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Article

A Water Resources Planning Tool for the Jordan River Basin

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Abstract: The Jordan River basin is subject to extreme and increasing water scarcity. Management of transboundary water resources in the basin is closely intertwined with political conflicts in the region. We have jointly developed with stakeholders and experts from the riparian countries, a new dynamic consensus database and—supported by hydro-climatological model simulations and participatory scenario exercises in the GLOWA (Global Change and the Hydrological Cycle) Jordan River project—a basin-wide Water Evaluation and Planning (WEAP) tool, which will allow testing of various unilateral and multilateral adaptation options under climate and socio-economic change. We present its validation and initial (climate and socio-economic) scenario analyses with this budget and allocation tool, and invite further adaptation and application of the tool for specific Integrated Water Resources Management (IWRM) problems.

Keywords: Jordan River; climate change; water database; scenario development; water management

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1. Introduction

In many basins around the world increasing water demand is leading to the overexploitation of limited water resources and more frequent and more pronounced periods of extreme water scarcity [1]. Despite broad acceptance of the principles of Integrated Water Resources Management (IWRM see [2]), which calls for a multifaceted approach to resolving water management issues, responses often still focus narrowly on supply side management, or the "hydraulic mission" [3], which includes large-scale infrastructure projects, such as dams, reservoirs and water transfers. The Jordan River basin has been no exception to this. Water resources management in the Jordan River Basin is further complicated by the transboundary nature of most surface and ground water resources as well as the transboundary and contested allocations and uses of water resources [4].

The Jordan River basin as a whole (Figure 1) is subject to extreme water scarcity. Per-capita annual water availabilities in the three riparian countries included in this analysis exceed all typical scarcity thresholds by far (Israel: 325 m^3, Jordan 150 m^3, Palestine 70 m^3, normally the threshold is set at 1,700 or sometimes at 1,000 m^3) [5]. Rainfall in the basin is highly variable in space and time. It ranges from more than 900 mm per year in the north of Israel to less than 100 mm south of the Dead Sea, with rainfall occurring only in the winter months. Most of the runoff is generated in the upper catchment (north of Lake Tiberias), while the lower (southern) part of the basin has only a few significant perennial tributaries (see Table 1). Hence, southern and eastern parts of the basin depend more strongly on water transfers and/or groundwater (GW). Accordingly, the main aquifers are overexploited, e.g., in Jordan by about 100% above recharge rates [6]. Despite many supply and demand management measures already implemented, water resources are seriously overexploited in the basin, most evident from the lack of freshwater flowing in the lower Jordan and the shrinking Dead Sea (sea level drops by about 1 m per year causing new problems, e.g., loss of habitats, cultural heritage, touristic value and also increased groundwater discharge from surrounding aquifers). Water scarcity is expected to worsen in the future, as more than 80% of the global climate models are projecting a decrease in precipitation for the region [7] and continued rapid population and economic growth is increasing water demand.

Figure 1. Jordan River Basin, including the upper catchment north of Lake Tiberias and the lower catchment south of the lake. The upper catchment is shared between Lebanon, Syria and Israel, the lower catchment is shared between Syria (Yarmuk), Jordan, Palestine and Israel. Map source: ESRI Data & Maps, 2006.

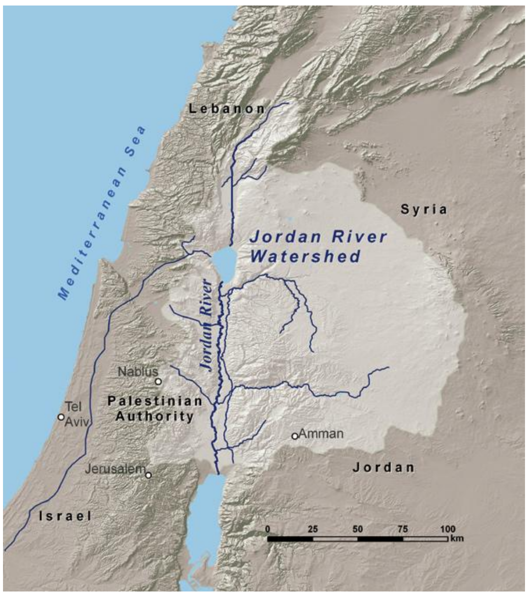


Table 1. Approximate water budget for average year (see data section further below for period over which averaging took place and for details on the method used (in million m^3–MCM)).

Surface Water Supply	**Annual Streamflow (MCM)**
Upper Jordan River (Hazbani, Dan, Hermon)	676
Yarmouk River	495
Zarqa River	85
Lower Jordan River–East side wadis	43
Lower Jordan River–West side wadis	40
Total Supply	1,339
Groundwater and Other Supplies	**Annual Net Production (MCM)**
Mountain Aquifer *–Groundwater/Springs	693
Jordan–Groundwater/Springs	139
Israel–Local Groundwater/Springs	534
Israel–Flood Capture	164
Israel–Desalination	42
Total	1,572
Water Demand	**Annual Demand (MCM)**
Jordan Municipal	100
Jordan Agricultural	103
West Bank Municipal	102
West Bank Agricultural	161
Israel Agricultural–in basin	357
Israel Municipal–in basin	10
Israel Agricultural–out of basin	766
Israel Municipal–out of basin	805
Upper Yarmouk Diversion to Syria	360
Total Demand	2,764

* Israel and West Bank Palestine both draw from the Mountain Aquifer; Note that Israel's desalination capacity has now reached about 250 MCM per year, but we have used an average value (42 MCM) for the baseline situation.

While the riparians of the Jordan River basin (Jordan, Palestine, Israel, Syria, Lebanon–here for data availability reasons only the first three are included) have initiated a number of demand-side measures, the key responses to the increasing water scarcity are still focused on supply-side interventions. In recent decades, large-scale water withdrawals and transfers have reduced flows in the lower Jordan River to about 1/10th of their historic level [8]. Now, even bigger infrastructure projects are underway or planned, in particular a chain of desalination plants along the Mediterranean coast and a new water transfer from the Red Sea to the Dead Sea also to provide desalinated water.

The issues of water scarcity within the Jordan River basin are so pronounced that no proposal (structural or non-structural) is left off the table. The extent to which these efforts can work together to resolve water shortages within the region, however, must be evaluated in the context of hydrological and operational regimes that govern the distribution and allocation of water throughout the basin.

To date, while there have been several tools developed to consider water management within portions of the Jordan River basin [9-13], no tool has been developed for integrated, spatially explicit and basin-wide (trans-boundary) assessments of land and water supply and demand management options. The objective of this study is to report on the development and testing of an analytical, quantitative and spatially explicit IWRM tool that can be used in subsequent studies to evaluate and compare different structural and non-structural water management interventions under a range of uncertainties associated with the evolution of future water supplies and demands. We use the Water Evaluation and Planning (WEAP) system to develop a water resources planning tool for the Jordan River basin. This tool provides a consistent basin-wide framework in which we have consolidated the best available water data from the riparian countries Jordan/Palestine/Israel. The development of the WEAP tool presented here (including the data consolidation, water system configuration, and scenario development) has been undertaken in a continuous dialogue with local project partners and other stakeholders.

With this tool in place, we can begin to address system-wide effects, spatial response patterns, and tradeoffs between different unilateral or multilateral adaptation options, such as new transfer schemes, additional non-conventional water supplies, improved demand management and loss reduction, wastewater reuse and rainwater harvesting. This model will allow for the further testing of different combinations of these options under a range of climate and socio-economic change scenarios, which project future water supply and demand until the year 2050. The WEAP model serves as an integrated database and analysis tool that can be used to evaluate the scenarios which have been generated as part of the GLOWA Jordan River project, as well as other scenarios and strategies.

2. Methods and Data

The WEAP system has been used to consolidate water-related data and to simulate current and future management and allocation rules for the Jordan River basin, as provided by the local project partners. WEAP is a water resources modeling and planning tool, which in its simplest form is similar in structure to other water allocation decision support tools: MODSIM [14], RiverWare [15], HEC-ResSim [16], and Oasis [17]. It also provides advanced features that allow it to link dynamically to other models and software, such as Qual2K, MODFLOW, PEST, Excel, and GAMS. The flexibility of the tool to adapt to different levels of data availability and its user-friendly graphical user interface make it a suitable tool to use in a basin such as the Jordan River, where data can be scarce and stakeholder interest is high [18].

WEAP has been widely used in dozens of basins around the world [19] to support collaborative water resources planning by providing a common analytical and data management framework to engage stakeholders and decision-makers in an open planning process [20-23]. The tool allows for the integration of demand and supply-based information together with hydrological simulation capabilities to facilitate integrative analysis of a user-defined range of issues and uncertainties, including those related to climate, changing human and ecosystem water demands, and infrastructure development. The user-defined demand structure and water allocation priority and supply preference designations drive the linear programming allocation algorithm for the water balance [18].

The WEAP system was selected to model the Jordan River basin because it utilizes a scenarios-based approach that facilitates the exploration of a wide range of demand and supply options for balancing competing operational objectives. Additionally, WEAP allows for a reduced level of complexity to represent water systems, which, in combination with the graphical user interface, facilitates the testing of several scenario combinations independently by policy makers and other stakeholders. The usefulness of this approach has recently been confirmed by the Jordanian Ministry of Water and Irrigation adopting WEAP as a central tool in their Nation Water Master Plan [24]. In the MENA region (in particular in Morocco, Tunisia, Jordan, Palestine, Lebanon, Syria), a WEAP version coupled with the ModFlow groundwater model has been applied to address conjunctive surface and groundwater management [23]. Within the Jordan River basin, WEAP is used to develop and assess a variety of scenarios that explore adaptation measures, such as additional non-conventional resources or water transfers, as well as socio-economic changes or policies affecting population growth or the patterns of water use. A detailed description of WEAP is found in [18].

Within the Jordan River basin, the WEAP model provides a consistent transboundary framework for addressing environmental, technical, socio-economic, institutional and political aspects of water management that could not be addressed in national sub-basin models alone. As described below, these aspects are integrated in WEAP as different scenarios, e.g., of technical development/water use efficiency, as well as socio-economic development in the form of population and GDP growth and associated growth in water demand. Institutional and political aspects have been represented in WEAP via participatory scenario development with stakeholders from all three countries, in particular from the main water management institutions, Jordanian Ministry of Water and Irrigation, Israel Water Authority and Palestinian Water Authority. A separate paper is currently produced on this participatory scenario development [25]. At the same time, WEAP represents the water system at a reduced complexity, which facilitates participatory scenario development and analysis with water managers and other stakeholders within the basin.

The WEAP Model of the full Jordan River Basin has been developed with increasing support from partners in all three countries involved, based on initial national sub-basin WEAP models, e.g., for the upper Jordan River [9], the West Bank [10], Jordan Valley [11] and the Amman-Zarqa basin [12]. The basin-wide WEAP model presented here consistently integrates and aggregates the more detailed databases and topologies of these sub-basin WEAP models.

Most of the data entered into the Jordan River WEAP model have been obtained from–or at least cross-checked by–official sources, *i.e.*, the Jordanian Ministry of Water (MWI) and Irrigation, the Palestinian Water Authority (PWA) and Ministry of Agriculture (MoA) or the Israeli Water Authority (IWA). Improving the underlying data structure and data quality is a continuous ongoing process. All data are checked for inconsistencies and harmonized across countries. The resulting new consensus database presents a major step forward, beyond the only other multi-lateral water database for the Jordan River region from the EXACT project [26] which is static, non-spatially explicit and not available in electronic form. The WEAP database is constantly updated with improved data when these become available. The data entry into WEAP via (.csv) spreadsheets facilitates the update of individual parameters. WEAP then recalculates simulation results based on the latest data.

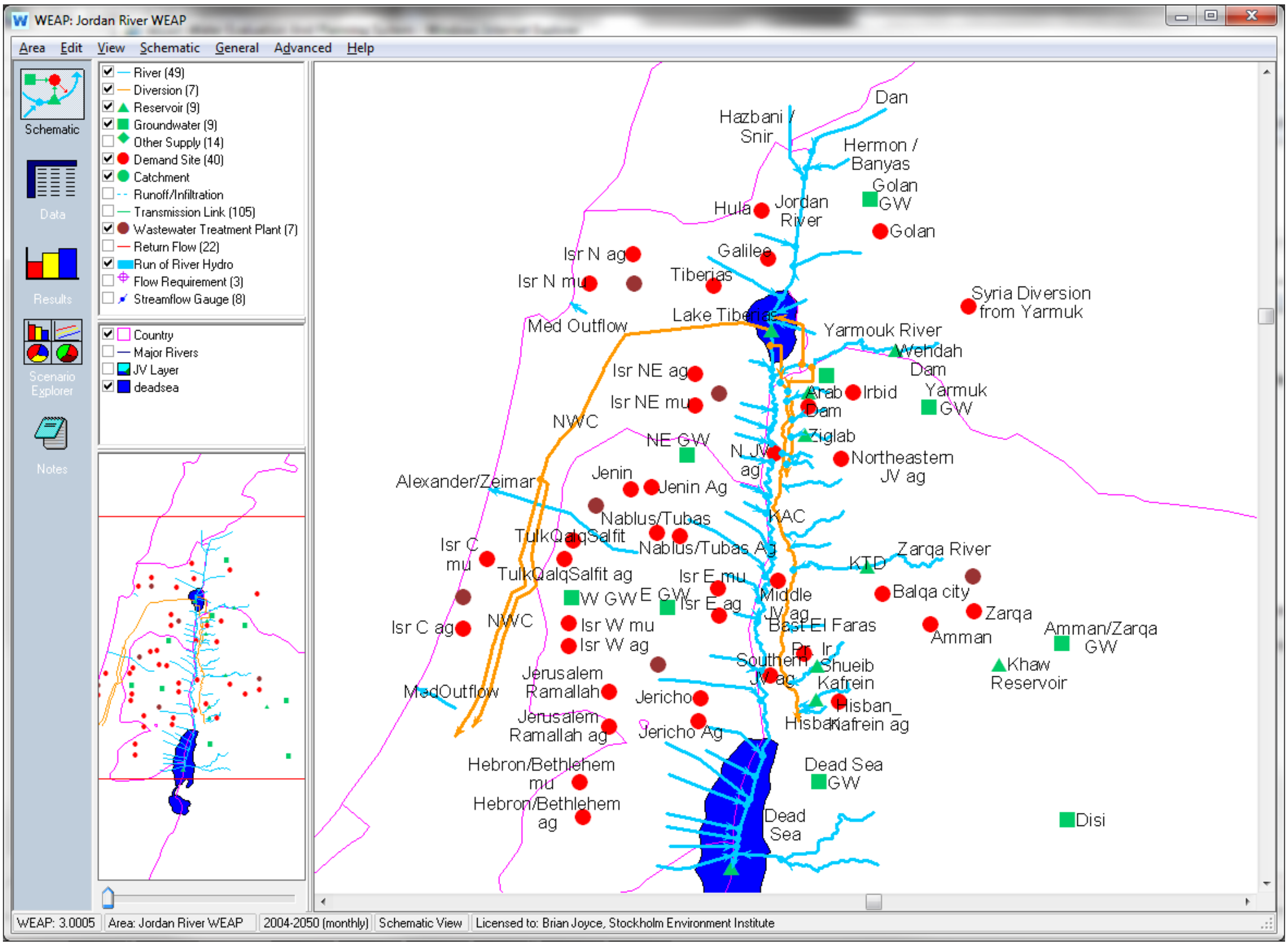
The Jordan River WEAP model is run at monthly time steps, so all input data, irrespective of their original temporal resolution, are aggregated (or in a few cases disaggregated) to monthly resolution. Disaggregation, e.g., for some less well monitored wadis or groundwater aquifers, has been done by overlaying measured annual data with monthly variations from the nearest available basin.

2.1. Network Topology

The geographical focus of the Jordan River WEAP model is the river basin and includes representations of the main water management features within the watershed. This includes all of the major tributaries, the major groundwater aquifers, the main reservoirs/water bodies (Lake Tiberias/Kinneret, the Dead Sea, and Al Wehdah, Arab, Ziglab, Shueib, and Kafrein dams), the major irrigation canal (King Abdullah Canal, KAC which also transfers water to the Jordanian highland); the major trans-basin diversion (the National Water Carrier, NWC, which transfers water from the basin to the coastal plains in Israel), and the agricultural and municipal demands that are associated with these supply sources. Also, relevant external supplies are included in the model, such as the Disi aquifer, which in the future will provide additional water to the basin, and a series of desalination plants along the Mediterranean, which are expected to reduce the demand for water from the NWC.

The WEAP schematic (Figure 2) shows, how the main features of the Jordan River water system have been aggregated and represented in WEAP as so-called supply and demand nodes, transmission links between these nodes and water allocation rules (demand and supply priorities)–not shown.

Figure 2. Conceptual representation/model schematic of the Jordan River water system in WEAP, with Lake Tiberias dividing the basin into an upper (upstream of the lake) and lower (downstream of the lake) part.



2.2. Water Supplies and Demands

The data compiled from the respective national sources describe the temporal and spatial distribution of water supplies and demands for the different parts of the basin. While most of the data is representative of historical conditions from the recent past (*i.e.*, 10–15 years), some of the discharge data for the larger tributaries dates back as far as 1970. These data were used to construct a baseline scenario that represents current water management conditions.

Average annual supply and demand data for the baseline situation are summarized in Table 1. Depending on the type of data, different historical periods were used:

- river and wadi flows use average records for the period 1970–2000, wherever the data was available, the same period was used for groundwater.
- water demands and delivery data is based on 2000–2005, records.
- for water sources being developed (such as desalination or treated waste water) the actual production quantities for the year being referenced were used

Whenever the full historical period could not be obtained, data was taken from shorter time series (e.g., for some eastern side wadis data was only available for the period 1990–2005), or from nearest data series (e.g., for some demand nodes data was only available for the time period 2002–2007).
The data suggest that on an average annual basis total demands account for approximately 95 percent of the developed supplies. When we account for operational constraints and the timing of peak demands, however, we find that total demands are rarely fully met. Also, we calculate agricultural water demands from irrigated areas and associated crop water demands, not from real food demands of the basin population (which are primarily met by importing food and that way saving the amount of water that would be required for local production—also called imports of "virtual water").

This water balance emphasizes the disparity between the relatively wet upper Jordan River catchment with low population density and the drier lower Jordan with higher population density/water demand—and the even higher water demands outside of the basin (which cannot be met by natural water supplies alone—not shown here).

2.3. Surface Water Supplies

The three main tributaries (Hazbani, Dan, and Hermon) in the upper catchment provide the bulk of the Jordan River discharge and feed Lake Tiberias (see Table 1). The next largest tributaries to the Jordan River are the Yarmuk and the Zarqa Rivers in the lower catchment of the Jordan River (*i.e.*, below Lake Tiberias), with the Zarqa River mostly carrying the wastewater of the largest city in the basin, Amman. The western and eastern side wadis of the lower Jordan together represent less than 10% of total basin discharge. The sum of discharge from all tributaries implemented in the regional WEAP model adds up to 1339 MCM per year, which matches the literature value of 1300 MCM [8] well.

Monthly discharge data have been implemented in WEAP for all gauged tributaries to the Jordan River, representing the respective inter- and intra-annual supply-side variability. Many of the smaller tributaries (*i.e.*, wadis), however, do not have sufficiently long or detailed records. Thus, the available data was used to estimate average annual and monthly discharge for each of these wadis.

2.4. Groundwater and Other Supplies

All aquifers in the Jordan River basin were aggregated to the level of detail used in the EXACT project to describe groundwater basins. Groundwater recharge data for each basin from the EXACT database have been supplemented and updated with newly available national data. Each groundwater basin was connected in WEAP through transmission links to all those demand nodes that are known to receive water from it. Groundwater sources are considered to the extent that they contribute to water availability in the Jordan River basin. This may be through direct provision of water to basin's demand nodes or provision of water to other nodes which are connected to the basin (e.g., also GW sources providing water to Israeli demands along the coast, which are also supplied by water from Lake Tiberias), or the provision of water to demand nodes which produce return flows to the Jordan River catchment (e.g., water from the Azraq basin supplied to municipal demands in Amman, which return wastewater to the Zarqa river).

2.5. Agricultural Water Demands

Agricultural water demands from national statistics were aggregated to the main irrigation districts in the Jordan Valley (northern, middle and southern), in the upper Jordan River catchment, and to six aggregated West Bank governorates. Other agricultural demands outside of the basin (in Israel) have only been included to the extent that they affect water withdrawals from the Jordan River (through the National Water Carrier) or from the Mountain Aquifer.

Each agricultural demand node represents the respective agricultural area multiplied by the average irrigation requirement per hectare in the respective part of the basin. Areas and area-specific irrigation requirements were implemented individually in WEAP for the main crops in each node as detailed as available.

We only account for blue (*i.e.*, irrigation) water use at this stage (future efforts will add green water, *i.e.*, rainfed agriculture). Where real agricultural water use and withdrawal data are not available (in particular the Jordanian demands in the Jordan Valley), we use in WEAP net irrigation requirements, calculated according to [27]. With that we underestimate the agricultural water demand, due to the difference between gross and net irrigation requirement. We simulate in WEAP the observed seasonal pattern of irrigation with two cropping seasons in the Jordan Valley, one in spring and one in fall, and one cropping season with maximum irrigation water requirement in summer in the rest of the basin. More detailed crop water use functionalities implemented in the WEAP-Mabia module (similar to the CropWat model of the Food and Agriculture Organisation (FAO) will be used in more detailed analyses of irrigation water demands and gaps that will be described in subsequent papers.

2.6. Municipal Water Demands

All municipal demands drawing water from the Jordan River basin are captured in WEAP as aggregate municipal demand nodes. Each node represents the respective population multiplied by the average per capita water demand in that area. Municipal demands in the West Bank for example are represented by one demand node per aggregated governorate. Given the severe resource and political restrictions in Jordan and the West Bank respectively, which constrain the municipal water use, we agreed with local project partners to apply a hypothetical per capita demand of about 50 m^3 per year which is slightly higher than the WHO recommendation of 130 L per day (or 47.5 m^3 per year). Israeli municipal demands are represented in WEAP by real per capita consumption taken from national statistics.

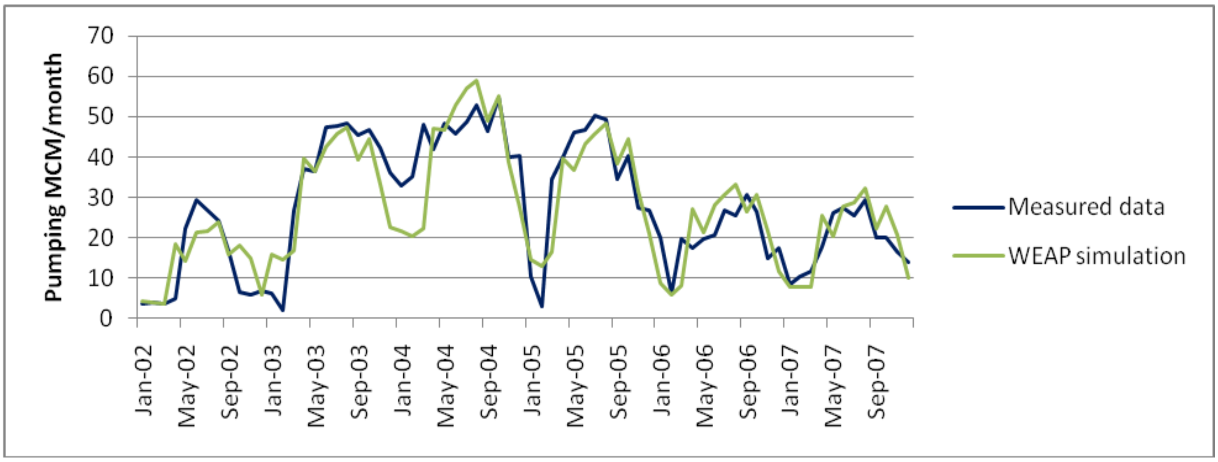
In this study, we have applied WEAP in its basic form as a water budget and allocation model, without using any of the WEAP options to simulate individual processes (such as runoff generation, groundwater recharge, vegetation or crop water use, *etc*.). As such, WEAP simulation results entirely depend on the quality of the input data (e.g., river discharge, groundwater recharge, urban and agricultural demands, *etc*.) in combination with the topology of the water system (*i.e.*, the location and interlinkages of demand and supply nodes), and the priorities specified for water demands, supplies and allocations.

Hence, calibration and validation of model's process parameters and simulations in a strict sense (e.g., comparing simulated against measured river discharge) is not possible. However, we have validated some of the key system components, *i.e.*, the main aquifer (Western Mountain Aquifer), the main reservoir (Lake Tiberias), and the main water transfer (National Water Carrier) for their water stores and fluxes against independent measurements.

2.7. Validation for Pumping from the National Water Carrier

Water demands in the Mediterranean coastal plains of Israel are largely met from the National Water Carrier (NWC), which transfers water from the upper Jordan River that is stored in Lake Tiberias. Pumping of water through the NWC is driven in WEAP by all demands which are linked to this conduit, and it is constrained by the availability of water in the Lake. Since most demand nodes connected to the NWC are also linked to additional surface and groundwater nodes, we implemented demand priorities, access restrictions and intra- and inter-annual variation according to the specifications of our Israeli partners, in order to represent the system realistically. We have then validated the NWC pumping by comparing the rates at the outlet of Lake Tiberias as simulated by WEAP with official pumping rates provided by the Israeli Water Authorities for the years 2002 to 2007, showing good agreement (Figure 3).

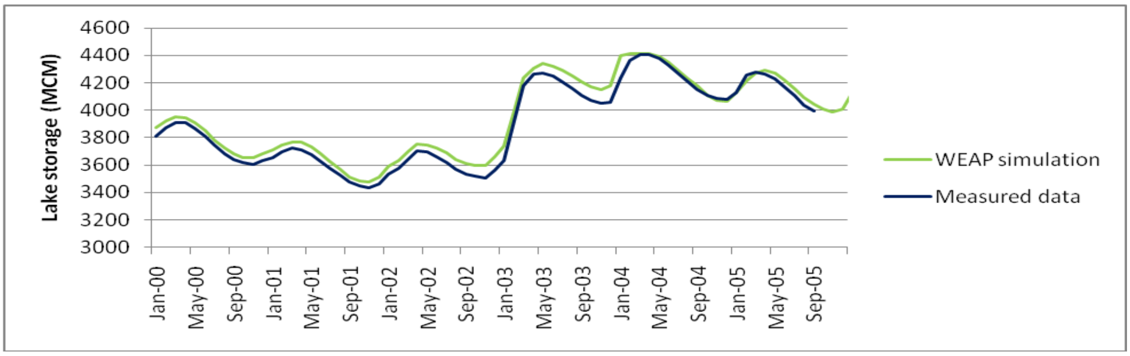
Figure 3. Comparison of WEAP simulated *vs*. measured pumping by the NWC (in million cubic meters–MCM per month).



2.8. Validation for Lake Tiberias Storage

WEAP integrates all river discharges and consumptive water uses of the upper Jordan River catchment as inflows into Lake Tiberias (see Figure 2). We used all available discharge measurements and demand data from the upper catchment including also the pumping from the Lake by the NWC. Missing demand data were filled with aggregated demands from the sub-basin WEAP model by [10]. We then compared the resulting lake storage changes over time, simulated by WEAP with measured values [28,29]. WEAP simulations match the measured values which were obtained for the years 2000 to 2005 well (Figure 4).

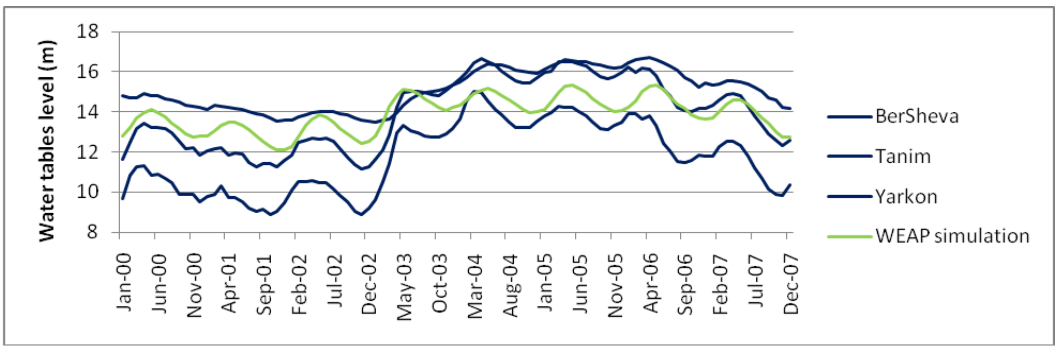
Figure 4. Comparison of WEAP simulated *vs.* measured lake volume in million cubic meters (MCM).



2.9. Validation for the Western Mountain Aquifer

The Western Mountain Aquifer is a main water source providing water to Israeli and Palestinian demands within Israel and the West Bank. The transboundary groundwater aquifer also provides spring water and is subject to artificial recharge. In order to validate the overall balance of abstractions, spring flows and recharge, measured changes of the groundwater tables were compared to the groundwater tables simulated by WEAP in Figure 5. In WEAP groundwater was implemented without accounting for dynamic flows within the aquifer. Figure 5 compares the change of the average water table of the aquifer with the measured water tables of three representative groundwater wells for which data could be obtained for. The overall balance and the general behavior of the stored water in the aquifer are reproduced correctly.

Figure 5. Comparison of WEAP simulated average change in aquifer level *vs.* measurements in different parts of the Western Mountain Aquifer.



In the lower Jordan below Lake Tiberias, validation against measured flows or storage is not yet possible, but subject to ongoing GLOWA research. Due to excessive water withdrawals in the upper Jordan and Yarmuk, discharge of the lower Jordan River has been reduced to less than 10% of the natural flow [8]. The only remaining flow in the lower Jordan consists of aquifer inflows of unknown quantity and highly polluted effluents, saline spring deviations and occasional flash floods. It cannot be used yet to calibrate or validate the WEAP model.

2.10. Scenario Analysis with WEAP

The Jordan River WEAP model as described above allows for the analysis of various global change and water management scenarios. Scenarios are self-consistent story-lines of how a future system might evolve over time. These can address a broad range of "what if" questions [30]. This allows us to evaluate the implications of different internal and external drivers of change, and how the resulting changes may be mitigated by policy and/or technical interventions. For example, WEAP can be used to evaluate the water supply and demand impacts of a range of future changes in demography, land use, and climate. The result of these analyses can be used to guide the development of adaptation portfolios, which are combinations of management and/or infrastructural changes that enhance the water productivity of the system.

Initial supply-side scenarios within the WEAP model have been based on another sub-project of GLOWA and the work of [31,32], who implemented outputs from the ECHAM 4 global climate model and the MM5 regional climate model [33] in a hydrological model (TRAIN) to evaluate future water availability as well as future irrigation water demand. While hydro-climatological scenarios based on different emission scenarios, different global and regional climate models and different hydrological impact models always span a wide range of future water situations, we have based this initial WEAP analysis on the outcome of a “middle-of-the-road” (*i.e.,* the SRES A1B climate scenario which assumes a moderate increase in greenhouse gas emission), according to which water supplies may be reduced by 30 percent and irrigation water demand may increase by 22 percent by the middle of the 21st century compared to the 1990s. For the purposes of WEAP scenario development, these changes were implemented in WEAP via linear reductions over time in mean annual discharge and groundwater recharge for all supply nodes, and a linear increase in irrigation water demand for all agricultural demand nodes.

This simplified approach presumes that the issues of water scarcity will magnify, while the pattern of wet and dry years remains unchanged. In reality, droughts are likely to increase in frequency and intensity [7], which may in fact pose more severe risks to the Jordan River water system than changes in annual averages. To assess the vulnerability of the system to these changes, it will be necessary to consider ensembles of scenarios that describe the full range of hydro-climatological variability. Addressing the uncertainty associated with these projections and their impact on water management is the focus of our ongoing research.

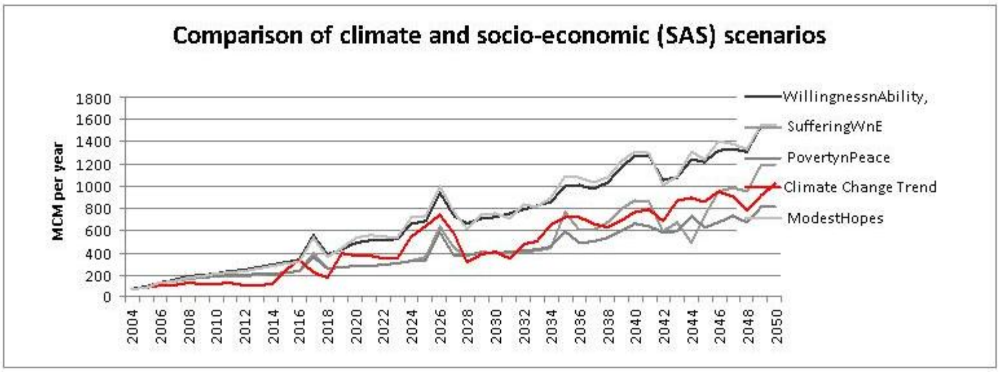
As part of yet another subproject of GLOWA, initial socio-economic scenarios of future water demand are being developed jointly by scientists and stakeholders from all partner countries, in a so-called Story And Simulation (SAS) approach [25, 30]. Based on agreed upon storylines and expert judgment, population growth, economic development, and technological trends have been consistently projected into the future until the year 2050. The resulting four quantitative scenarios cover different combinations of high or low economic growth and high or low degree of transboundary collaboration over water. For each of the four scenarios, the resulting trends in water demand were calculated separately for Israel, Jordan and the West Bank. To our knowledge, this is the only scenario exercise for the Jordan River basin that combines qualitative expert knowledge with quantitative science-based results. However, the development of these scenarios is an ongoing iterative process and the figures presented here (Figure 6) are therefore provisional. Further scenario analysis will focus on different adaptation options and their effectiveness under the global change scenarios described above.

3. Results

The Jordan River represents one of the most severe cases of a “closed” basin [1], with all of its blue water resources fully allocated and some severely overexploited. The Jordan River basin has developed over the past half century into a very complex system of strongly interconnected water supplies, demands and transmissions [34]. Several external and internal drivers of change are constantly increasing pressure on the—mostly transboundary—water resources, while adaptation measures have generally been implemented unilaterally and not across sectors.

The Jordan River WEAP system represents this situation at reduced complexity by aggregating supplies and demands in a limited number of nodes and transmission links, based on the latest available data from key national institutions such as the Jordanian Ministry of Water and Irrigation (MWI), the Palestinian Water Authority (PWA) and Ministry of Agriculture (MoA) and the Israeli Water Authority (IWA). Within the GLOWA project consistent demand and supply scenarios have been developed in a continuous dialogue with these Israeli, Jordanian and Palestinian stakeholders and based on state-of-the-art hydro-climatological scenarios. Implementing the results of these efforts enables an initial comparison of the effects of future changes and adaptation options, as a basis for more detailed analyses of specific management aspects. Representative for the type of analysis which the Jordan River WEAP model enables–and which will be undertaken in future detailed studies, we present in Figure 6 a projection of annual basin-wide unmet demands for four different socio-economic demand scenarios (assuming no climate change) and one climate change scenario (assuming no change in demand, except for climate driven increase in irrigation water demand) as described in the methods chapter.

Figure 6. Projections of basin-wide annual unmet demand for four different socio-economic (SAS) scenarios and a "middle-of-the-road" (SRES A1B) climate scenario. The four socio-economic scenarios depicted in Figure 6 stand for the four different combinations of positive regional economic development *vs.* economic recession and regional collaboration *vs.* unilateral actions.



By comparing the relative changes over time between these scenarios, we find similar contributions to future unmet demands from GLOWA's socio-economic (demand) and climate (supply) projections. Furthermore, this initial analysis indicates that by middle of the 21st century, the change in unmet demands is likely to significantly exceed current variability in unmet demand. Figure 6 also shows that the assumptions, used in socio-economic scenarios about population and economic development, have strong effects on future (unmet) demands. In the course of the development and testing of the Jordan River WEAP model, we found this to be a suitable tool for communicating to water managers the effects of different scenarios and the associated uncertainties, and for further analyzing system responses to changes in the underlying assumptions [35]. This assessment was confirmed by the decision of the Jordanian Ministry of Water and Irrigation to adopt WEAP as central tool in their National Water Master Plan. Recently also the Palestinian Water Authority is increasingly employing WEAP in its assessments.

4. Discussion

We have jointly developed with local partners a new basin-wide water database and a scenario planning tool—WEAP—which enables for the first time, the visualization of the combined effects of different socio-economic development trajectories under different climate change scenarios and corresponding adaptation options.

The climate scenario selected for this initial study (SRES A1B) is based on greenhouse gas emission projections, which are below the actual trends [36,37]. Further analysis of climate change effects, based on more realistic trends, can be expected to arrive at much stronger reductions in water availability and stronger increase in irrigation demand. More rigorous analysis of potential climate change effects on water resources in the Jordan River basin will evaluate a range of emission scenarios and hydro-climatological realizations as well as the GLOWA multi-model ensemble mean scenario.

The socio-economic scenarios have been developed as consensus storylines jointly with experts from the key ministries and water authorities from Jordan, Israel and Palestine. Accordingly they are based on the best available expert knowledge on relevant driving forces such as population growth, economic and technological development, land use, *etc*. For a complete basin perspective, it would be desirable to integrate the Lebanese and Syrian expertise and perspectives in future WEAP development.

Also based on the GLOWA stakeholder dialogues, a number of initial stylized adaptation options have been included in this proof-of-concept Jordan River WEAP model, including:

- Disi aquifer, assuming a transfer of 125 MCM/yr fossil groundwater to Amman, starting in 2015 [38]
- Desalination along the Mediterranean coast, assuming a stepwise increase in desalination capacity from currently about 250 to 700 MCM/yr by 2015, primarily for meeting demands in the coastal cities
- Red Sea–Dead Sea Conduit, assuming a delivery of 600 MCM/yr of desalinated water to southern and middle Jordan and southern West Bank and Israel after 2020 [38]
- Agricultural demand management, assuming a uniform reduction in agricultural demands by 50% (which would increase virtual water dependency from about 80% now to about 90%)
- Municipal demand management, assuming a reduction of all losses by 50%, *i.e.*, to a level common in other regions of the world
- Rainwater harvesting, assuming harvestable amounts per sub-catchment according to [39,40]
- Wastewater treatment, assuming sufficient new treatment capacity in the north of Jordan and in the West Bank to treat and reuse all municipal wastewater

However the analysis of the basin-wide and spatially explicit effects of these adaptation options is still ongoing, so we cannot present results yet.

The integration of available supply and demand data with system linkages and feedbacks in a consistent framework, as developed with the Jordan River WEAP model, will enable a new level of IWRM planning, by assessing different combinations of local and global change effects and different portfolios of adaptation as well as water reallocation options. The transparent structure and user-friendly options for updating data and scenario assumptions provide a good basis for participatory and problem-oriented analyses as well as for negotiations over reasonable and equitable water use such as described in Brooks *et al*. [4].

Some of the limitations of our approach are related to the fact that collaboration/joint model development and evaluation between Israeli, Palestinan, Jordanian partners and in particular with Syrian/Lebanese partners is difficult or not possible at all for political reasons. While this is of limited relevance at this stage for the Lebanese sub-basin, due to the low water resource development, the omission in WEAP of detailed infrastructure development in Syria could be of concern [see e.g., 5]. For the moment, we have used uniform reduction in the flow rate of the Yarmuk River as a proxy.

Another limitation is the heterogeneous availability of water data across the basin, in particular for groundwater data. We are addressing this gap by developing in GLOWA detailed WEAP-ModFlow applications [41] and underlying detailed databases for individual aquifers. Furthermore the lack of reliable projections of future climate variability [7] reflects in our WEAP simulations. We are only now beginning to assess the full range of uncertainties across all climate scenarios and global and regional climate models associated with changes in variability and annual averages.

Lastly, the specific situation of the lower Jordan, with only a few percent of the natural runoff remaining, fed primarily by wastewater return flows, deviated saline spring discharge and occasional flash floods [8], does not currently allow a full hydrological validation. With the limited validation of key system components, we can only show that we represent the major system components and behavior correctly. For other details, our analysis represents more a sensitivity analysis than a calibrated and validated simulation in a strict sense.

5. Conclusions and Outlooks

To our knowledge, this is the first trans-boundary, quantitative and spatially explicit scenario analysis of the Jordan River water system under global change. It indicates that climate and socio-economic change are both key drivers of future water scarcity in the basin. The fact that some of the socio-economic scenarios result in higher, and others in lower, total unmet demands, compared to the business-as-usual scenario, indicates that population and economic policies play a crucial role in ensuring future water security in the Jordan River basin. The Jordan River WEAP model can support more detailed policy analysis towards this end.

According to the WEAP principle of keeping the system representation as simple as possible without losing the key structures and functions, water supplies and demands have been represented as highly aggregated nodes. Based upon this initial Jordan River WEAP model, it is now possible to specify system characteristics and processes in more detail—e.g., individual crops and their irrigation requirements, technologies for improving water use efficiency, water quality restrictions for certain uses, benefits from institutional change and related water reallocations, *etc*.—depending on the question to be addressed.

We have limited the initial analysis of the Jordan River to the basic functions of WEAP, without using its capabilities of simulating hydrological processes ("catchment nodes") or crop water use (Mabia module) or coupling to a groundwater model (WEAP-ModFlow). These options will be used for in-depth analyses of specific sub-systems of the Jordan River basin and mitigation potentials of non-conventional water, wastewater re-use, green water use in rainfed and runoff agriculture, *etc*.

Further WEAP-based analyses will also address tradeoffs for different adaptation options, not only in terms of the volumes of additional water generated or saved, but also for their affordability, effectiveness, spatial distribution and degree of centralization. For example, small-scale distributed rainwater harvesting and supplementary irrigation systems in combination with water savings in agriculture, may increase resilience against future shocks and surprises through their inherent diversity and redundancy [42,43], compared to a single large-scale water transfer scheme such as the planned Red Sea—Dead Sea Canal (RDC). Future water system analyses with WEAP will also account for improved green water management, which can help to reduce the pressure on blue water resources [44,45].

Another important consideration in adaptation planning is the water-energy nexus. Given that the Jordan River region is deficient in water and and at the same time in conventional energy resources (not in solar energy though), the high energy intensity of adaptation options such as seawater desalination or pumping of RDC water from below sea level to the highlands has to be taken into account in future IWRM strategies. For possible integration of WEAP-based water assessments with energy assessments see [46]. WEAP-based cost benefit analyses need to take future increases in energy costs of different adaptation options into account.

With that outlook, we invite further collaboration on WEAP-based assessments, tailored to the respective analytical question and stakeholder requirements, and on improving the underlying Jordan River data base, and thereby the reliability of the scenario analyses.

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