An assessment of strategies for sustainability priority challenges in Jordan using a Water-Energy-Food Nexus approach

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An assessment of strategies for sustainability priority challenges in Jordan using a Water-Energy-Food Nexus approach

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Abstract This study aimed at supporting robust decision-making for planning and management of water-energy-food Nexus systems in the country of Jordan. Nexus priority challenges in Jordan were identified as 1) water scarcity, 2) agricultural productivity & water quality, and 3) shift to energy independence. We created a water-energy-food Nexus model that integrates three modelling frameworks: 1) the Water Evaluation and Planning system WEAP model to estimate water demands, supplies and allocation; 2) the MABIA model to estimate crop production, and, 3) a GIS-based energy modelling tool to estimate energy requirements of the water system. Through a set of scenario runs, results show how desalination is needed to address water scarcity, but it has to be coupled with low-carbon electricity generation in order to not exacerbate climate change. Improving water productivity in agriculture improves most of the studied dimensions across the water-energy-food security nexus; however, it does little for water scarcity at the municipal level. Reducing non-revenue water can have positive effects on municipal unmet demand and reduction of energy for pumping, but it does not improve agricultural water productivity and may have negative feedback effects on the Jordan Valleys aquifer levels. Energy efficiency can support energy intensive projects as desalination by substantially reducing the load on the energy system, preventing increased emissions and achieving a more resilient water system. Finally, when all interventions are considered together all of the major drawbacks are reduced and the benefits augmented, producing a more holistic solution to the WEF Nexus challenges in Jordan.

Keywords Nexus · WEF · WEAP · MABIA · GIS ·

1 Introduction

To accomplish the 2030 sustainable development agenda and its 17 Sustainable Development Goals (SDGs), it has been proved to be essential to account for the strong interconnections between SDGs and their underlining systems [1,2]. Often, those interlinkages are evaluated as connections between biophysical systems as the water, energy and food (WEF) Nexus [3]. This approach brings clarity about the positive and negative consequences that an action towards one system can have upon the other systems [4,5,6], and calls for transformational changes in the way we manage strategic resources like water, energy and food [5].

Historically, strategies and policies for water, energy and agriculture systems have been produced independently (i.e. in silos), not accounting for interconnections between the three systems. In response, analytical frameworks on the WEF Nexus have been shown to be instrumental to achieve a holistic management of

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resource systems [7,8,9,10]. Nexus studies have been implemented in a variety of geographical settings, including transboundary aquifers [10,11,12], river basins [9], national [13], regional [14] and city cases [15]. Many of such studies have been focused on the Near East and North Africa (NENA) region [8]. This can be attributed to the increasing water scarcity in the region, which not only jeopardizes food security, but also puts pressure in groundwater aquifers and increases energy needs for groundwater pumping.

Jordan share similar challenges as its NENA neighbors, which has increased the need of Nexus studies in the country [16,17,18,19]. Jordan is a natural-resources-scarce country with as much as three-quarters of its land covered by deserts. This is translated into one of the lowest renewable water resources available per person in the world (i.e less than 100 m3 per year) [20]. In consequence, safe water abstraction yields are often exceeded, which has led to overexploitation of aquifers [21]. The majority of withdrawals are of groundwater (59%), followed by surface water (27%) and treated wastewater (14%) [20].

The dependence on groundwater resources requires growing amounts of energy for pumping, due to the decreasing water table levels of almost all aquifers in the country [22]. As a result, around 14.9% of the supplied electricity in the country is consumed by water pumping and other water services. Moreover, additional energy requirements are foreseen with expanding water supply through desalination and wastewater treatment. In contrast, due to the limited domestic conventional energy resources, Jordan relies on fossil fuel imports to supply its energy needs (i.e. mainly oil and natural gas). Imported energy covered around 93% of the domestic demand in 2018 [23]. These creates the need for Jordan to develop strategies to increase its energy independence through e.g. Renewable Energy Technologies (RETs). Installed capacity of RETs increased from 18.5 MW to 1,130 MW between 2014 and 2018, and to around 1,900 MW in 2020, reaching around 15% share of the generated electricity [23,24]. These has the potential of supporting the water sector activities while increasing energy security.

On the other hand, the agriculture sector accounts for the largest share of water demand (52%), where again, groundwater is the main source [20]. Only 30% of the agricultural land is irrigated, however, it represents 90% of the agricultural production. Furthermore, as consequence of its water-scarce nature, Jordan faces increasing food insecurity being forced to import around 87% of its food [25].

Although, to date, a number of Nexus studies have been implemented in Jordan, most of them have focused on analysing the water-poverty [17] or the water-energy Nexus [18,19]. The WEF Nexus was considered by [16], but only the water-for-agriculture needs were evaluated and its related energy requirements, not accounting for the intricate connections that the national water-energy-food system posses. Thus, the aim of this study is to support a transformational change into WEF systems planning and management in Jordan. We implement an integrated model that couples a water balance model with an agricultural production model, and a Geographic Information System (GIS)-based energy model, capturing key spatial factors along the country. We show how evaluating solutions to the water scarcity problem trough a WEF Nexus lens, provides deeper understanding into the intersectoral challenges and can support decision-making for a more sustainable future.

2 Background

As part of this study, a participatory approach was used involving key actors on the WEF Nexus in Jordan. This approach consisted of a stakeholder-driven and model-supported robust nexus decision-making framework [26], combining methods from the FAO WEF methodology [27] and the Transboundary Basin Nexus Assessment (TBNA) methodology developed by the United Nations Economic Commission of Europe (UNECE) [9,28]. Two Nexus Dialogue workshops were delivered with the aim of identifying pressing challenges, potential solutions and achieving a better comprehension of the Nexus dynamics in the country. Both workshops involved key decision makers and stakeholders – i.e. experts, resource managers and policy-makers – in Jordan to articulate their goals, challenges they face and potential solutions. These activities consisted of Problem Formulation Exercises taking place in March and December 2019. The main goal of these workshops was to solicit input from the key actors groups involved in the governance of the resources in question. This enabled us to define the scope of the analysis towards integrated solutions for sustainable planning. Insights from the stakeholders revealed the demands, opportunities and constraints of their system, identifying sectorial challenges (i.e. Water, energy and food sectors) and the effects that the challenges trigger on the other sectors (details in the *supplementary information*). The priority challenges identified were 1) **water scarcity** with the highest priority, followed by 2) **agricultural productivity & water quality**, and 3) **shift to energy independence**.

Building on the inputs received from the workshops, we developed a WEF Nexus model to evaluate possible outcomes of instituting policy and infrastructure strategies. These aimed at solving priority challenges under a wide range of critical uncertainties through scenario exploration.

3 Methods

3.1 The WEF Nexus quantitative model for Jordan

In light of the challenges and potential solutions identified in the participatory approach and in order to inform sustainable development, we developed a WEF Nexus model allowing stakeholders to assess the impact of selected nexus interactions. The model is based on the integration of three modelling frameworks: 1) the Water Evaluation and Planning system (WEAP) model: to estimate water demands, supplies and allocation in order to assess the sustainability of the water system; 2) the MABIA model: to estimate crop production based on the availability of water, and, 3) a GIS-based energy modelling tool: to estimate the energy requirement for water pumping, water desalination and wastewater treatment (see Figure 1).

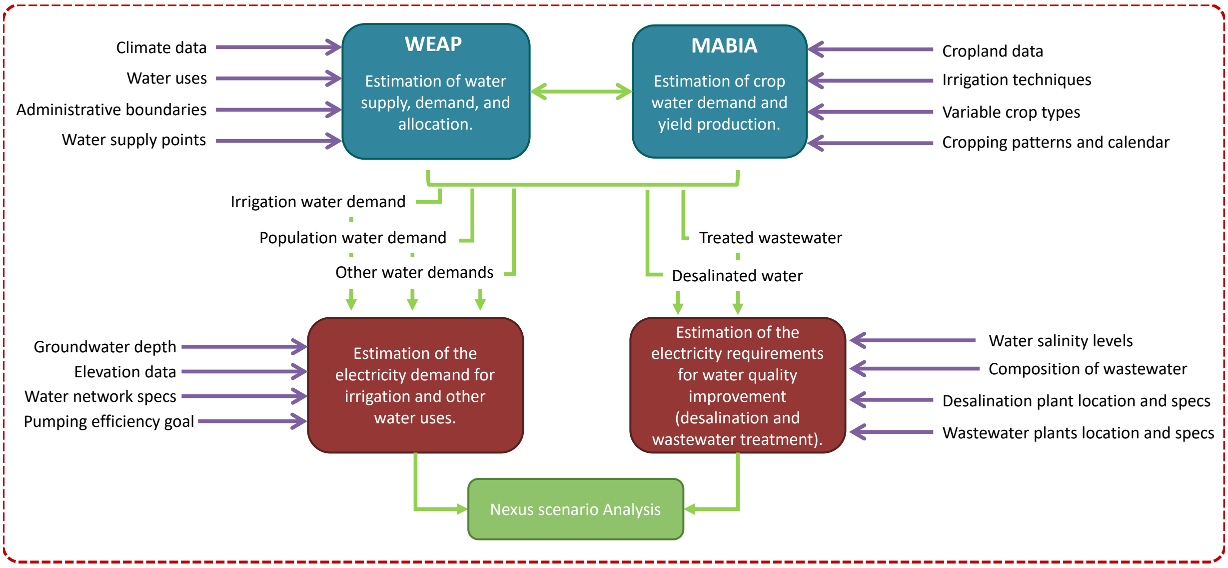


Fig. 1: Methods and data flows.

The model uses WEAP and MABIA to estimate water supplies based on climate-driven hydrological routines that calculate rainfall runoff and groundwater recharge. It estimates usage patterns for the main water sectors, evaluates the productivity of cropping systems under different climate futures and assess their impact on the water system. The energy component implements GIS-based methodologies to estimate energy requirements for groundwater and surface water pumping, new water desalination projects and major wastewater treatment plants. Finally, different scenarios are evaluated for solutions targeting at least one of the challenges, and an integration of all tested solutions.

3.2 The WEAP hydrological and agricultural model

Over the past decade, the Jordanian Ministry of Water and Irrigation (MWI) has developed a water resources allocation model in order to assess potential strategies to address the gap between water supplies and demands (see Figure 2). The model considers the distribution and consumption of water resources in Jordan through:

- Water demand: 94 water demand sites aggregated by governorate, including domestic, commercial, refugees, tourism, industrial and agriculture use.

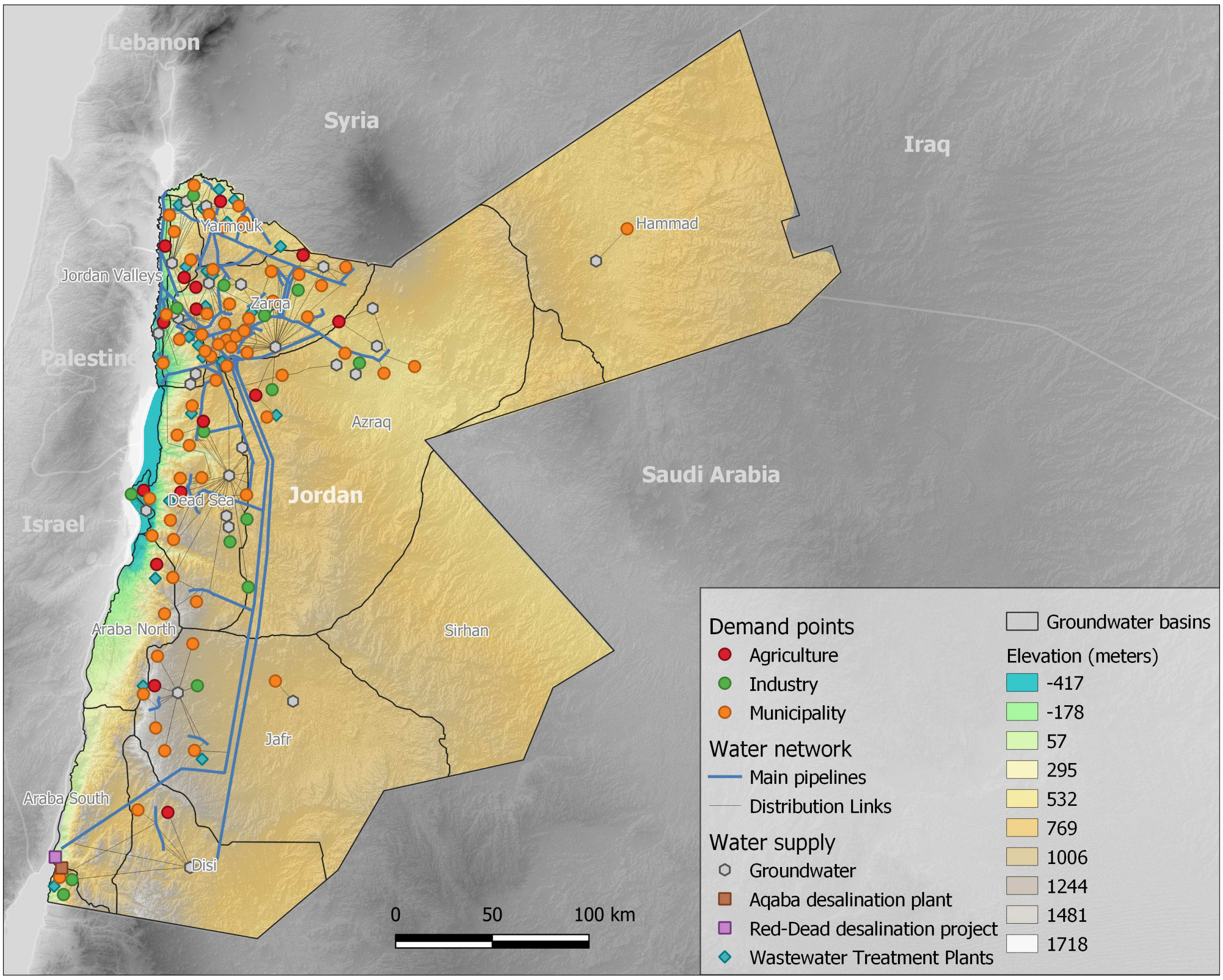


Fig. 2: WEAP model schematic – representation of the water system in Jordan.

- Groundwater supply: 12 major groundwater basins and 26 groundwater units representing well fields.
- Surface water supply: rainfall-runoff flows in wadis, Yarmouk flows from Wehdah dam, and Lake Tiberia inflows to King Abdullah Canal (KAC).
- Desalinated water supply: the existent Aqaba desalination project and the planned Red-Dead desalination project with their conveyance systems.
- Water distribution network: 67 pipelines and canals connecting water supplies and demands. The conveyance system is represented with a coarse resemblance to reality, but with enough quality to capture the system magnitude and the geospatial differences between supply and demand points (e.g. location, elevation, water table depth and conveyance distance).

The already existing Jordan WEAP model represents the main components of the water system in Jordan and uses the best available data for quantifying the physical features of the system as it currently exists. However, the model represents agriculture water demand as fixed values, which does not allow for accurate simulation of hydrologic processes. Moreover, the current method does not include crop yield simulation which is necessary to project economic values of crop. These drawbacks prevent policy makers to know the qualitative impact of climate change on yields. To solve this, we enhancement the WEAP model with the MABIA method, which simulates daily irrigation demand and related climatic variables. This update allows users to interact dynamically with different climate futures and provides a higher resolution to represent energy demand by the agriculture sector.

3.2.1 The MABIA method

The MABIA-WEAP package (originally developed in the Institut National Agronomique de Tunisie by Dr. Ali Sahli and Mohamed Jabloun) was used to make daily simulations of evapotranspiration, irrigation needs and climatic and crop-specific variables. The method estimates reference evapotranspiration (ET_{ref}) and soil water capacity based on the FAO Penman-Monteith method [29].

Crop- and site- specific parameters as planting date, root depth, depletion and yield response factors, were taken from the FAO 56 Drainage Paper [29]. Historical climatic data (i.e. 1948-2016) was acquired from the Princeton Climate and Weather data, based on given altitude and latitude of the desired site. The data set includes minimum, maximum, and mean temperatures, pressure, and relative humidity. Then, the MABIA algorithm used latitude and longitude to estimate solar radiation. Moreover, irrigation-specific parameters as irrigation schedule, fraction wetted and irrigation efficiency, were defined based on data provided by local stakeholders.

3.3 GIS-based Energy model

The strategy of the energy model captures the WEF nexus by using GIS-based methods for quantifying electricity requirements for different processes. These processes, include the conveyance of water for agricultural irrigation, the extraction of groundwater, and the conveyance of water for drinking, industrial and other purposes. In addition, the model estimates electricity requirements for wastewater treatment and sea water desalination. GIS methods were selected to prevent, as much as possible, the aggregation of spatial dimensions, which was supported by the geospatial nature of the WEAP model. This approach allowed us to couple outputs from the WEAP-MABIA analysis to spatial objects of the WEAP schematic (see Figure 2), capturing elevation and groundwater depth differences from remote-sensed data throughout the country. A representation of the energy model is shown in Figure 3.

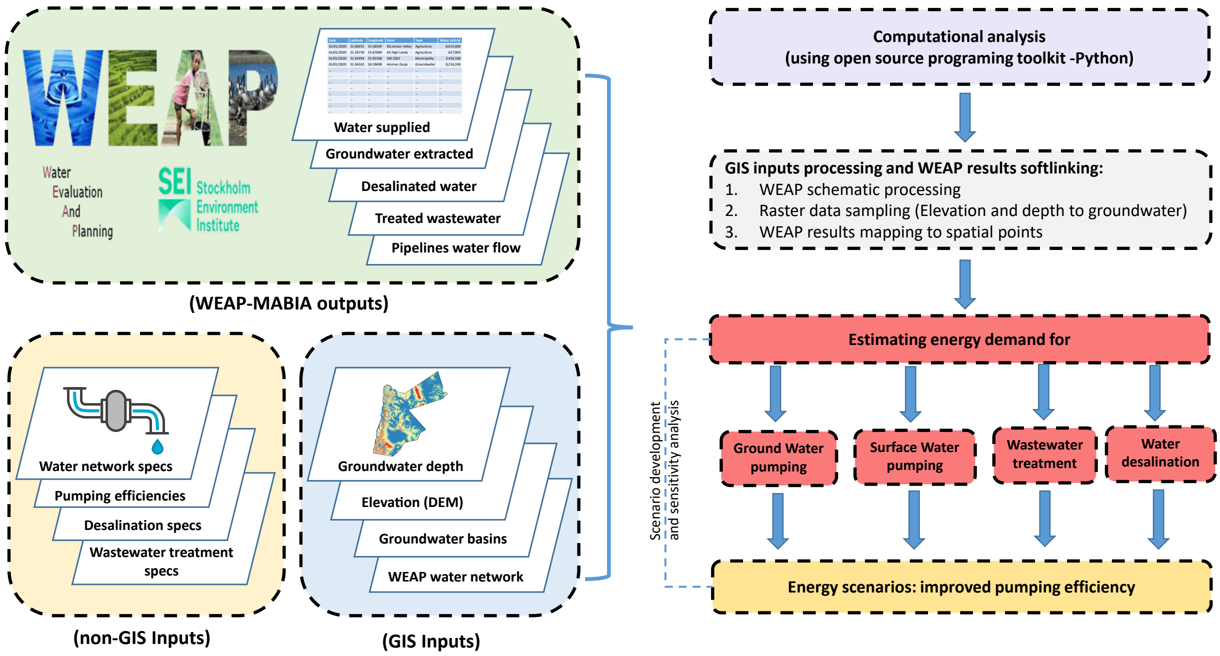


Fig. 3: GIS-based energy model – data inputs and model workflow.

3.3.1 Estimating energy demand for groundwater pumping

Energy for water pumping can be expressed as the energy required to lift water from groundwater sources and to overcome friction in pipes, pumps, and other elements of the distribution system used for conveyance across the land surface. Electrical energy, or electricity (kWh), is expended when a unit volume (m^3) of water passes through a pump during its operation [30].

The electricity demand (E_D (kWh) Equation 1) depends on the efficiency of the pump, the pipeline length and diameter, pipe material roughness or friction factor, and the volumetric demand for water.

$$E_D = f(d,\ Q,\ P,\ t,\ f_1) \tag{1}$$

Where d is the distance through which the water is lifted, Q is the required volumetric amount of water, P is the pressure required at the point of use, t is the time over which the water is pumped (assuming a constant head), and f_l is the friction loss along the distance within the distribution system. Electricity demand for water pumping can then be calculated as described in Equation 2.

$$E_D = \frac{SSWD \cdot \rho \cdot g \cdot TDH_{gw}}{PP_{eff}} \times \frac{1}{3600} \times \frac{1}{1000} \tag{2}$$

Where Seasonal Scheme Water Demand SSWD (m^3) is defined as the total volume of water required over a selected season, $\rho(kg/m^3)$ is the density of water, $g(m/s^2)$ is the acceleration of gravity ($9.81 m/s^2$) and $1/3600(s/h) * 1/(1000(W/kW))$ are factors to convert from Joule units to kWh.

Moreover, TDH_gw (m) represents the Total Dynamic Head and PP_{eff} (%) accounts for the Pumping Plant efficiency. The calculation of the Total Dynamic Head is estimated using Equation 3.

$$TDH_{gw} = EL + SL + OP + FL \tag{3}$$

Where EL (m) is the Elevation Lift, SL (m) expresses the Suction Lift, OP (m) stands for Operating Pressure and accounts for the pressure needed based on the application and conveyance system, and FL (m) expresses the Friction Losses in the piping systems.

Finally, the overall power required for pumping water is determined as per Equation 4.

$$PD_{gw} = 9.81 \cdot PSWD \cdot TDH_{gw} \cdot PP_{eff} \tag{4}$$

Where $PSWD\,(m^3/s)$ is the peak water demand within the SSWD period.

3.3.2 Estimating energy demand for surface water conveyance

Surface water conveyance in Jordan, happens through a wide and complex pipeline network, covering the country from south to north (see Figure 2). Such network gets water from several supply points, including groundwater, surface water and desalination plants. Once the water is in the network, it is conveyed to every demand point throughout the country – however, some demand points, especially some agricultural sites, source their water directly from groundwater aquifers.

Energy requirements for surface water conveyance are estimated by capturing geospatial characteristics of every demand site, pipeline section and supply point. By knowing the location and elevation of every point, the Elevation Lift EL can be computed as the elevation difference between every start- and end-point of every pipeline section. The length of each section was calculated using geospatial functions from the Python package GeoPandas and the monthly water flow throughout every section derived from the WEAP model. Then, the energy for water conveyance was estimated using the previously described methodology and adding specific characteristics to the main pipelines (i.e. diameter and roughness factor).

3.3.3 Estimating energy requirements to improve water quality

The main wastewater treatment plants were captured in the WEAP model (see Figure 2), for which energy requirements were modelled based on the type of treatment technology and the number of treatment stages. When specific data from a treatment plant was not available, international standards on energy intensity of wastewater treatment were used at 0.6 kWh/m3 using the active sludge treatment process [31].

Similarly, energy requirements for water desalination were modelled according to specifications of the Aqaba desalination plant and preliminary estimations of the energy intensity of the Red-Dead desalination project, at 5 kWh/m3 and 3.31 kWh/m3 respectively [32]. The additional energy required for pumping water from the Red Sea up north, was considered into the surface water conveyance methodology.

3.4 Scenario analysis

A set of scenarios were analyzed in order to explore nexus interactions and the impacts of different measures targeted to one of the systems (i.e. water, energy or agriculture), on the other systems. A time horizon of 30 years was selected, covering the period from 2020 to 2050. All of the scenarios were formulated and agreed on with the project stakeholders. The scenarios evaluated were:

No intervention scenario takes a Business as Usual approach where the main current trends (in terms of demand, supply and growth) are unchanged. It assumes that domestic demands will increase over time, with refugees staying (but no new refugees coming), and agriculture and industry not growing over time.

Reduce non-revenue water (NRW) scenario assumes a reduction of non-revenue water by 20% by year 2050 — non-revenue water is the amount of water that is either lost in the transmission and distribution processes due to technical issues, or withdrawn and consumed without authorization from the water authorities. The reduction is set as a goal for each municipality to achieve by year 2050.

New water resources (desalination) scenario assumes the construction of the Red Sea-Dead Sea project and associated desalination plant (with capacity of 110 MCM/yr). The production of desalinated water from the plant will start by year 2025 with a quarter of its capacity, and will reach full capacity by year 2029. This water will be transported by pipeline systems from south to north of the country, in order to supply the main urban areas.

Increased agricultural water productivity scenario considers a combination of interventions targeting to increased crops water productivity. These interventions include improving the efficiency of irrigation schemes and the use of controlled micro-climates such as greenhouses.

Integrated strategies scenario examines the combination of interventions in other scenarios, including non-revenue water reduction, construction of the Red Sea-Dead Sea desalination and conveyance project and increasing agricultural water productivity.

Pumping energy efficiency considers the gradual improvement and modernization of the water network. Pumping energy efficiency is gradually increased starting from the individual efficiency of each pumping system (i.e. groundwater pumps and conveyance pipelines) and reaching an average target efficiency by year 2050. This strategy is parallel to all scenarios, being tested for the previous 5 scenarios presented.

Moreover, an online interactive visualization platform was developed, in order to allow decision-makers to explore results and draw relevant insights. This platform was used in workshop environments with stakeholders in charge of the governance of WEF resources in Jordan.

3.4.1 Effects of increased evapotranspiration

Historical reference evapotranspiration data indicates an increasing trend in evapotranspiration in the country that will potentially impact hydrology and crop water requirements. To assess the impact of evapotraspiration, all scenarios were evaluated under two conditions:

- No increasing trend in evapotranspiration, and
- A drier future with an increasing trend in evapotranspiration applied to hydrology and irrigation requirements.

4 Results and discussion

In this study we developed a WEF Nexus model in order to support the implementation of SDG target 6.4 of the 2030 sustainable development agenda and to define the safe boundaries for water sustainability in the country of Jordan. For this, we enhanced with the MABIA method the current WEAP hydrological model owned by the Jordan Ministry of water. The MABIA method implements simulations of daily irrigation water demand and crop yields for several crop types in the country. Therefore, it allows users to evaluate effects of future climates on crop production. Moreover, the WEAP-MABIA model was coupled with a custom-made GIS-based model to account for the different energy-for-water requirements throughout the country. A series of scenarios, covering a time period from 2020 to 2050, were evaluated in order to test how different interventions targeted at least one of the sectors affected the other sectors. Finally, an open source online visualization platform was developed, in order to enable stakeholders to access all data generated with the model and explore results in detail.

Table 1: Scenario analysis summary of results. The No intervention scenario is highlighted with gray background (taken as the reference case). Colored arrows are used to denote positive or negative differences between tested scenarios and the No intervention scenario for selected indicators.

Scenario	Municipal unmet demand (%) *	Agricultural unmet demand (%) *	Aquifer water table depth (m) **	Energy demand (GWh) *	Agricultural productivity (kg/m3) *
No intervention	17.1%	38.3%	AZ -139 m JV -63 m DS -174 m	3694	3.27
Reduced NRW	12.8% ↓	38.6% –	AZ -139 m – JV -70 m ↑ DS -171 m ↓	3314 ↓↓↓	3.26 –
New Resources	11.8% ↓↓	38.0% –	AZ -139 m – JV -63 m – DS -161 m ↓↓	3912 ↑	3.27 –
Increased water productivity	17.1% –	34.6% ↓	AZ -133 m ↓ JV -51 m ↓↓ DS -167 m ↓↓	3582 ↓	3.78 ↑
Integrated strategies	7.8% ↓↓↓	34.7% ↓	AZ -133 m ↓ JV -58 m ↓ DS -152 m ↓↓↓	3470 ↓↓	3.76 ↑

↓: positive decrease ↑: positive increase ↑: negative increase –: no significant change
AZ: Amman Zarqa aquifer JV: Jordan Valleys aquifer DS: Dead Sea aquifer
* Last decade average (2040-2050) ** Last year value (2050)

Broadly speaking, there was not a perfect scenario that targeted all challenges identified in the participatory approach (Table 1). Therefore, it can be argued that to achieve a holistic solution a combination of interventions is needed. In this section, first we present results for the No Intervention scenario and the implications of increased evapotranspiration in a warmer future. Then we cover each scenario results, comparing them to the No Intervention scenario and discussing the broader sustainable development implications.

4.1 No intervention scenario

Results show that without intervention, water demands from the municipal and agriculture sectors could be increasingly unmet at a rate of around 17% and 38% respectively in the last decade (i.e. from 2040 to 2050, see Table 1) (unmet demand works as a water scarcity indicator by measuring the gap in percentage of the water that is actually delivered against the water that is demanded). However, the effects of increased evapotranspiration in that regard were not significant. Moreover, agricultural water productivity (i.e. unit of crop produced over unit of water applied) would constantly decrease over the entire period (Figure 4). Increased evapotranspiration exacerbates this by reducing the water productivity over the last decade in about 9% average.

Aquifers would continue to be drawdown (Figure 4) affecting the water supply for agricultural production, domestic drinking water and energy for pumping needs. Moreover, increased evapotranspiration substantially increases drawdown in the Jordan Valley aquifer, in about 18 meters more by year 2050 against the historical

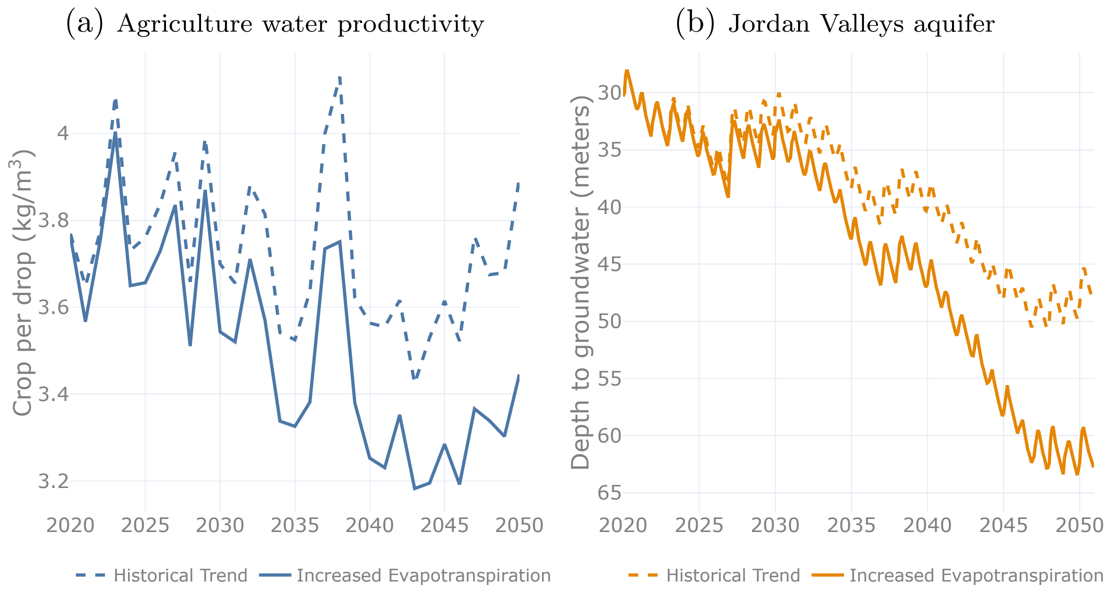


Fig. 4: No Intervention scenario under two climate futures results for: (a) Crop production per unit of water irrigated (kg/m^3); and (b) Aquifer drawdown of the Jordan Valleys aquifer.

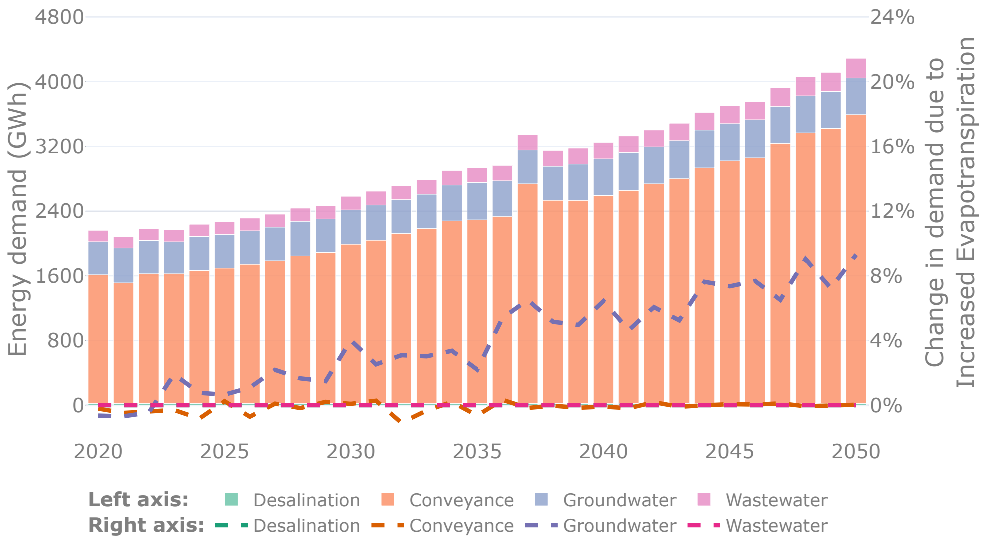


Fig. 5: Energy requirements for the different water uses in the no intervention scenario for two climate futures (left axis: energy demand in the Historical climate conditions; right axis: percentage change in demand due to increased evapotranspiration).

climate trend (Figure 4). On the other hand, energy requirements would increase due to aquifer drawdown and the need to convey more water from south to north (Figure 5). However, increased evapotranspiration would affect only energy requirements for groundwater pumping with an increase in average by about 6.8% in the last decade, which is directly related to the increase in aquifer drawdown.

The effects of increased evapotranspiration in the system can be explained by the water allocation hierarchy in the country. Jordan supplies first its domestic and industrial demands and leaves agriculture at the lowest priority. Thus, a warmer future would produce greater evapotranspiration, reducing both the amount of surface water availability and the water that percolates and recharges the groundwater aquifers. To com-

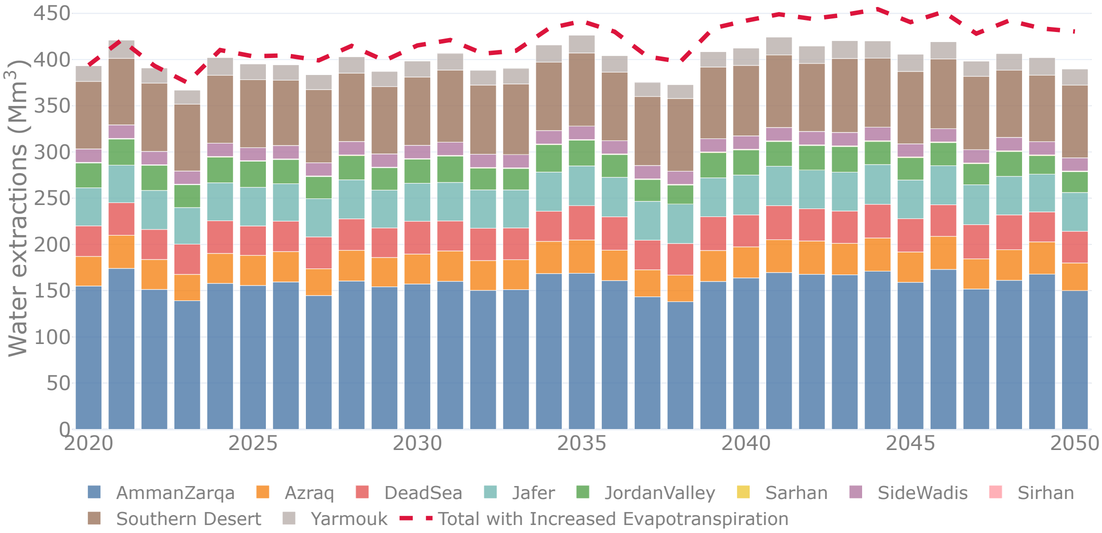


Fig. 6: Groundwater extractions in the No intervention scenarios, under two climate futures. Historical climate is represented by the bars and Increased Evapotranspiration by the dashed line.

pensate for that, more water is pumped from the groundwater aquifers (Figure 6). These is evidenced by an overall increase in groundwater extraction of 7.5% average in the last decade (Figure 6), being the Jordan Valleys the aquifer most affected (13.6% average increase in the last decade). As a consequence, the levels of the aquifers are substantially reduced, specially in the Jordan Valley which sustains an important share of the agricultural activity in the country. Although the extraction of more water maintains the same level of water deliveries to the agriculture sector, the warmer climate exerts more stress in crops affecting the agricultural water productivity (Figure 4).

4.2 Reduced non-revenue water scenario

Domestic water scarcity showed to be improved by implementing measures to reduce non-revenue water. Unmet municipal demands were reduced annually in average by 4.3% in the last decade compared against the No Intervention scenario (Table 1 and Figure 7). However, agricultural unmet demands did not see substantial improvements as most of the inefficiencies in water transport and distribution happen at the municipal level (Figure 7). As a result, agriculture water productivity continued to decrease at a similar rate as without intervention (Figure 7). In addition, a negative feed back effect is seen over the Jordan Valley aquifer with an additional decrease of the water table levels of around 7.7 meters by year 2050 (Table 1 and figure S4 in *supplementary information*). This happens because the agricultural areas of the Jordan Valleys region typically use substantial amounts of treated wastewater to irrigate. Reduced non-recoverable losses means less water being discharged into the Zarqa River from the Samra wastewater treatment plant. This in turn creates the need to extract more groundwater for agricultural irrigation in the region (see figure S5 in the *supplementary information*), thus affecting negatively the levels of the Jordan Valleys aquifer. On the other hand, the Dead Sea aquifer saw a slight improvement of its levels in about 3.4 meters by year 2050 against the Non Intervention scenario (Table 1 and figure S4 in *supplementary information*). Finally, energy demand for water conveyance decreased by an average of 380 GWh in the last decade due to reduced losses in the system (Figure 7). This is a significant improvement in energy use, which would decrease Green House Gases (GHG) emissions and support the shift to the energy independence of the country.

4.3 New water resources (desalination) scenario

Domestic water scarcity was alleviated by adding new water resources from the Dead Sea - Red Sea water desalination project. This measure increased the availability of water, which had a direct effect on unmet

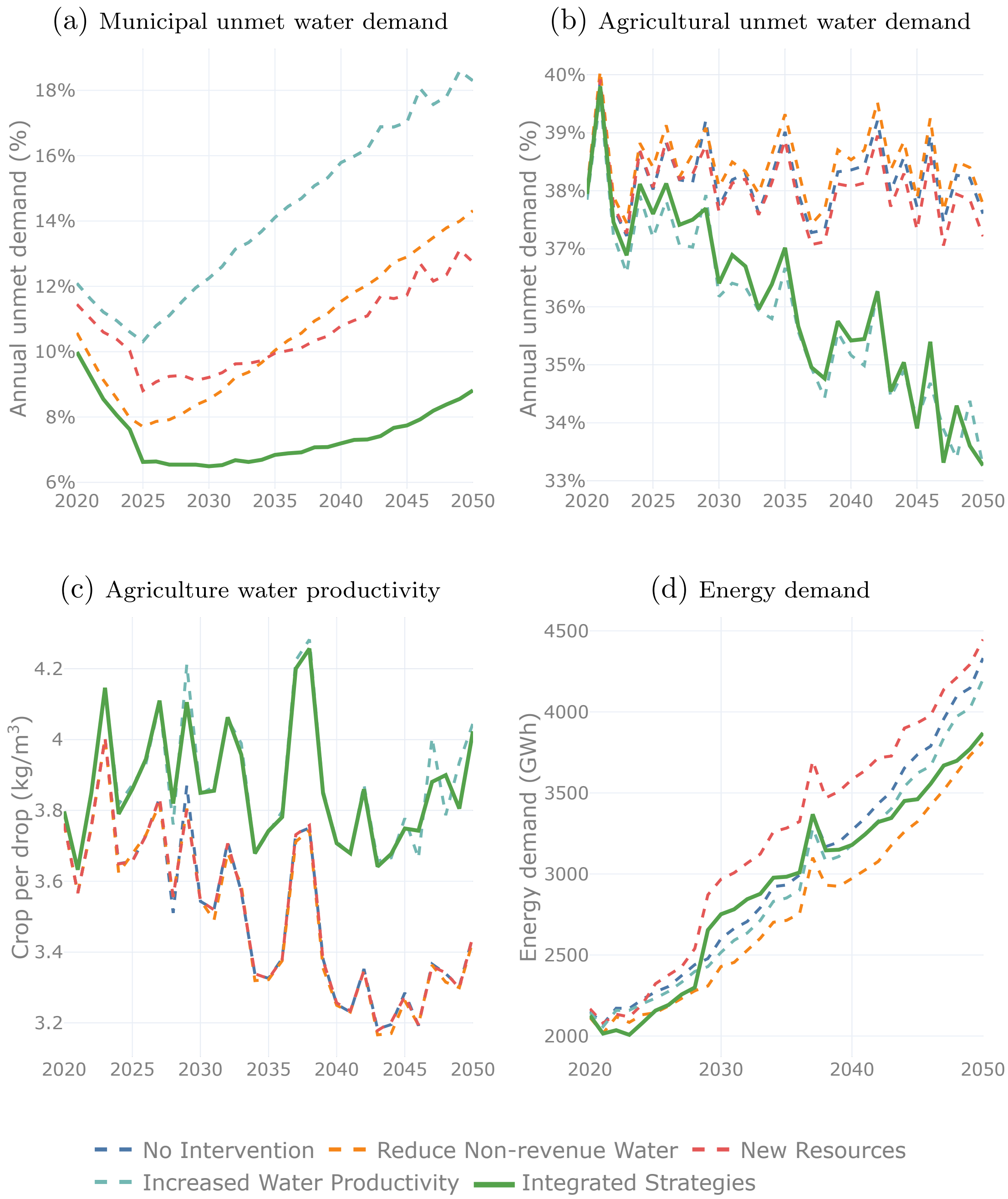


Fig. 7: Main results for all scenarios in an increased evapotranspiration future (i.e. warmer future), (a) unmet demand in the municipality sector (the No Intervention and the Increased Water Productivity scenarios have the exactly the same values, making both lines to overlap); (b) Unmet demand in the agricultural sector; (c) Agricultural water productivity; (d) Total energy demand for groundwater pumping, water conveyance, wastewater treatment and sea water desalination.

demands. Unmet municipal demands decreased by an annual average of 5.3% in the last decade (Table 1 and Figure 7). However, as agriculture irrigation has the lowest priority in water allocation, most of the new available water was directly consumed by the municipal sector, translating into little improvement in unmet demand in agriculture (Figure 7). Moreover, water levels in the Dead Sea aquifer saw a substantial improvement of about 12.8 meters by year 2050, whereas other aquifers remained with similar drawdowns as without intervention (Table 1 and figure S4 in *supplementary information*). This outcome is logical, as the Dead Sea - Red Sea project plans to pump sea water from south (Red Sea) to north of the country, desalinate it and use the resulting brine to help recover the Dead Sea levels. On the other hand, agriculture water productivity continued to decrease at a similar rate as without intervention (Figure 7). This is also due to the water allocation hierarchy, reducing the probability for agriculture using the new water resources (i.e. desalinated water).

As the major trade-off, energy demand for water conveyance and desalination substantially increased in average by about 218 GWh in the last decade (Table 1 and Figure 7). Moreover, a major increase of about 400 GWh of energy would be seen in year 2029 when the desalination project starts operating. This substantial increase in energy needs, will exert great pressure in the energy system for it to ensure new generation capacity. Although Jordan counts with high solar energy potential, it has recently restricted new installations of intermittent renewable supply and instead opted for boosting generation with fossil fuels produced locally. This will have repercussions in GHG emissions, hindering progress of Jordan's National Determined Contributions (NDC) and clearly having trade-offs with SDG target 7.2 on increasing substantially the share of renewable energy in the global energy mix by 2030. Shifting to energy independence could also be affected if Jordan keeps its high dependence on fossil fuel imports to supply the energy-for-water requirements, especially with the additional energy needs from the new desalination water resources.

4.4 Increased agricultural water productivity scenario

To increase agricultural water productivity, a combination of interventions targeted to produce more crops with less water are applied (e.g. improving efficiency of irrigation schemes, using controlled micro-climates as greenhouses for crop harvesting). With these interventions, unmet agricultural demand decreased in average by 3.7% in the last decade, which is the best improvement between all tested scenarios (Table 1 and Figure 7). However, as this measure targets only the agriculture sector, unmet municipal demands remained the same as without intervention (Figure 7). Furthermore, this scenario was the only one that achieved an improvement on agriculture water productivity, considerably increasing the crop production per water unit by an annual average of 15.6% in the last decade (Figure 7). The more efficient use of water in agriculture was positively translated into less water extractions, with consistent improvements over all aquifer drawdown trends (figure S4 and S5 in *supplementary information*). The Jordan Valley, Dead Sea and Amman Zarqa aquifers saw a decrease in drawdown of 12.2, 7.4 and 5.5 meters by 2050 respectively against the No Intervention scenario. As consequence, energy demand for groundwater pumping decreased in about 112 GWh by year 2050. Similar to the reduce Non-Revenue water scenario, this result would cause reductions in GHG emissions and support the shift to energy independence in Jordan.

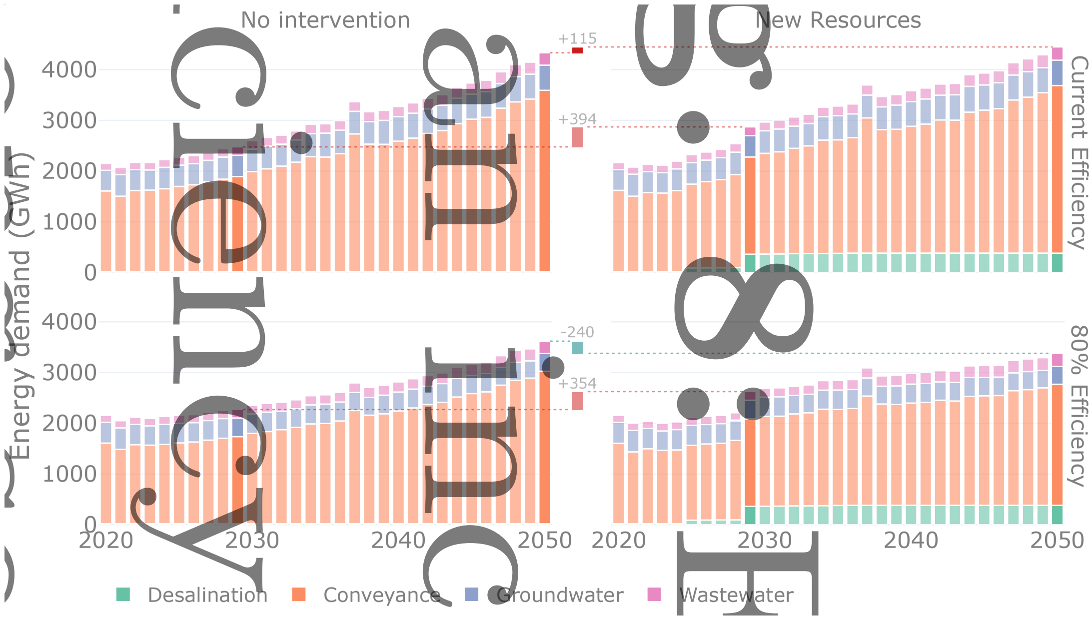
4.5 Adding improved pumping energy efficiency

The current energy efficiency for pumping of the water system throughout Jordan is low, at around 50% in average. Therefore, we tested a goal of achieving 80% average pumping efficiency by year 2050 applying a linear growth from current 2020 levels. The improvement of energy efficiency would help to assess the effect that modernizing pumps and water networks may have in the energy system.

Results are presented for the No Intervention scenario and the New Resources scenario in order to capture the state of affairs and the worst case scenario in terms of energy requirements (Figure 8). In both scenarios, improving pumping efficiency flattened the growing energy requirements for conveyance and groundwater pumping. Moreover, energy requirements by year 2050 were even lower in the New Resources scenario with improved efficiency than in the No Intervention scenario without efficiency improvements. This is specially important as the New Resources scenario had the greatest increase in energy requirements for water desalination and conveyance. Thus, energy efficiency can be seen as an important complement to water scarcity solutions as it can reduce the load on the energy system, support the shift to energy independence, improve the resilience of the water system and even reduce the cost of crop production.

4.6 Integrated strategies scenario

All of the tested strategies had benefits and drawbacks, but non of them targeted holistically the WEF Nexus challenges in Jordan. Reducing Non-Revenue water uses helps towards municipal water scarcity and



No intervention
New Resources
Current Efficiency
80% Efficiency
Energy demand (GWh)
4000
3000
2000
1000
0
2020
2030
2040
2050
+115
+394
-240
+354
Desalination
Conveyance
Groundwater
Wastewater

involving key stakeholders in Jordan: 1) **water scarcity**, 2) **agricultural productivity & water quality**, and 3) **shift to energy independence**. Four scenarios were evaluated, including a No Intervention scenario that captured the current state of affairs taking a "business as usual" approach. In the three other scenarios we evaluated how measures to reduce Non-revenue water, produce New water resources and Increase agricultural water productivity would reduce water scarcity, affect crop production, alleviate aquifer drawdown and impact the energy system. In addition the effects of increased evapotranspiration (due to a warmer climate) were also analyzed.

Results show how increased evapotranspiration would further exacerbate sustainability challenges. Aquifers would see extra drawdown due to increased groundwater pumping in order to maintain deliveries of water demand. Higher temperatures are the main cause of this as evapotranspiration in the surface increases, reducing the amount of surface water available and the amount of recharge from water percolation to groundwater aquifers. Agricultural water productivity (i.e. crop per drop) would be negatively affected mainly due to higher heat stress in crops, and energy requirements for groundwater pumping would be substantially increased due to lower aquifer levels.

It can be argued that there is not one perfect solution that address all challenges holistically. This is apparent as none of the tested sectorial solutions targeted all combined challenges; instead, some solutions even had negative effects on other sectors. Therefore, integrated strategies are needed to target holistically the challenges among all sectors. This is evidenced by four key findings: (i) desalination is needed to address water scarcity, but it has to be coupled with low-carbon electricity generation in order to not exacerbate climate change; (ii) agricultural water productivity in agriculture is a win-win across the water-energy-food security nexus; however, it does not target the issue of municipal water scarcity; (iii) reducing non-revenue water can have positive effects on municipal unmet demand and reduction of energy for pumping, but it does not improve agricultural water productivity and may have negative feedback effects on the Jordan Valleys aquifer levels; (iv) energy efficiency can support energy intensive projects as desalination, by substantially reducing the load on the energy system, preventing increased emissions and achieving a more resilient water system. In light of this, when all interventions are considered together under an Integrated Strategies scenario, all of the major drawbacks were reduced and the benefits enhanced, producing a more holistic solution to the WEF Nexus challenges.

As future research, Climate Change representation could be enhanced by implementing climate projections into the model and evaluating effects of different climate futures into the systems. The geospatial representation and resolution of the WEAP model could be improved to better position demand and supply sites and achieve a more detailed water transmission and distribution system. Whereas, scenarios could be developed to evaluate how energy requirements from different solutions could be sustainably met.

Nonetheless, the outcomes of this study helped decision-makers and key stakeholders in charge of the governance of the three resource systems, to understand the trade-offs and synergies of sustainable solutions for Jordan. Moreover, the participatory approach and the resultant WEF Nexus model constitutes the first framework for analysing new strategies in the country under a WEF Nexus sustainability lens. This supports decision-making with data-driven insights and promotes holistic governance involving actors from the different resource systems.

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Conflict of interest

The authors declare that they have no conflict of interest.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request. Results can, however, be explored in the Jordan WEF Nexus interactive visualization platform at https://jordan-nexus-model.herokuapp.com/. Code for the GIS-based energy model and the softlinking of models is available under MIT license at https://github.com/KTH-dESA/FAO.

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