEM (Protocol S3). Extrapolations from ground measurements in Jordan are also made to estimate evaporation – which is a major water loss according to MWI/JVA (2002) – and sedimentation (Protocols S4 and S5).

Irrigation water demands are derived from remotely sensed land use maps and precipitation, crop water requirements (Allen et al. 1998), and standard irrigation efficiencies (Protocol S6).

Hydrological modeling

In this study, the lump model GR2M developed by Mouelhi et al. (2006) is chosen, because of its simple formulation, to derive river basin outflows that will supply our distributed river basin model. This rainfall–runoff hydrological model relies on two parameters (the capacity of a soil moisture reservoir and an underground water exchange parameter; see the calibration in Protocol S1). The model also requires two input variables only – precipitation and evapotranspiration (ETP) – to produce a discharge on a monthly time step. The resulting outflows from GR2M are separated between base flow (moving minimum over a 12 months period) and runoff (remaining flow). The latter is then spatially disaggregated at the location of each reservoir using precipitation and drainage area ratios to produce the incremental inflows (Protocol S1). Average values of these incremental inflows over the historical period are given in Table 1 for information. The base flow corresponds to the groundwater flow reaching the outlet of the basin, and depends on groundwater withdrawals, irrigation return flows, and infiltration inside rivers (Protocol S2).

The monthly PERSIANN-CDR (Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Climate Data Record) product is used for our modeling. This dataset covers the latitude band 60°S-60°N with a 0.25° spatial resolution from 1983 onwards. It is generated from the PERSIANN algorithm that predicts rainfall using geostationary satellite GridSat-B1 infrared data, and relies on 2.5°-resolution gridded precipitation from Global Precipitation Climatology Project (GPCP) gauges for monthly bias correction (Ashouri et al. 2015). We measure an average PERSIANN-CDR precipitation for 1983-2015 over the YRB of 239 mm/year (Fig. 2) – i.e. 64% of the 372 mm/year estimated by Salameh and Bannayan (1993) for the pre-development stage. The decline is consistent with the 30% rainfall drop for the second half of the 20th century compared to the pre-development period considered by the same authors. Locally, to address the coarse spatial resolution of PERSIANN-CDR data compared to the size of the YRB, its reservoirs watersheds or crop areas, the precipitation data are corrected based on isohyets found in general hydrological studies of the YRB (Burdon 1954; Barnes 2009; Salameh and Bannayan 1993) for further use as input data for the hydrological modeling and for the assessment of crop water requirements (Protocol S1).

The seasonal distribution of PERSIANN-CDR rainfall in the YRB is verified afterward in the section Validation.

Multi-Agent Simulation

Because the whole system depicted in Fig. 3 is managed by multiple riparian countries, government agencies, water users and infrastructure operators, we need a modeling framework that enables multi-scale interactions between all those agents. Shoham and Leyton-Brown (2009) define multi-agent systems as “systems including agents that have diverging information, or different information or both, and performing in the same environment”. Unlike optimization problems, there is no global supervising structure. Agents are autonomous entities that interact with others and take their own decisions. Levels of interactions between agents thus characterize levels of cooperation. In water resources system applications, agents correspond to decision-makers having access to some information from different parts of the system (i.e. MAS environment), and pursuing different and often competing objectives. Decision making processes are implemented from hypotheses based on the kind of political regime and organization inside the countries, and on international relations for transboundary study cases. Such hypotheses are made following the analyst’s interpretation of all contracts or agreements available, either implicit statu quo processes or explicit policy documents.

A MAS model is then developed using the Pynsim architecture (Knox et al. 2018). It relies on a network made of nodes and arcs, which is particularly useful to represent spatially distributed agents inside the same river basin system (Harou et al. 2009). Nodes symbolize reservoirs, aquifers, consumption sites, and diversion systems; and arcs symbolize rivers, pipes, canals, and groundwater transfers. The main asset of Pynsim, though, lies in the capacity to define different institutional levels of managing agents, from individual actors who manage one site to institutions who supervise interactions within the water resources system (Knox et al. 2018). These agents are integrated in a single computing framework where human and institutional decisions complement the physical processes from a traditional arcs and nodes representation.

In the MAS model of the YRB, the agents represent their real-world counterparts ranging from government agencies to water users. The hierarchical organization of the agents is depicted on Fig. 4. At the highest level, we find the riparian countries who typically interact within the framework of bilateral treaties (if any). At the intermediate level, the operators of the main reservoirs and diversions allocate water in space and time based on the intersectoral allocation policies dictated by their government. In Jordan, this top-down approach reflects the institutional regime and decision-making in the water sector where the Ministry of Water and Irrigation oversees water resources management and planning. In Syria, such a top-down policy making approach is consistent with an authoritarian regime. Regarding Israel, we made the assumption that the development of land and water resources in the occupied Golan Heights would need the approval of the government. At the lowest level, the extent of water use by farmers and municipalities is influenced mostly by policies regarding land use and groundwater extraction. Further downstream, at Adasiya-YP (Fig. 3), water exchanges with Lake Tiberias are taking place. These water transfers follow the terms of the Peace Treaty between Jordan and Israel.

The political and physical interactions between Israel and Jordan are also represented in Fig. 4 where we can see the Treaty of Peace and the corresponding water exchanges between Adasiya and Lake Tiberias. There is no connection between Syrian and Jordanian institutions because there is no effective cooperation between the two countries, despite the signature of the 1987 agreement (Hussein 2017).

At the level of reservoir operators, we assume that those operators follow the standard operating policy (SOP; Protocol S7): local water demands are met first and excess water is stored and eventually spilled when the reservoir reaches its maximum storage capacity (Etana Syria 2015). Note that this assumption is further discussed in the section Validation. As for the Wahda dam operator, this agent releases water from the reservoir only when the inflows make the simulated storage larger than the storage that has been measured on the ground by JVA (Validation step), or more water in case the outflow is not sufficient to satisfy the *allocation* (scenario analysis step; see the section Consequences on the water transfers as per the 1994 Treaty of Peace). Other agents are defined to characterize Jordanian and Israeli controllers of the diversion systems at Adasiya and the Yarmoukeem Pool.

Water users are linked to water sources based on the land use maps and detailed imagery available in Google Earth. For irrigated crop areas close to dams listed in Table 1 and built for irrigation purpose, farmers are assumed to withdraw water from reservoirs first to try to meet the demand and then from aquifers if there is not enough water in the reservoirs (Etana Syria 2015).

For the other irrigated crop areas, water is directly withdrawn from aquifers. Households from large cities near dams are also considered as they are assumed to use the reservoirs as their primary source of water and to contribute to the decrease of their storage. Other water usages have been ignored (see Protocol S6).

The validation of agent-based models can be challenging due to limited social data and the large number of interactions between the agents and their environment (Heath et al. 2009; Ligtenberg et al. 2010; Filatova et al. 2013; Bert et al. 2014). However, in our MAS, the agents' behavior is essentially reactive (not proactive), meaning that the number of interactions is much more limited. The validation approach adopted in this study is the same as traditional modeling efforts where we compare the simulated river discharges at Wahda dam and Adasiya to historical observations. Individual decision-making processes have been calibrated with on-the-ground observations, using remote sensing analyses or based on signed agreements (see the equations in Protocols S6 and S7).

Scenarios over the Historical Period

Different scenarios representing alternative theories (either narratives from the riparian countries or complementary ideas that have yet to be fully explored) regarding the hydrological changes in the YRB are simulated with the Pynsim MAS model. Such scenarios are implemented by modifying input data (precipitation, infrastructure or land use) for the modeling.

The five scenarios are:

1. **No precipitation decline**. A higher precipitation is considered to produce the 422 hm^3/year natural flow at Adasiya that was expected by Jordan in the feasibility study of the Wahda dam (MWI/JVA 2002). This scenario models the Syrian narrative.
2. **Listed dams only**. Only dams listed in the Syria–Jordan agreement (i.e. all dams except Qunaitera and Avnei Eitan al-Golan; Table 1) are modeled. This scenario simulates the Jordanian narrative.
3. **No groundwater pumping development**. Crop water requirements in areas located far from reservoirs remain unchanged after the signature of the agreement between Syria and

Jordan in 1987. This scenario shows the effects of assumptions in the 1953 and 1987 agreements that ignore groundwater pumping.

4. **All dams active 2013-present**. All dams continue to operate in 2011 as in prior years. This scenario assumes conditions continue as though the Syrian civil war did not occur.
5. **Aggregate effects**. Combination of the four prior scenarios with increased precipitation, only dams listed in the Syrian-Jordanian agreement, no groundwater pumping development, and continued operation of the dams after 2011.

It must be stressed that, due to the uncertainty on all the remote sensed data used in this study, the sensitivity of the model is tested in the section Sensitivity analysis further below with regard to three independent hydrological parameters: (*i*) the estimated natural flow, (*ii*) infiltration and irrigation return flows to the aquifer, and (*iii*) crop water requirements.

RESULTS AND DISCUSSION

Remote Sensing Observations

The evolution of cumulative storage capacity and cumulative water stored in reservoirs of the YRB (except Wahda; see Protocol S3) is presented in Fig. 5. These results enable us to do a first qualitative analysis of the impact of the construction of dams on the discharge observed downstream (Fig. 2). We note that the pre-1995 growth of the cumulative storage capacity does not seem to have affected the hydrological regime of the river during the same period of time. However, without precipitation data for years between the pre-development phase (pre-1960s) and 1983, it is difficult to consistently conclude on the impact of the new dams. Indeed, as mentioned in the Introduction, rainfall seems to have strongly varied during this period of time. On the contrary, while the cumulative storage capacity remained the same between 1999 and 2006, the runoff declined and the filling of the reservoirs was affected. The reasons behind these changes should then be found in the late 1990s multi-year drought (Kelley et al. 2015) and/or in increasing water withdrawals for irrigation purpose (Aw-Hassan et al. 2014). The consecutive low Yarmouk River flow and low reservoir water storage coincide with the 2007-2008 drought. Higher precipitation in the subsequent years (period 2009-2012), though, did not materialize in higher discharges downstream, as more water has been stored in the reservoirs. Finally, it seems clear that the disuse of many reservoirs in 2013, after the Syrian civil war started, led to less water stored in the YRB and to larger runoff discharges during the following years.

Next, the model is validated with historical measurements and afterwards the scenarios defined in section Scenarios over the Historical Period are tested to quantitatively complement the qualitative results.

Validation

The Pynsim MAS simulation model is run to recreate the observed flow at the Wahda dam and Adasiya over the historical period (Fig. 6).

Qualitatively, the model reproduces well the seasonality of the Yarmouk River flow. The fact that we can capture well the intensity of peak flow events over a 30-year period is an indication that the contribution of PERSIANN-CDR precipitation to runoff (and thus to baseflow) is properly captured. The model also replicates well the three periods initially identified at the Wahda dam station (Fig. 2): (*i*) the stationary period before 1999, (*ii*) the subsequent collapse of both the base flow and the runoff, and (*iii*) the return of runoff in 2013. The fact that the simulated base flow collapses in 1999, at the exact same time as in the observations, also validates the reasoning behind the definition of a threshold on groundwater abstractions (see Protocol S2). The slight difference in the rate of the base flow reduction may be explained either by errors on irrigation requirements (or a change in irrigation efficiency) or by the simplistic representation of the aquifer's dynamics in the modeling. The contrasted quality of the results for certain years (e.g., 1990, 2004, 2014 at Wahda; or 1993 at Adasiya) may be caused by errors in PERSIANN-CDR data, by the difficulty to locally calibrate this precipitation dataset (or the GR2M model; see the section Sensitivity analysis on that matter below) or by a few temporary changes in the operation of the Syrian reservoirs.

As indicated in the section Multi-Agent Simulation, we made the assumption that the reservoirs were operated using the standard operating policy (SOP). To test the validity of this assumption, we compare simulated storages in Syria and in the occupied Golan Heights to remote sensing observations (see Protocol S3). With a correlation coefficient of 0.66, we conclude that SOP captures relatively well the operation of the main reservoirs over the 1998-2015 period. Differences between model estimates and remote-sensed values are potentially influenced by errors on the assessment of natural inflows, land use, irrigation requirements, crop–water source association, reservoir operation or just remote-sensed storage estimates.

As for the results at the outlet of the YRB, we calculate the $Bias$ (Eq. 1 and the modified Kling-Gupta efficiency-statistic (KGE' in Eq. 2; Gupta et al. 2009; Kling et al. 2012) to measure the quality of the simulated flows:

$$Bias = \mu_s - \mu_o \tag{1}$$

$$KGE' = 1 - \sqrt{(r-1)^2 + (\beta-1)^2 + (\gamma-1)^2} \tag{2}$$

where r is the correlation coefficient between simulated and observed flows, $\beta = \mu_s/\mu_o$ is the bias ratio with μ the mean discharge, $\gamma = CV_s/CV_o = (\sigma_s/\mu_s)/(\sigma_o/\mu_o)$ is the variability ratio with CV the coefficient of variation and σ the standard deviation, and s and o indices stand for *simulated* and *observed* data respectively. The KGE' is chosen over the Nash-Sutcliffe efficiency because it better captures the variability of flows in the Yarmouk River.

We then obtain $Bias$ values of -2.46 hm^3/month and -0.02 hm^3/month, and KGE' values of 0.64 and 0.90 for discharges at Adasiya and the Wahda dam respectively. The contrasted results for the $Bias$ come from the large differences between simulated and observed flows during particular years as mentioned above (e.g., $Bias$ of -92.51 hm^3/month and -86.26 hm^3/month at Adasiya for February and March 2003). However, the KGE' values reveal that the MAS model is able to reproduce fairly accurately the historical flows at Wahda (upstream) and to a less extent at Adasiya. The lower performance at Adasiya is mainly due to the fact that the river discharges at that location are strongly influenced by the releases from the Wahda dam.

Scenario Analysis

Causes of the Yarmouk River flow changes

In this section, we analyze the results of the scenarios presented in the section Scenarios over the Historical Period. The analysis focuses on the inflow into the Wahda reservoir because (*i*) most dams and irrigated crops in the YRB are located upstream from that reservoir (Fig. 3), and (*ii*) the flow at Adasiya is strongly influenced by the operation of that reservoir.

We observe that the base flow still sharply decreases in 1999 with the *no precipitation decline* and *listed dams only* scenarios (Fig. 7, top). It means that neither the reduced precipitation nor the unlisted dams caused that major hydrological change. On the contrary, the stationary base flow after 1999 under the *no groundwater development* scenario confirms that increased groundwater abstractions strongly impacted the base flow (as explained in the Introduction). If groundwater pumping had not developed since 1987, the groundwater table would have remained at the same level and the base flow would not have been affected.

The difference between the annual flow for each scenario and the simulated *historical* flow is presented in Fig. 7 (bottom). This figure shows the impact of each scenario on the Yarmouk discharge. Until 1999, our simulations show that anthropogenic activity had little or no effect on the Yarmouk River flows. The main difference between the *historical* and *aggregate effects* flows lies in the precipitation decline that mostly has effects during the runoff (winter) season. From 2000 onwards, however, the impact of large groundwater withdrawals is particularly clear as the gap between the simulated *historical* and *no groundwater development* scenarios keeps increasing until the base flow completely disappears in 2006. In 2013, our modeling shows that the destruction/disuse of Syrian dams led to an increase of the runoff by 25.7 hm^3/year (i.e. +87%) on average over the period 2013-2015. This value is consistent with the ~25 hm^3/year estimate from Müller et al. (2016). It must be stressed that this sudden increase did not alleviate water scarcity in Jordan though, as more than 500,000 Syrian refugees entered the country during the same period of time (UNHCR 2017). The simulation of the *listed dams only* scenario finally reveals that the impact of the unilateral construction and operation of dams by Syria and Israel is marginal over the whole 1983-2015 historical period.

Moreover, provided that groundwater abstractions had remained at the 1987 level, Jordan would likely have received a discharge close to the 117.6 hm^3/year that it expected to fill the Wahda reservoir. Indeed, with the simulation of the *no groundwater pumping development* scenario, the modeled flow reaching Wahda during the period 2006-2012 remains close to 100 hm^3/year higher than the ~15 hm^3/year measured by MWI/JVA during this period (Fig. 2). In other words, groundwater extraction – rather than precipitation decline or dam construction – is the cause of the decline in Yarmouk flow at Wahda dam.

Sensitivity analysis

To assess the robustness of the conclusions regarding the collapse of Yarmouk River flows, a sensitivity analysis is carried out for three independent hydrological parameters:

1. **The natural inflows to each reservoir**. Because the estimate of the Yarmouk River historical discharge varies significantly from one reference to another, scenarios are simulated with the most extreme values found in the literature: 400 and 500 hm^3/year (Libiszewski 1995).
2. **Wadi and irrigation return flows to the aquifer**. Infiltration is one of the main factors affecting base flow. This parameter is usually estimated using rules of thumb based on the case study's soil properties, and can vary in the ratio of one to two (Mohan and Vijayalakshmi 2009). Here, we assess the impact of a change by ±10% (average error considered by Dewandel et al. 2007).
3. **Crop water requirements (CWR) estimated with the FAO Penman-Monteith method**. After conducting ground measurements, Al-Bakri et al. (2016) and Bastiaanssen (2015) decreased some of FAO's crop coefficients by ~15% to estimate irrigation water use in Jordan (Protocol S6). The sensitivity of the model to CWR estimates is then assessed by running the scenarios with CWR modified by ±15% in all countries.

We simulate the four prior scenarios (*historical*, *no precipitation decline*, *listed dams only*, *no* *groundwater pumping development*) using each of the three values (lower, standard, larger) for each parameter (natural flow, infiltration percentage, crop water requirements estimate). The results of the $4 \times 3 \times 3 \times 3 = 108$ simulations are shown on Fig. 8 in terms of (*i*) average yearly flows and (*ii*) 25th percentile of monthly flows between the start of the collapse of the Yarmouk River flow and the beginning of the civil war (period 2000-2010). We consider in the following that the average yearly flow serves as an indicator for both base flow and runoff, and that the 25th percentile of monthly flows indicates base flow differences between the various simulations.

The examination of Fig. 8 reveals that the model is more sensitive to a change in both infiltration and crop water requirements than to the historical annual flow: natural flow simulations can thus be visually aggregated to analyze the nine combinations of CWR and infiltration. Three main patterns can be observed:

1. Reduced groundwater pumping has the largest effect on average yearly streamflows and 25th percentile of monthly flows (base flow) in seven of the nine combinations of CWR and infiltration: {-15%, -10%}, {-15%, -}, {-, -10%}, {-, -}, {-, +10%}, {+15%, -}, {+15%, +10%}. For the 10% higher infiltration rate and 15% CWR reduction rate, *no groundwater pumping development* still has a strong influence on 25th percentile flow and the *no precipitation decline* has an equal or slightly larger effect. These results reinforce the base case results.
2. In three combinations ({-15%, -}, {-15%, +10%}, {-, +10%}), the base flow remains at a certain level above 1 hm^3/month and total yearly flows above 75 hm^3/year with any scenario, including the *historical* one. These situations are then not realistic because base flow and total Yarmouk flows are supposed to decline in the *historical* scenario representing the historical Yarmouk River flow monitored by MWI/JVA. For the other combinations, the existence of a base flow each time requires the reduction of groundwater pumping, although the effect is quite limited for the 10% infiltration reduction and 15% CWR increase. This last finding also corroborates the fact that the increase in groundwater abstraction is the main cause to the decline of base flows.

3. In one combination {+15%, -10%}, the recharge of the aquifer is extremely limited and the base flow collapses no matter the scenario. In this case, it seems that the surface water would not have been sufficient to meet the agricultural demand. Farmers close to the reservoirs would then have pumped more water from the aquifer, while, at the same time, the aquifer would have less recharged due to the decreased infiltration. In this situation, the Yarmouk River flow would have decreased with any of our scenarios, and the main cause of the flow decline would probably have been the general growth of agricultural demand close to the Syrian reservoirs.

It must be stressed that this sensitivity analysis is largely specific to our case study. As the water sources, usages and management policies may be different in other basins, we suggest that a similar sensitivity analysis be conducted for other applications of the method to corroborate any findings when no on-the-ground information is available.

Consequences on the water transfers as per the 1994 Treaty of Peace

The analysis of this section is conducted over the post-treaty period (1994-2015). All scenarios defined in the previous section are considered but the *all dams active* one since it only affects the Yarmouk flows after 2013. Israel and Jordan both receive the largest percentage increases in water under the *no groundwater pumping* scenario (Table 2). The scenario in which Syria would have solely built the dams listed in the 1987 Syria–Jordan agreement is the only one that leads to very small increases in flow. For all scenarios, Israel's relative percentage increase is larger than for Jordan and this result confirms that Jordan bears larger hydrological risk under the Jordan–Israel Treaty of Peace.

Future Scenarios

We examine three future scenarios for the years 2016-2025 with the aim to identify (*i*) potential water flows of the Yarmouk as the Syrian civil war winds down, and (*ii*) how Jordan can support the post-war recovery to simultaneously assist Syrians and promote Jordan's own hydrological interests. Each scenario assumes precipitation is the same as for 2006-2015 (236 mm/year on average, similar to the historical 239 mm/year average). We recognize that future conditions (social, hydrological, and other) are highly uncertain in conflict areas such as the Yarmouk basin in Syria, and the precision of results critically depends on scenario assumptions. The principal value of these future scenarios is to compare results across conditions that may manifest in the post-war period and help basin states see what role, if any, they could play in recovery efforts:

1. **Status quo**. The water resources system configuration remains the same as in 2015 (7 dams in disuse because of the Syrian civil war; Table 1).
2. **Re-operate dams**. Starting in 2018, Syrians independently rebuild and re-operate dams that fell into disuse to their prior capacities.
3. **Higher irrigation efficiency**. Donor organizations promote and support Syrian farmers to rebuild and redevelop their irrigation systems to increase efficiency by 10%, reaching 60% and 80% from surface water and groundwater sources respectively from 2018 onwards.

In the *status quo* scenario, inflow to the Wahda dam would slightly increase with a *higher irrigation efficiency* in Syria (Fig. 9). According to our simulations, Jordan and Syria would respectively receive 2.4 and 5.6 hm^3/year more water than with the *status quo* of damaged Syrian dams remaining in disuse. This increase may indicate a potential benefit for Jordan to help Syrian farmers upgrade their irrigation networks so long as saved water flows to the Wahda dam. As for the scenario that considers the rehabilitation of the Syrian dams destroyed or damaged during the civil war, Jordan can expect the Yarmouk River flow to significantly decrease and return to the 2010 low flow state.

CONCLUSIONS

A multi-agent simulation model of the entire Yarmouk River basin water system (infrastructure, water supply and demand, reservoir capacities and operating rules, irrigation policies, institutional interactions) has been built from remote sensing products and two time-series of monthly flows near the outlet of the basin only. This modeling effort was undertaken while most of the basin is in the midst of a civil war since 2011, and for which no detailed ground data has ever been available.

The model has been validated over the historical period 1983-2015 (KGE' = 0.64 and 0.90 for its two gauging stations).

We have used the model to assess the contributions of natural and anthropogenic factors in the collapse of the Yarmouk flows. Our results indicate (i) the unilateral construction of dams that are not listed in the 1987 agreement between Syria and Jordan (Jordanian narrative) seems to have had a limited impact on the flow regime changes; (ii) a 36% precipitation decrease since the first half of the 20th century (Syrian narrative) has partly led to the river flow decline; and (iii) groundwater over-abstraction by Syrian highland farmers (theory hardly mentioned) can explain most of the decrease in Yarmouk flows.

Our sensitivity analysis on three hydrological parameters (crop water requirements, infiltration and natural flow estimates) reveals that if we had considered higher irrigation water withdrawals and lower infiltration, the Yarmouk River flow would have collapsed no matter which scenario is considered. In that case, the main cause of the flow decline would probably be the general growth of agricultural demand close to the Syrian reservoirs.

There are two limitations to our work that stem from difficulty to access reliable data in a complex and ever-changing region. First, we interpolated and extrapolated land uses over a 30-year period from three land use maps generated for 1984, 1998, and 2014. Second, there is little information on aquifer dynamics. In the case of the reduced groundwater pumping scenario we assumed that the base flow would increase if groundwater average recharges exceeded its average losses over a 24-month period that characterizes a certain transit time inside the aquifer.

Two reasons may explain why groundwater overextraction has not been publicly discussed by the riparians: groundwater extraction is not mentioned in the Jordanian–Syrian agreement (groundwater regulation is unfortunately largely ignored in international water law; Eckstein and Eckstein 2005); and until now, there has not been a tractable method to quantify the effects of groundwater extraction on stream flow, particularly a method that works using extremely limited ground data and that could be applied in a war-torn region.

By modeling institutional interactions as per the 1994 Treaty of Peace between Jordan and

Israel, we have assessed the relative contributions of these natural and anthropogenic factors on the sharing of the Yarmouk waters between the two countries. This has also been useful when testing future scenarios to estimate how Jordan and Israel can support the post-war recovery of Syria while promoting their own hydrological interests.

The approach developed in this paper is based on freely available remote sensing data and modeling tools (for land use, dams characterization method, precipitation, hydrological modeling and systems modeling). The tools and results can be used in basins where riparian countries and stakeholders share information or they do not. Outside parties can also use the tools and results with less reliance on basin parties for critical information. The methodology has the potential to target issues hampering an effective cooperation between parties, and to provide decision-support information in cases requiring further negotiations.

DATA AVAILABILITY

All model and code are available in a repository online (Avisse 2020). PERSIANN-CDR, Landsat satellite imagery, SRTM data, and streamflow data were provided by a third party. Direct requests for these materials may be made to the provider as indicated in the "Acknowledgements".

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SUPPLEMENTAL DATA

Protocols S1-S7, Fig. S1 and Table S1 are available online in the ASCE Library (ascelibrary.org).

REFERENCES

Ababsa, M. (2010). “Agrarian counter-reform in syria.” *Agriculture and Reform in Syria*, Raymond Hinnebusch, Lynne Rienner Publishers and University of St Andrews Centre for Syrian Studies, Boulder.

Ababsa, M. (2013). “Crise agraire, crise foncière et sécheresse en syrie (2000-2011).” *Maghreb - Machrek*, 215(1), 101–122.

Al-Bakri, J. T., Shawash, S., Ghanim, A., and Abdelkhaleq, R. (2016). “Geospatial techniques for improved water management in jordan.” *Water*, 8(4).

Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. (1998). *Crop evapotranspiration: Guidelines for computing crop water requirements*. Number 56 in FAO Irrigation and drainage paper. Food and Agriculture Organization, Rome.

Ashouri, H., Hsu, K.-L., Sorooshian, S., Braithwaite, D. K., Knapp, K. R., Cecil, L. D., Nelson, B. R., and Prat, O. P. (2015). “Persiann-cdr: Daily precipitation climate data record from multisatellite observations for hydrological and climate studies.” *Bulletin of the American Meteorological Society*, 96(1), 69–83.

Avisse, N. (2020). “Navisse/yarmouk-system: PyNsim model of the Yarmouk River system, <https://doi.org/10.5281/zenodo.3742293>.

Avisse, N., Tilmant, A., Müller, M. F., and Zhang, H. (2017). “Monitoring small reservoirs’ storage with satellite remote sensing in inaccessible areas.” *Hydrology and Earth System Sciences*, 21(12), 6445–6459.

Aw-Hassan, A., Rida, F., Telleria, R., and Bruggeman, A. (2014). “The impact of food and agricultural policies on groundwater use in Syria.” *Journal of Hydrology*, 513, 204–215.

Barnes, J. (2009). “Managing the waters of Ba‘th country: The politics of water scarcity in Syria.” *Geopolitics*, 14(3), 510–530.

Bastiaanssen, W. (2015). “Satellite-based estimation of evapotranspiration, soil moisture and biomass production for two irrigated areas in Jordan.” *Report for the Ministry of Water and Irrigation*, MWI, Maurik.

Beaumont, P. (1997). “Dividing the waters of the river Jordan: An analysis of the 1994 Israel–Jordan Peace Treaty.” *International Journal of Water Resources Development*, 13(3), 415–424.

Bert, F. E., Rovere, S. L., Macal, C. M., North, M. J., and Podestá, G. P. (2014). “Lessons from a comprehensive validation of an agent based-model: The experience of the pampas model of argentinean agricultural systems.” *Ecological Modelling*, 273, 284–298.

Biglarbeigi, P., Giuliani, M., and Castelletti, A. (2018). “Partitioning the impacts of streamflow and evaporation uncertainty on the operations of multipurpose reservoirs in arid regions.” *Journal of Water Resources Planning and Management*, 144(7), 05018008.

Burdon, D. J. (1954). “Infiltration rates in the Yarmouk basin of Syria-Jordan.” *Association Internationale d’Hydrologie Scientifique*, 2(37), 343–355.

Courcier, R., Vénot, J.-P., and Molle, F. (2005). “Historical transformations of the lower Jordan river basin (in Jordan): Changes in water use and projections (1950-2025).” *Comprehensive Assessment Research Report 9*, Comprehensive Assessment Secretariat, Colombo.

Dewandel, B., Gandolfi, J., de Condappa, D., and Ahmed, S. (2007). “An efficient methodology for estimating irrigation return flow coefficients of irrigated crops at watershed and seasonal scale.” *Hydrological Processes*, 22(11), 1700–1712.

Eckstein, Y. and Eckstein, G. E. (2005). “Transboundary aquifers: Conceptual models for development of international law.” *Ground Water*, 43(5), 679–690.

Etana Syria (2015). “The Yarmouk basin: Between conflict and development.” *Report No. 11*, Etana Syria, <http://www.etanasyria.org/uploads/files/7202_Etana%20files-The%20Yarmouk%20Basin%20-11%20En%20-%20final.pdf>.

FAO (2009). *Irrigation in the Middle East region in figures: AQUASTAT survey - 2008*. Number 34 in FAO Water Reports. Food and Agriculture Organization, Rome.

Filatova, T., Verburg, P. H., Parker, D. C., and Stannard, C. A. (2013). “Spatial agent-based models for socio-ecological systems: Challenges and prospects.” *Environmental Modelling & Software*, 45, 1–7.

Gül, A., Rida, F., Aw-Hassan, A., and Büyükalaca, O. (2005). “Economic analysis of energy use in groundwater irrigation of dry areas: a case study in Syria.” *Applied Energy*, 82(4), 285–299.

Gupta, H. V., Kling, H., Yilmaz, K. K., and Martinez, G. F. (2009). “Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling.” *Journal of Hydrology*, 377(1), 80–91.

Harou, J. J., Pulido-Velazquez, M., Rosenberg, D. E., Medellín-Azuara, J., Lund, J. R., and Howitt, R. E. (2009). “Hydro-economic models: Concepts, design, applications, and future prospects.” *Journal of Hydrology*, 375(3), 627–643.

Heath, B., Hill, R., and Ciarallo, F. (2009). “A survey of agent-based modeling practices (january 1998 to july 2008).” *Journal of Artificial Societies and Social Simulation*, 12(4), 9.

Hof, F. C. (1998). “Dividing the Yarmouk’s waters: Jordan’s treaties with Syria and Israel.” *Water Policy*, 1(1), 81–94.

Hussein, H. (2017). “Whose ‘reality’? Discourses and hydropolitics along the yarmouk river.” *Contemporary Levant*, 0(0), 1–13.

Ibrahim, W. Y., Batzli, S., and Menzel, W. P. (2014). “Agricultural policy effects on land cover and land use over 30 years in Tartous, Syria, as seen in Landsat imagery.” *Journal of Applied Remote Sensing*, 8(1), 083506.

Israel and Jordan (1994). “Treaty of peace between the State of Israel and the Hashemite Kingdom of Jordan.

Kaisi, A. and Yasser, M. (2004). “Participatory management of water resources for agricultural purposes in Syrian Arab Republic.” *Participatory water saving management and water cultural heritage*, Hamdy A. (ed.), Tüzün M. (ed.), Lamaddalena N. (ed.), Todorovic M. (ed.), Bogliotti C. (ed.), 243–253. Options Méditerranéennes : Série B. Études et Recherches; n. 48.

Kelley, C. P., Mohtadi, S., Cane, M. A., Seager, R., and Kushnir, Y. (2015). "Climate change in the Fertile Crescent and implications of the recent Syrian drought." *Proceedings of the National Academy of Sciences*, 112(11), 3241–3246.

Kling, H., Fuchs, M., and Paulin, M. (2012). "Runoff conditions in the upper Danube basin under an ensemble of climate change scenarios." *Journal of Hydrology*, 424, 264–277.

Knox, S., Meier, P., Yoon, J., and Harou, J. J. (2018). "A python framework for multi-agent simulation of networked resource systems." *Environmental Modelling & Software*, 103, 16–28.

Lei, X., Zhao, J., Yang, Y.-C. E., and Wang, Z. (2019). "Comparing the economic and environmental effects of different water management schemes using a coupled agent-hydrologic model." *Journal of Water Resources Planning and Management*, 145(6), 05019010.

Libiszewski, S. (1995). *Water Disputes in the Jordan Basin Region and their Role in the Resolution of the Arab-Israeli Conflict*. Center for Security Studies and Conflict Research at the ETH Zurich / Swiss Peace Foundation, Zürich, Switzerland, occasional paper (environment and conflicts project), no. 13 edition.

Ligtenberg, A., van Lammeren, R. J., Bregt, A. K., and Beulens, A. J. (2010). "Validation of an agent-based model for spatial planning: A role-playing approach." *Computers, Environment and Urban Systems*, 34(5), 424–434.

Mohan, S. and Vijayalakshmi, D. (2009). "Prediction of irrigation return flows through a hierarchical modeling approach." *Agricultural Water Management*, 96(2), 233–246.

Mouelhi, S., Michel, C., Perrin, C., and Andréassian, V. (2006). "Stepwise development of a two-parameter monthly water balance model." *Journal of Hydrology*, 318(1), 200–214.

Müller, M. F., Yoon, J., Gorelick, S. M., Avisse, N., and Tilmant, A. (2016). "Impact of the Syrian refugee crisis on land use and transboundary freshwater resources." *Proceedings of the National Academy of Sciences*, 113(52), 14932–14937.

MWI/JVA (2002). "Al-Wehdah dam project: Updated feasibility." *Report no.*, The Hashemite Kingdom of Jordan, Ministry of Water and Irrigation/Jordan Valley Authority, Amman.

Pereira-Cardenal, S. J., Riegels, N. D., Berry, P. A. M., Smith, R. G., Yakovlev, A., Siegfried, T. U., and Bauer-Gottwein, P. (2011). "Real-time remote sensing driven river basin modeling using radar altimetry." *Hydrology and Earth System Sciences*, 15(1), 241–254.

Rosenberg, D. E. (2006). "The Yarmouk River agreements: Jordan-Syrian transboundary water management, 1953 - 2004." *Arab World Geographer*, 9(1), 23–39.

Rougé, C., Tilmant, A., Zaitchik, B. F., Dezfuli, A. K., and Salman, M. (2018). "Identifying key water resource vulnerabilities in data-scarce transboundary river basins." *Water Resources Research*, 54.

Salameh, E. and Bannayan, H. (1993). *Water resources of Jordan: present status and future potentials*. Friedrich Ebert Stiftung, Amman.

Salman, M. and Mualla, W. (2008). "Water demand management in Syria: centralized and decentralized views." *Water Policy*, 10(6), 549–562.

Shentsis, I., Inbar, N., Rosenthal, E., and Magri, F. (2019). "Assessing water consumption and aquifer discharge through springs based on the joint use of rain and flow data in the Yarmouk River Basin." *Environmental Earth Sciences*, 78(12), 368.

Shoham, Y. and Leyton-Brown, K. (2009). *Multiagent systems: Algorithmic, game-theoretic, and logical foundations*. Cambridge University Press, New York, USA.

Syria and Jordan (1953). "Agreement between the Republic of Syria and the Hashemite Kingdom of Jordan concerning the utilization of the Yarmuk waters.

Syria and Jordan (1987). "Agreement between the Syrian Arab Republic and the Hashemite Kingdom of Jordan concerning the utilization of the Yarmuk waters.

UN-ESCWA and BGR (2013). "Inventory of shared water resources in Western Asia." *Report no.*, United Nations Economic and Social Commission for Western Asia and Bundesanstalt für Geowissenschaften und Rohstoffe, Beirut.

UNHCR (2017). "Syria regional refugee response: Inter-agency information sharing portal, <http://data.unhcr.org/syrianrefugees/country.php?id=107>.

World Bank (2001). "Syrian Arab Republic irrigation sector report." *Report No. 22602-SYR*, World Bank, Rural Development, Water and Environment Group, Middle East and North Africa Region, Washington.

Yorke, V. (2016). *Jordan's Shadow State and Water Management: Prospects for Water Security Will Depend on Politics and Regional Cooperation*. Springer International Publishing, Cham, 227–251.

List of Tables

TABLE 1. Dams considered in the modeling.

Name	Operator's country	Listed?	Coordinates (East, North)[a]	Completion year	Disuse year	Capacity (hm^3)	$\bar{q}_{nat}$ (hm^3/year)
Al-Manzarah	Israel	Yes	223485, 282845	1982	-	2.3	0.3
Avnei Eitan al-Golan		-	223991, 246480	1982	-	2.3	0.5
Abidin	Syria	Yes	228895, 242487	1989	-	5.5	0.4
Qunaitera		No	231404, 280519	2006	2013	33.9	9.3
Jisr al-Raqqad		Yes	234093, 253358	1991	-	11.0	1.4
Kudnah		Yes	236056, 270196	1992	-	30.0	5.4
Al-Ghar		Yes	235663, 249285	1990	2013	5.5	0.5
Saham al-Jawlan		Yes	236335, 245880	1995	-	20.0	0.6
Ghadir al-Bustan		Yes	237999, 260863	1987	-	12.0	1.9
Tasil		Yes	240680, 253980	1984	-	6.6	7.7
Adwan		Yes	245080, 243840	1986	2013	5.7	3.0
Ebtaa kabeer		Yes	254499, 247077	1972	2013	3.5	8.9
Sheick Miskin		Yes	255463, 252644	1982	2013	15.0	30.1
Roum		Yes	305526, 237106	1977	-	6.4	0.3
Sahwat al-Khadr		Yes	277060, 218989	1986	-	8.8	0.6
Dar'a al-Sharqi		Yes	254714, 223397	1970	2013	15.0	31.1
Tafas		Yes	247434, 240864	1982	-	2.1	6.9
Al-Ghariyah al-Sharqiyah		Yes	271627, 231346	1982	2013	5.0	11.7
Harran		Yes	304324, 223335	1980	-	2.0	0.3
El Wahda	Jordan	Yes	232104, 237922	2007	-	110.0	64.4

[a] Coordinates are expressed in WGS 84/UTM zone 36N (EPSG:32636).

TABLE 2. Consequences of each scenario on the transfers as per the 1994 Treaty of Peace between Israel and Jordan 1994.

Beneficiary's share		Historical	No precip. decline	List. dams only	No GW pump. dev.	Aggregate effects
Jordan	Avg. flow (hm^3/year)	116.7	133.5	117.9	145.1	150.2
	Diff.[a] (%)	-	+14.5	+1.0	+24.4	+28.7
Israel	Avg. flow (hm^3/year)	39.1	53.9	39.7	55.7	67.5
	Diff. (%)	-	+37.9	+1.5	+42.7	+72.9
Jordan River	Avg. flow (hm^3/year)	16.9	48.5	17.2	25.8	64.0
	Diff. (%)	-	+187.0	+1.9	+52.6	+278.7

[a] Difference with the simulated historical flow.

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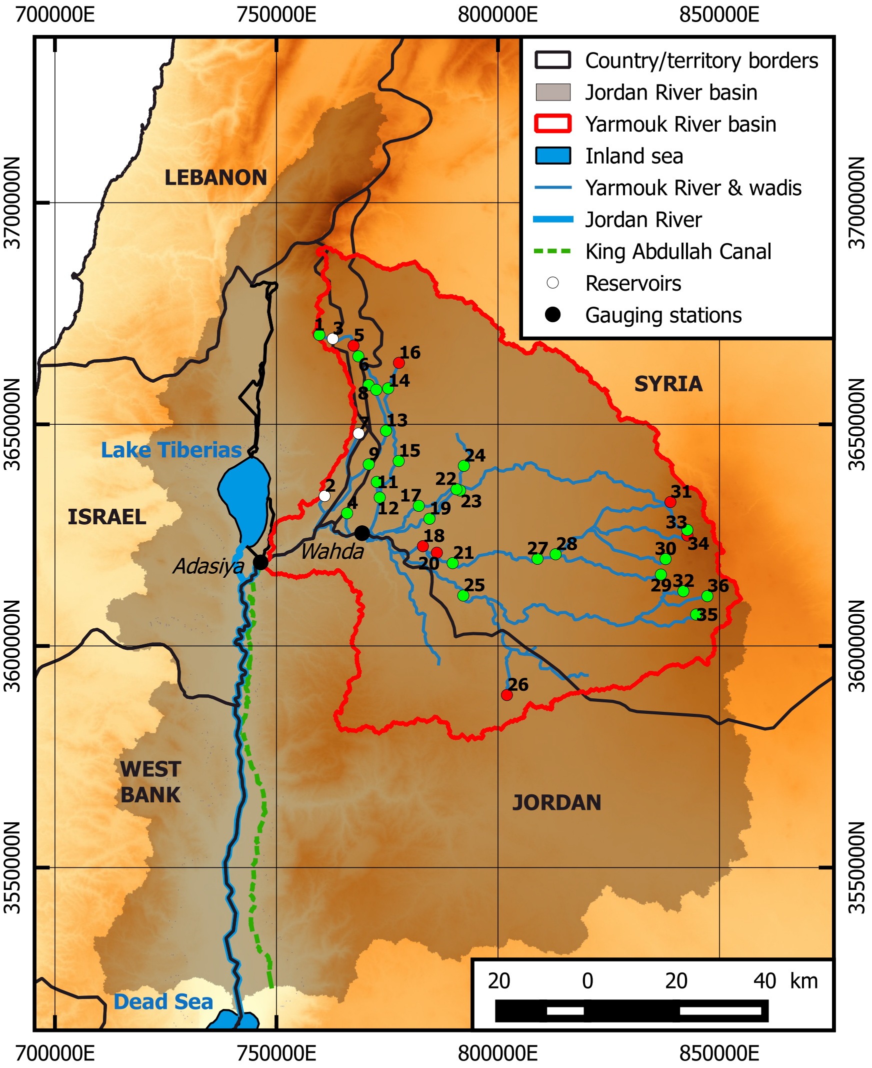

Fig. 1. The Yarmouk River basin as part of the Jordan River basin, with reservoirs other than Wahda detected using remote sensing – colors refer to the inclusion in the bilateral agreement between Syria and Jordan (1987); see Fig. 3. All coordinates are expressed in the Coordinate Reference System WGS 84/UTM zone 36N (EPSG:32636), in which 1 unit equals 1 m.

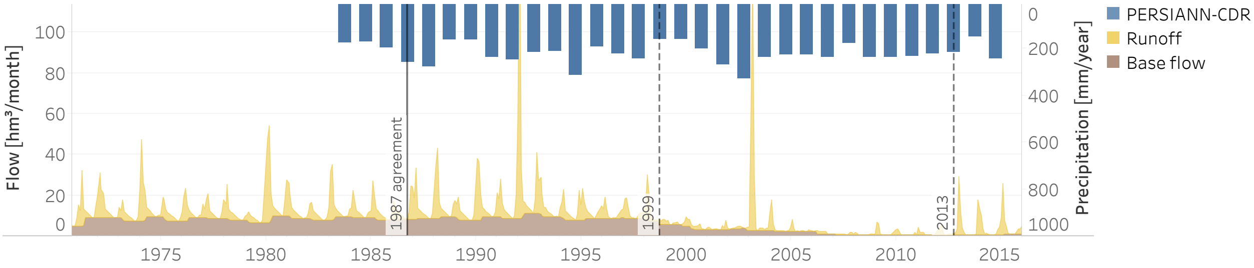

Fig. 2. Yarmouk River flow – expressed in terms of base flow (moving minimum over a 12 months period) and runoff (remaining flow) – measured at the station of the Wahda dam by the Jordanian Ministry of Water and Irrigation and the Jordan Valley Authority; and PERSIANN-CDR precipitation upstream from that station.

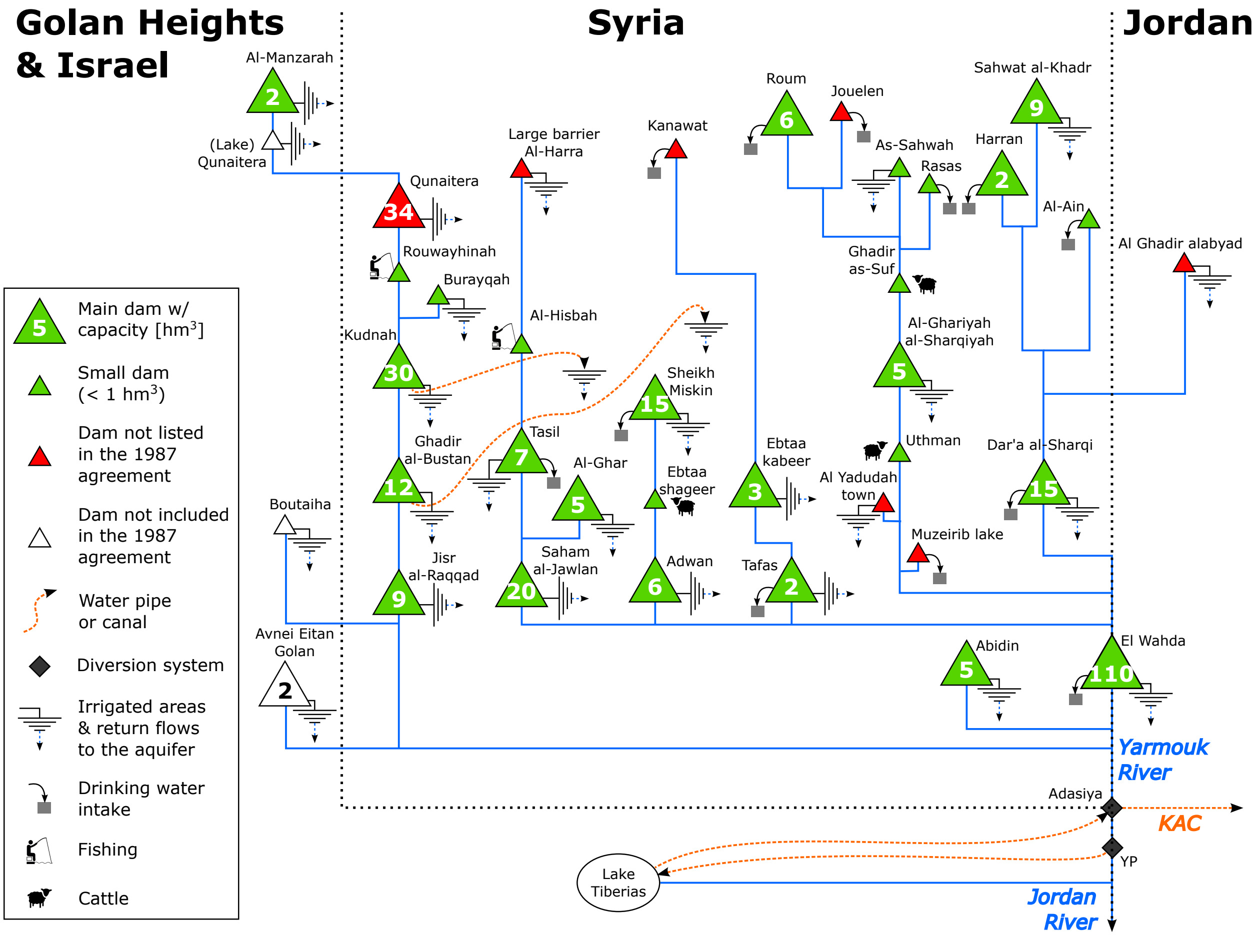

Fig. 3. Reservoirs, usages, wadis and canals detected in the Yarmouk River basin using remote sensing, and Yarmoukeem Pool (YP)–Lake Tiberias–KAC water exchange systems.

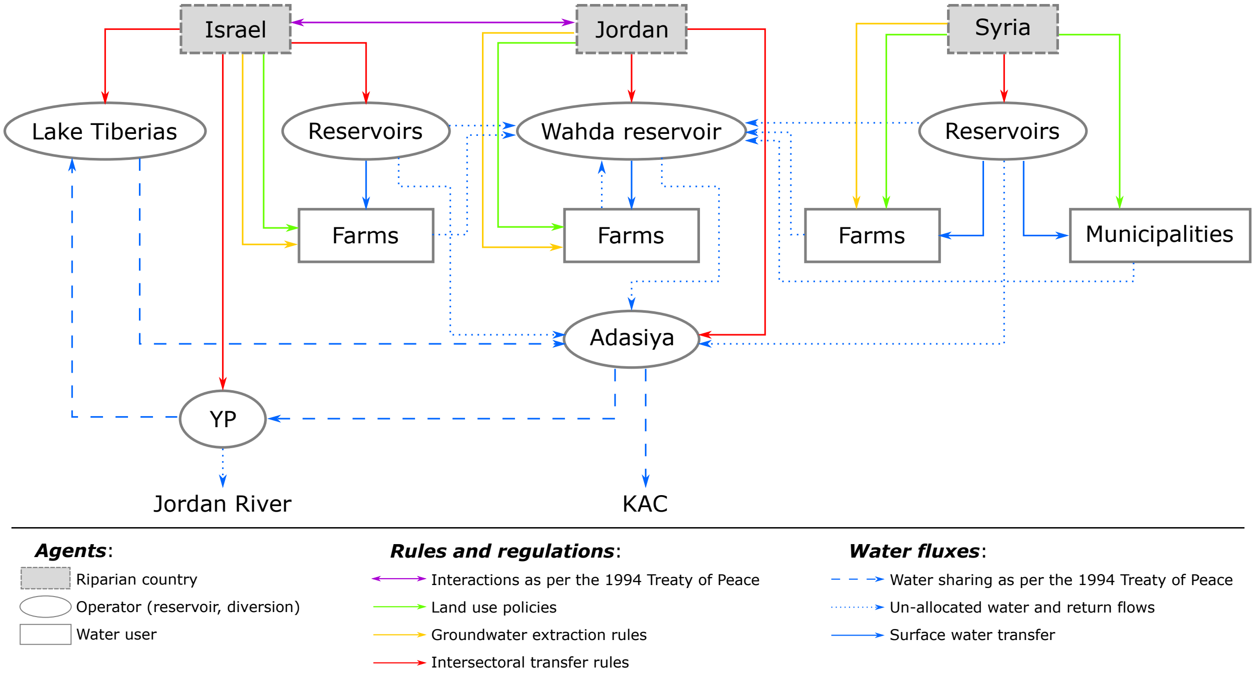

Fig. 4. Multi-agent representation of the Yarmouk River basin water resources system.

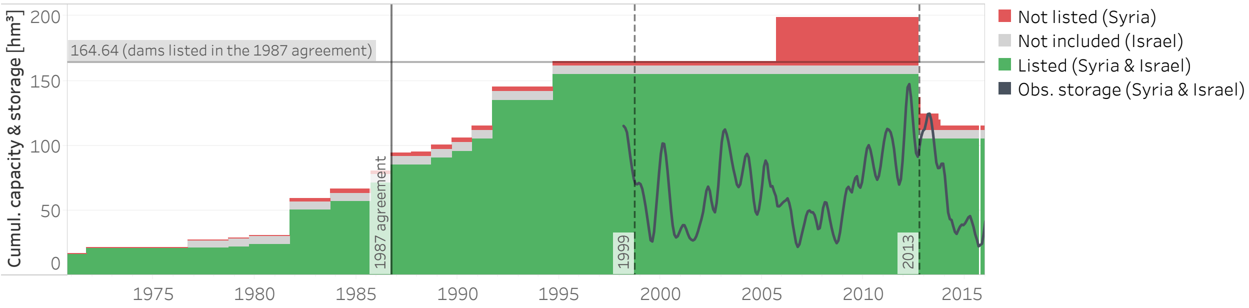

Fig. 5. Cumulative storage capacity and variations in Syria and the Israel-occupied Golan Heights. Capacities are sorted in terms of their inclusion in the agreement between Syria and Jordan 1987. Color codes for capacity categories are the same as in Fig. 1 and Fig. 3.

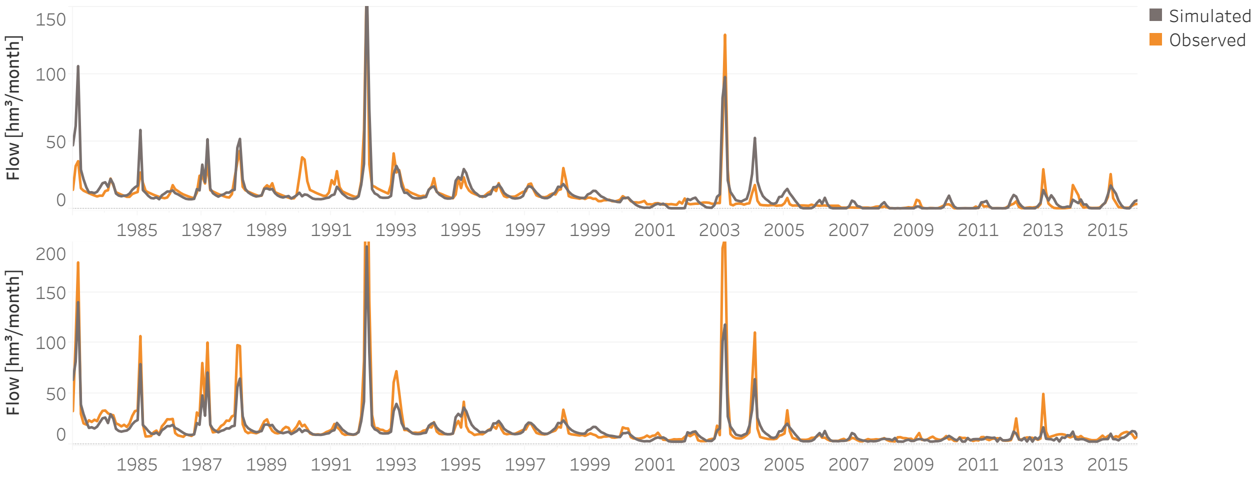

Fig. 6. Measured flows and simulation results of the historical flow at Wahda (top) and Adasiya (bottom) stations.

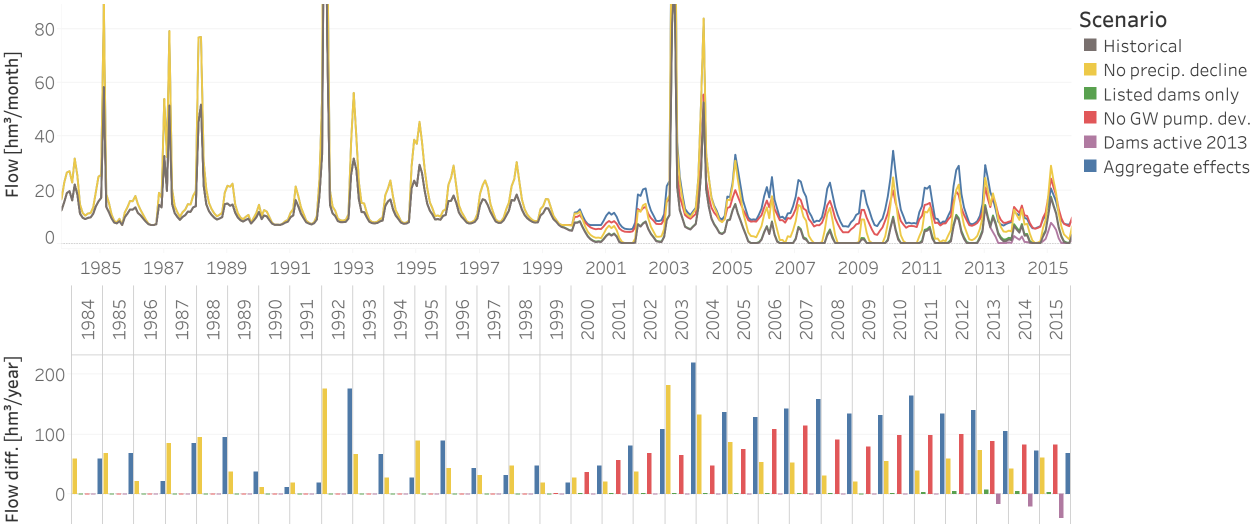

Fig. 7. Simulated flow at the Wahda dam location for the proposed scenarios (top), and water year flow difference with the historical run (bottom).

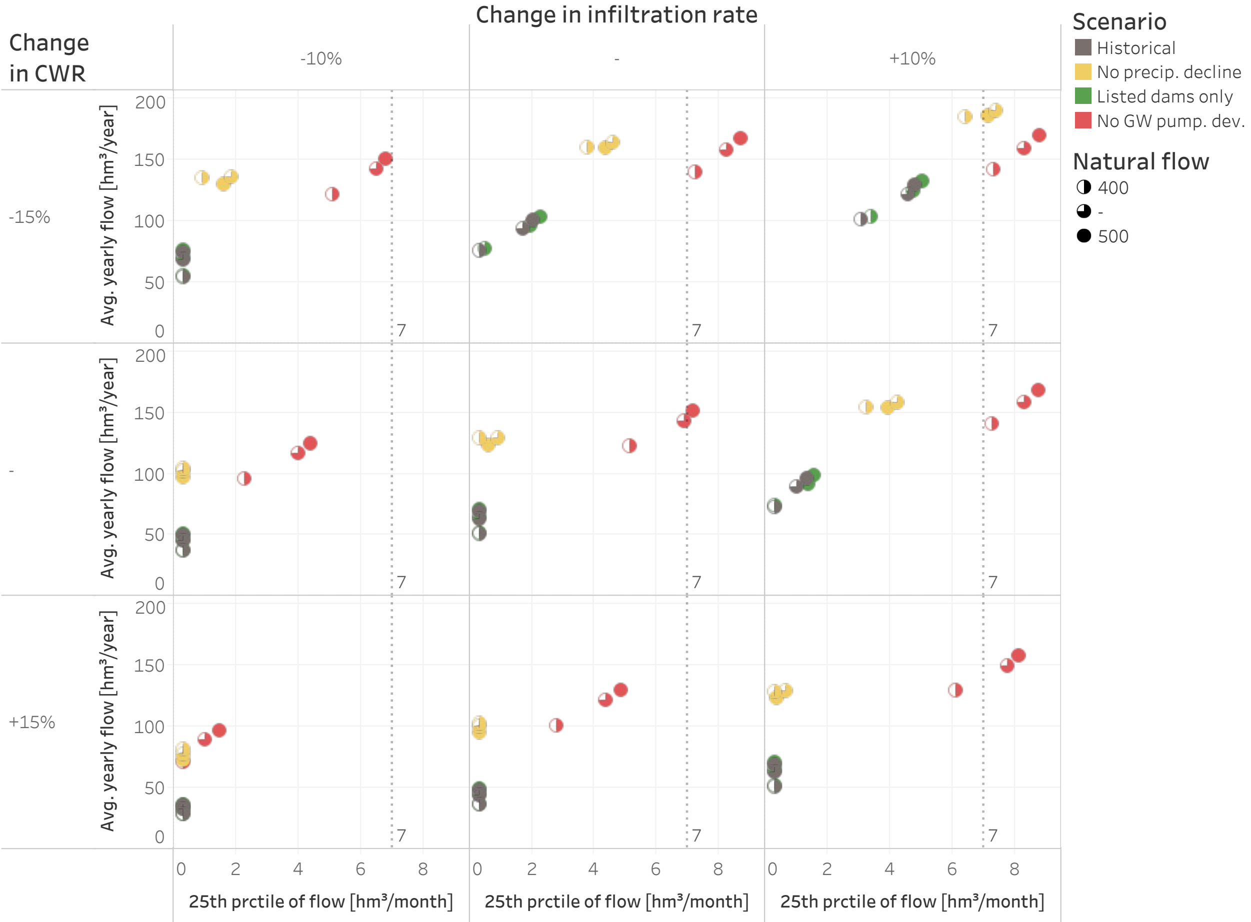

Fig. 8. Sensitivity analysis of the remote sensing-based MAS model to three hydrological parameters (crop water requirements CWR, infiltration, natural flow estimate). “-” refers to the standard value considered in the section Scenarios over the Historical Period. The threshold of 7 hm^3/month for the 25$^{\text{th}}$ percentile of monthly flows indicates the base flow measured at the Wahda dam station by MWI/JVA before the collapse of the Yarmouk River flow in 1999.

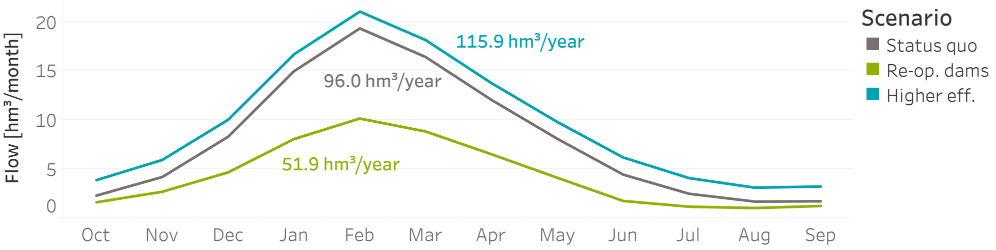

Fig. 9. Simulated flows at the Wahda dam location for future scenarios averaged over the period 2018-2025.