Modeling Water Supply and Demand for Effective Water Management Allocation in the Jordan Valley

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***Abstract*-Water in Jordan is scarce, yet key to its economic development. A fast growing population and expanding agricultural sector create demands for new water resources. We present a Water Evaluation and Planning (WEAP) model for the Jordan Valley (JV) to evaluate alternative water supply options. WEAP accommodates the extensive primary and secondary spatial data sets behind our empirical analysis and allows the simulation of various water supplys and demand scenarios. This paper reports on the implementation and calibration of the WEAP model against dam operating rules, showing that it is possible to reproduce historical dam volumes accurately enough by analysis. The paper then describes five alternative water supply scenarios for the JV: business-as-usual, increasing treated wastewater in irrigation, climate change, and two combined scenarios—climate change with increasing reuse, and altered patterns of agriculture to calculate the impact on the demand-supply gap by the year 2050.**

Keywords-Integrated Water Resource Management; Jordan Valley; Scenarios; Water Management; WEAP; Wastewater; Dams; Climate Change

I. INTRODUCTION

The Hashemite Kingdom of Jordan has extremely scarce water resources. As shown in Table 1 Jordan faced in 2006 a deficit of nearly 600 million cubic meter (m^3) of water, amounting to 39% of the total demand. The fertile Jordan Valley (JV), in particular, is an extensive water user, and the agricultural sector is likely to be strongly affected by water scarcity. Treated wastewater is an important additional source, contributing 25% of the surface water, about 90 MCM, and can be used to meet irrigation demand. In the future the demand for new unconventional water resources is expected to increase to mitigate the impact of water scarcity on the socio-economic well being of Jordan.

This study presents the initial steps in the development of a scenario model of water supply and the demand that can help decision makers plan future water allocation.

The key in the study is the role of dams in regulating the supply of water in the JV. The high rainfall variability in the JV is smoothed over by storing the water in dams, and decisions on water allocation are made based on dam levels at the end of the wet season. We simulate the current water allocation decision-making process, which – although we do not explore in this paper – would allow for the evaluation of alternative rules that take re-used wastewater and other non-conventional water sources into account.

We selected the Water Evaluation and Planning (WEAP) software (Yates et al. 2005) which is particularly suitable for the intended research objective as it incorporates a demand priority and supply preference approach to describe water resource operating rules that function as system demands to drive the allocation of water from surface water and groundwater supplies to demand centres (Yates et al. 2005). As such, WEAP is designed for constructing water management scenarios.

Our study area, the Jordan River, provides a rich source of primary and secondary data sets for the analysis described in this paper. Using these data sets, WEAP reproduces geographically specific agricultural production along the north-south flow of the river.

We note that we did not construct a hydrological model for this study, as considerable hydrological and climate modelling has already been carried out for the Jordan River, and the results of several of these studies were available to the authors.

TABLE 1 WATER SUPPLY-DEMAND REQUIREMENTS BY SECTOR FOR JORDAN (JVA 2007)

Demand Requirements	Ground Water	Surface water	TWW	Total
	MCM			
Domestic	214.00	79.75	0	293.7
Rural area	0.745	7		7.745
Industry & Remote Areas	44.89	3.527	0	48.421
Agriculture	244.81	176.366	90.9	512.146
Agriculture (High land)		77.46		77.46
Total Supply Demand	504.449	344.1	90.97	939.523
Actual Demand				1512
Deficit				572.47

II. STUDY AREA: JV WATER ALLOCATION

Amman receives water from the Jordan Valley and aquifers from southern and eastern outer basins. The major water source for farmers in the Jordan Valley is supplied via the JVA stage offices. Stage offices receive and process daily water requests, manage and regulate the supplies to farms, process billing and accounting, and register the cropping areas for a group of development areas. There are ten stage offices in the Jordan Valley from the north to the Dead Sea, and two stage offices in the Southern Ghor.

III. CURRENT WATER SUPPLY AND DEMAND

In this section we describe the current water demand and supply.

A. *Water Supply*

Flow from the Yarmuk River, upstream of the confluence with the Jordan River at the northern end of the valley, is fed into a concrete canal called the King Abdallah Canal (KAC). The KAC runs parallel to the river on the eastern bank for 69Km. Flows from side wadis are rechanneled to feed the canal.

In 2006 the Yarmuk River supplied the KAC with 55 MCM /year while a further 55 MCM/year was provided by the Tiberias carrier according to the peace treaty on October 26, 1994 (Treaty 1994). In addition to these surface flows, 25 MCM/year are pumped from the Mukhyba wells to the KAC. Additional inflows come from wadis that cut through the mountain ranges bordering the valley, providing another 6 MCM/year (JVA 2007). The North Jordan Valley (up to the conveyance to Der Alla) receives fresh water from KAC for agricultural purpose, while the Middle Jordan Valley receives blended water (treated wastewater mixed with fresh water) mainly from the King Talal Dam (KTD) via the KAC, the Zarqa River and the Zarqa Carriers (ZC1 & ZC2). In the North and Middle JV the agriculture water requirement is 110 MCM/year each.

The JVA indicates two seasons of supply and demand. The summer season is considered to start at the beginning of April to September 30th, while the winter season covers the period from the beginning of October to December 31st, and the period from January 1st to the end of March of the next year.

B. *Water Demand*

There are two main demands that are represented in the model: urban demand in Amman city and agricultural demand separated into the three agricultural areas: North JV, Middle JV and South JV. It is important to distinguish the three agricultural areas because each region uses water from different source and of different quality for irrigation.

Water requirements are calculated by the Jordan Ministry of Water and Irrigation (MWI) based on the records kept at the JVA stage offices.

In Jordan, agriculture consumes around 600 MCM of water per year. One-third of this amount (200 MCM) is consumed by the Jordan Valley. Almost 50% of this 200 MCM is reclaimed water. All in all, agriculture consumes less than 20 % of the freshwater resources from the JV.

In 2006, the total municipal water consumption was around 290 MCM. Of this, almost 42.6% was pumped into Amman Governorate while Ajloun received the smallest allocation, around 1.27 %. Out of this total, only around 111 MCM was treated in wastewater treatment plants. Around 40% of households are not connected to the sewer network system, but use cesspools. Thus, much of the influent is lost without recycling or reuse. Aside from the lost of the opportunity to reuse the wastewater, the cesspools are a likely source of groundwater contamination.

Within Amman city, the population according to the Jordan Department of Statistics (DOS) was 1.6 millions in 1994, and 1.9 millions in 2004, corresponding to an average annual growth rate of 2.0%. The population growth prior to 1994 (between 1979 and 1994) was 4.4 % per year, while since 2004 it has been growing at 3.7% per year. An official estimate of the annual water demand is 51m^3 per person per year, but the discrepancies between estimated demand and supply suggest that it does not capture all of the water supplied. Within the WEAP simulation we assume that 15% of the delivered water is not captured in this figure, and apply an annual rate of 60m^3 per year.

Amman currently uses around 102Mm^3/year (280,000m^3/d) of water, 60% of which comes from wells and 40% from the Zai WTP.

IV. REPRESENTATION IN WEAP

The major components of the water delivery system have been represented in WEAP. Demands and supplies are represented on a monthly basis for the years 1990-2006 for purposes of calibration, and from 2007 to 2050 for scenarios.

We included as much details as needed to properly characterize both demand and supply sources, subject to the availability of field data. The representations consist of the following main elements:

Distribution Systems: In the WEAP model, distribution systems are either irrigation or municipal supply (for Amman city). The water demand for Amman city is aggregate, while irrigation demand is partitioned by crop type, cultivated area and crop demand.

King Abdallah Canal (KAC) and Tributaries: The KAC and its tributaries are the primary water conduits in the region. Stream flows are estimated along each tributary on a monthly basis. There are 13 wadis and tributaries flowing to the KAC.

Water flows both from the Wadi Arab to the KAC and from the KAC to Wadi Arab. The KAC-to-Wadi Arab backpump is represented in WEAP as a diversion with a minimum flow requirement that is set to the historical flow.

Dams: Five dams are represented within WEAP (including Al Wihda dam, which is not currently operating, and is included only for scenario development). From north to south, the active dams are Wadi Arab, Ziglab (also called Sharhabiel Dam), King Talal (KTD), Shuieb, and Kafrien. Account is taken of inflows, outflows, releases, evaporative losses, and groundwater interactions.

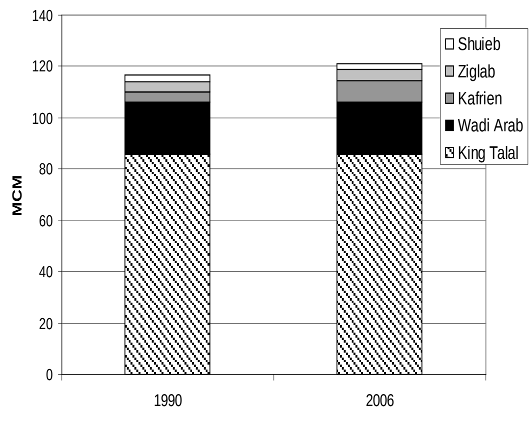

Figure 1 Gross storage capacity of JV dams (MCM)

The gross storage capacity of the dams is shown in Figure 1. As can be seen in the figure, the storage capacity of Kafrien dam was increased during the 1990-2006 period. In WEAP, this was represented by a step increase between 1995 and 1996. The most important dams by volume are King Talal (86 MCM gross storage, 75 MCM live storage) and Wadi Arab (20 MCM gross storage, 17 MCM live storage).

V. SIMULATION AND CALIBRATION

We calibrated dam volumes against simulated dam operating rules. As the decision processes carried out by the MWI are somewhat ad how, we introduced simple rules into a large extent captured the apparent water allocation.

Note that two allocation decisions are taken by the MWI:

1. How much potential irrigation and municipal water demand will actually be supplied.

2. How much water will be released from each dam to meet the required demand.

The calibration focuses on the second decision. For calibration, the water supplied to each distribution system (the “coverage” for the system) was set to its historical value, and the dam operating rules were simulated to meet that supply. Water allocation within WEAP is carried out by using user-specified priorities for demands and sources. The WEAP algorithm is implemented as a series of linear programming (LP) problems, iterated over demand and supply priorities. The algorithm is documented in Yates, Sieber, et al. (2005).

After observing the patterns of dam releases and volumes over time, the following priorities were specified within the JV WEAP application, where priority 1 is the highest priority:

Priority 1: KAC headflow, Wadi Arab backpump, North Agriculture

Priority 2: Ziglab dam, Amman city

Priority 3: Wadi Arab dam

Priority 4: Middle Agriculture, South Agriculture

Priority 5: KTD, KAC tailflow

Priority 6: Shuieb dam, Kafrien dam

The flow in the KAC as it exists in the study area (the tailflow), is modeled as an instream flow requirement that is tied to the volume of water within the KTD. It is given the same priority as the filling priority for KTD.

In addition to the priorities listed above, the Wadi Arab, Ziglab, Shuieb, and Kafrein dams have a “buffer” that slows down releases as the dams get emptier. The rate of release from the buffer zone is set by a buffer coefficient. The levels of the buffers and the coefficients were used as calibration parameters. The calibration parameters were constrained to lie between minimum and maximum values, as shown in Table 2. Otherwise, WEAP imposes constraints that reflect water availability.

TABLE 2 CALIBRATION PARAMETERS

Parameter	Minimum	Maximum	Initial Value	Run 1 Calib	Run 2 Calib
Top of Buffer (million m^3)					
Wadi Arab	3.1	20.0	9.1	16.2	16.4
Ziglab	0.4	4.3	2.4	3.2	3.2
Shuieb	1.43	2.30	2.12	2.30	1.93
Top of Buffer as fraction of storage capacity (dimensionless)					
Kafrein	0.00	1.00	0.25	1.00	0.58
Buffer Coefficient (dimensionless)					
Wadi Arab	0.10	1.00	0.20	0.10	0.13
Ziglab	0.10	1.00	0.75	0.10	0.10
Kafrein	0.10	1.00	1.00	0.67	0.10
Shuieb	0.10	1.00	0.50	0.10	0.10

The historical and estimated dam volumes for the three largest dams (King Talal, Wadi Arab, and Kafrien) are shown in Figures 2, 3, and 4. As can be seen from the figures, the relatively simple simulation operating rules and priorities reproduce the historical dam levels quite well.

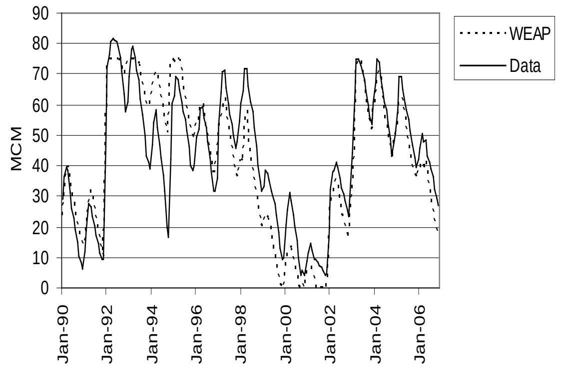

Figure 2 King Talal Storage, historical data and WEAP estimate

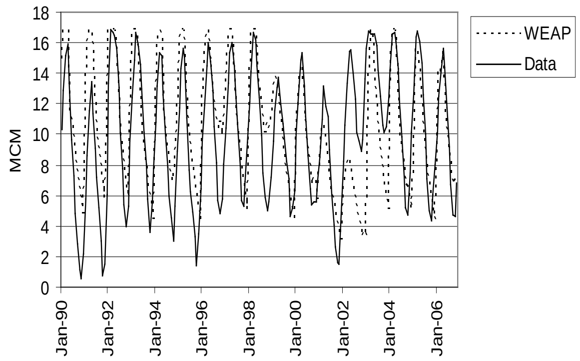

Figure 3 Wadi Arab Dam storage, historical data and WEAP estimate

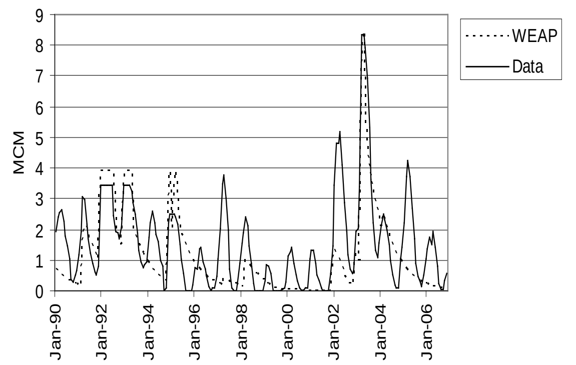

Figure 4 Kafrien Dam storage, historical data and WEAP estimate

VI. DEMAND SCENARIOS

In this section we construct demand scenarios in the model to analyze different management options.

As explained above, the model takes into account two types of demand: domestic (urban presented by Amman city) and agricultural demand within the JV. For domestic demand in the period 1991-2050, we kept the historical population growth trend obtained from the Department of Statistics (DOS) in Jordan and extended that same population growth to 2050. The population growth rate has changed in the past: before 1994 it was 4.4 % per year, then 2.02 % per year, and in 2004 to 3.7 %

per year. In the scenario we assumed continuous growth at 3.7% per year.

For agriculture all scenarios assumed a small increase in the cultivated area of 5 to 10% per year, to see the effect of changing water-saving measures on agriculture. This was considered to be reasonable given the limited water resources in the Jordan Valley. The change in agricultural area is shown in the following figure 5 for North, Middle and South JV:

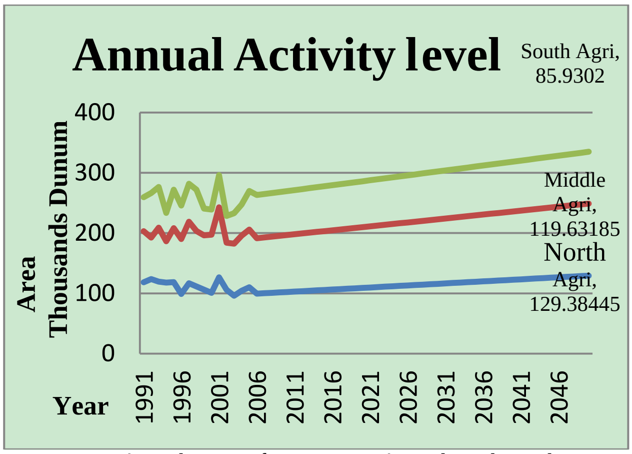

Figure 5 Annual activity for projecting Agriculture demand in JV

VII. SUPPLY SCENARIOS

An important aspect of modeling the water system in the JV is to understand how it operates under a variety of hydrologic conditions. We used WEAP's Water Year Method, which allows the use of the historical data to explore the effects of future changes in hydrological patterns. In this approach, a typical flow pattern is specified for a "normal" year and then scaled up and down for very wet, wet, dry, and very dry years. A scenario is characterized by a Water Year sequence. For this study we specified a water year as the average across the available historical data, from 1991 to 2006. Note that 1991 was a dry year. The non-normal water year type (very dry, dry, wet, very wet) were defined, following a statistical analysis of historical flows, by using a scaling factor of 0.65 for very dry, 0.75 for dry, 1.30 for wet, and 1.70 for very wet.

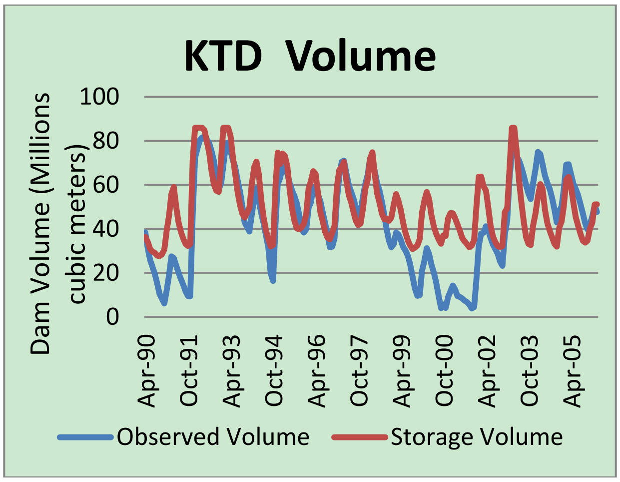

Figure 6 The simulation of KTD

Figures 6 and 7 represent the simulation for the King Talal Dam (KTD) and Wadi Arab after calibration.

The dam was calibrated using the historical data of reservoir storage from 1990 to 2006 provided by the Jordan Valley Authority (JVA). There was a distinct break in the time series in the year 1999, which we identified as a change in management regime, due to different approaches to control the dams. We represented this change in regime parametrically in the model by having two separate values for the parameter Buffer Coefficient, Top of Buffer and the buffer for the wadi Arab Dam, KTD and Ziglab Table 3.

TABLE 3 CALIBRATION PARAMETERS

Parameter	Minimum	Maximum	Initial Value
Top of Buffer (million m^3)			
Wadi Arab- High	10	100	100
Wadi Arab- Medium	10	100	85
Wadi Arab- low	10	60	40
King Talal – High	10	100	100
King Talal – Medium	10	100	85
King Talal- low	10	60	40
Top of Buffer as fraction of storage capacity (dimensionless)			
Wadi Arab Dam	3.1	20	9.1
King Tala	0.1	1	0.7
Ziglab	0.1	1	0.75
Buffer Coefficient (dimensionless)			
Wadi Arab	0.1	1	0.55
Ziglab	0.4	4.3	2.4

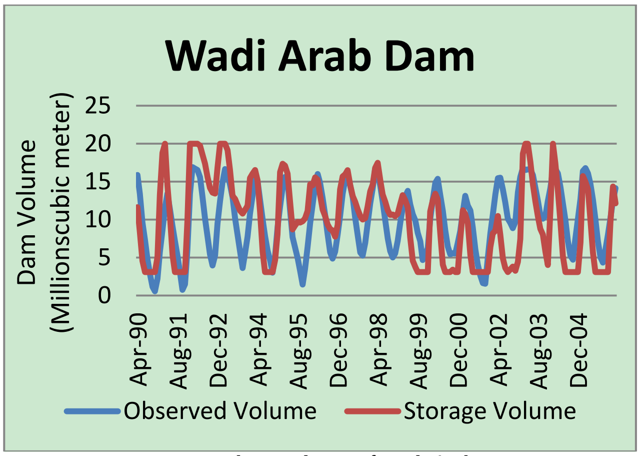

Figure 7 the simulation of Wadi Arab Dam

VIII. SCENARIO DEVELOPMENTS

C. *Business as Usual*

The business as usual scenario is the base scenario that extrapolates historical trends, to provide a baseline for the studied period.

D. *Increase Treated Wastewater North JV*

As documented in Alfarra et al. (2009), the wastewater reuse index (WRI), the ratio of actual wastewater reused to total generated wastewater, for all of Jordan in 2006 was 34.8 % while it was 45% at the Jordan Valley research area. The amount of wastewater reused in Jordan was 80 MCM in 2006, and in the Jordan Valley was 73 MCM in 2006. Thus the WRI indicates that there is considerable scope for expanding wastewater reuse.

For this scenario we increase the WRI to be 70 %, so that reused TWW will increase to 114 MCM. We assume that the increase be complete in 2012, and interpolate linearly between 2007 and 2012. Thus North agriculture receives TWW from 0 MCM reuse in 2007 increasing to 114 MCM by 2012.

E. Climate Change

For the climate change scenario we made use of the output from the GLOWA-Jordan River research project, which indicated that under mild climate change drivers (IPCC B2 scenario), (Kunstmann et al. 2007), by the period 2070-2099:

- Temperatures in the JV region could increase up to 4.5 °C
- Precipitation could fall by 25% (Watson et al. 1997)
- Runoff could fall by 23%

These results are consistent with the latest report by the Intergovernmental Panel on Climate Change (IPCC) in which declining precipitation and rising temperatures can lead to water shortages, and increased competition for increasingly scarce water resources (Peters et al. 2007; Bates et al. 2008). To apply these climate scenarios to the WEAP model, we assigned a water year sequence in which water inflow is reduced by 30% by 2050 by increasing the frequency of dry years in the region.

F. Combining the above Two Scenarios (Increase TWW Reuse and Climate Change)

This scenario combines the above two scenarios to evaluate the impact on demand and resources. The climate change scenario increases the stress on the resources and increases the unmet demand. Counteracting this trend is increasing TWW reuse. This allows us to see how the reuse of TWW helps reduce unmet demand as allocating unconventional water for agriculture releases the stress on the fresh water to be allocated for domestic uses.

G. Altered Patterns of Agriculture

In Jordan the date palm farms are encouraged by Ministry of Agriculture to introduce the high quality varieties of date palms like Barhee, Medjoul, Dejlet noor, and Khalas.

The date palm tree has low water consumption and is potentially a highly profitable crop. This makes it an attractive alternative both to traditional crops, which have low profitability, and other highly profitable crops with high water consumption, such as citrus and banana.

This scenario assumed changed pattern of agriculture that in the area of palm trees was expanded and those of banana trees and citrus were reduced. The range of these changes was between 20 to 40 percent.

IX. SCENARIO ANALYSIS AND RESULTS

We discuss the outputs of each of the scenarios below.

H. Business as Usual Analysis.

By projecting the past situation to the future we can see that unmet demand for different sectors increasing mainly for Amman city because population growth continues.

The demand of Amman city illustrated in the Business as Usual scenario reaches around 600 Mm^3 annually. (Amman city is partly supplied from the King Abdallah Canal).

In contrast to Amman city, there is not much increase in the agriculture sector due to the assumption that the agricultural area could not increase very much above the current area. The other factor affecting agriculture is the specific water demand for the crop area, which was kept constant throughout the scenario (until 2050), assuming no technological change.

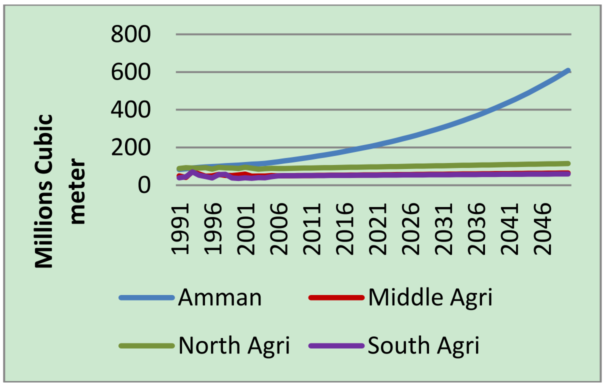

Figure 8 Comparison of the agriculture water demand with the demand of the Amman city for the period 1991- 2050, baseline scenario

The unmet demand can be noted in the following Figure 9. There is ongoing unmet demand for all agriculture sectors and also for Amman city, presenting a challenge for future planning.

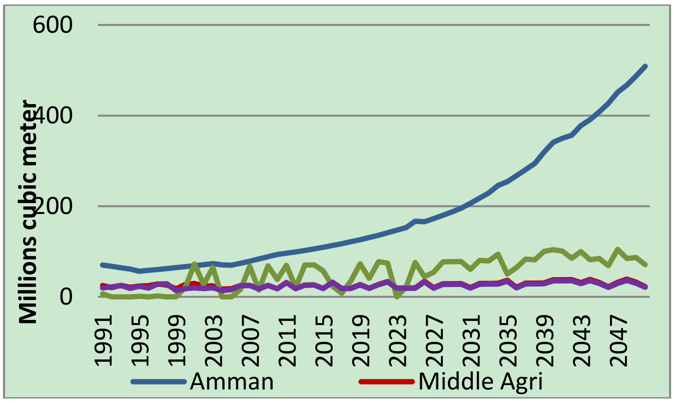

Figure 9 The unmet water demand for the period 1991- 2050, Business as usual scenario

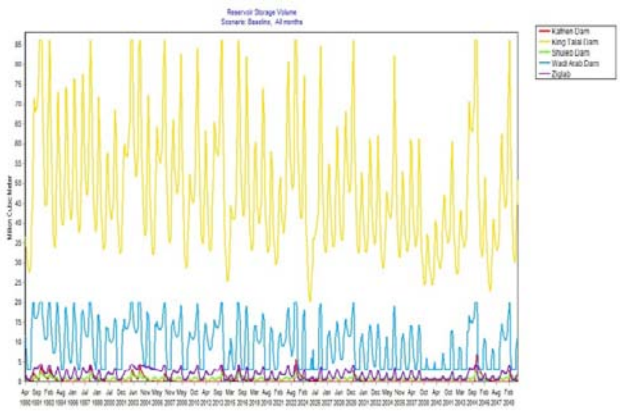

Figure 10 Reservoir storages in Business as usual scenario

I. Increase Treated Wastewater North JV

In this scenario, the impact on the northern agriculture sector can be seen in the following Figure 11. In particular, it can be seen that the unmet demand in the northern agriculture has been reduced significantly through the reuse of treated wastewater.

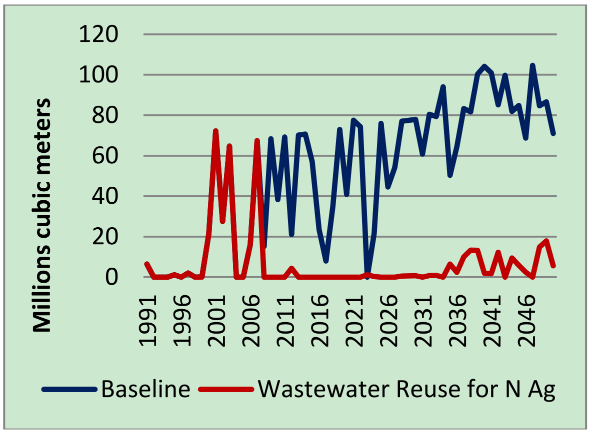

Figure 11 the unmet demand in North Agriculture sector, comparison between the base line scenario and increase the reuse

J. Climate Change

This scenario assumes a reduction in total inflow to the JV. The impact of the reduction is an increase in unmet demand, as seen in Figure 13.

Since Jordan is already an arid to semi-arid region, the climate change did not have a major influence on the dam storage volume 12.

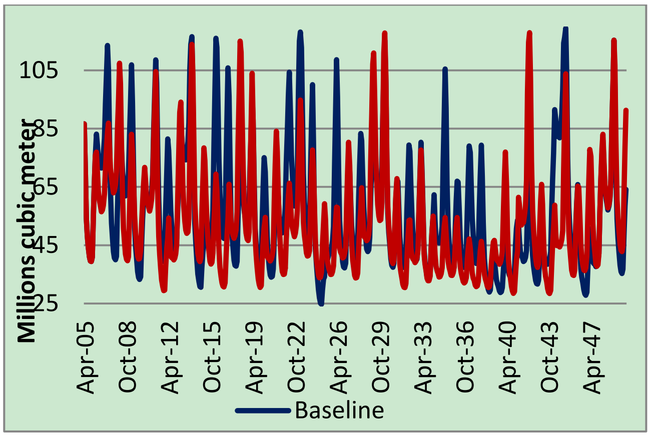

Figure 12 Comparison between the reservoir storage volume in the base line scenario and climate change

This is due to the fact that officials who are managing the dams are already dealing with this limiting situation by releasing water at the end of the rainy season reducing the demand part of their requirement but not meeting the full requirement.

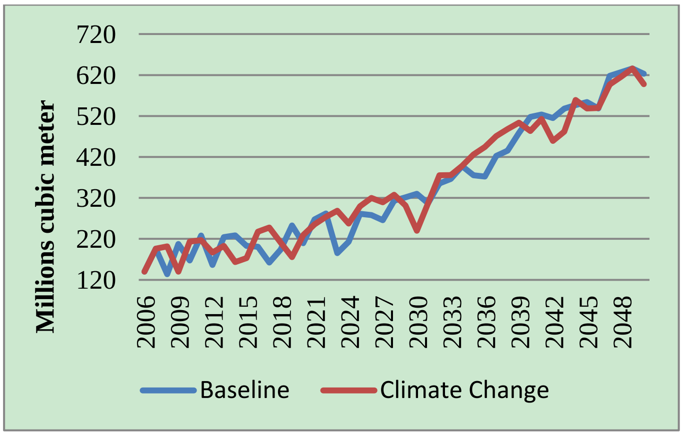

Figure 13 Unmet demand comparison between the baseline scenario and the climate change over the projected period (2006-2050)

Still the climate change which is applied here by reducing the inflow by 23% could potentially affect the region negatively and tax already limited water resources.

The policy questions that remain are how to reduce the stress on the region due to either increasing demands or climate change, and what sources of water and management options are available to manage drought.

K. Combining the above Two Scenarios (Increase TWW Reuse and Climate Change)

This scenario combines the above two scenarios—reuse of the treated wastewater and climate change—to see how this will influences the situation in the JV.

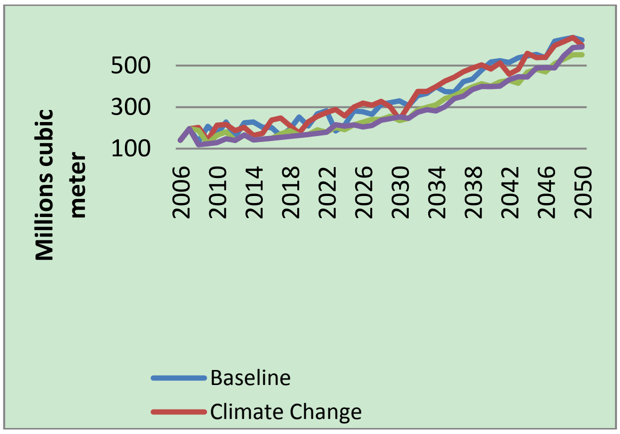

Figure 14 Unmet demand – comparison for the unmet demand for different scenarios

It can be seen from the above figures that one promising strategy to overcome the influence of climate change on the region is to increase the use of unconventional water (TWW) in agriculture. This will help to reduce the stress on freshwater, which then could be allocated for domestic uses.

L. Altered Patterns of Agricultur.

The main objective of this scenario is to analyze the impact on the storage reservoir when cultivating crops with less water demands. Figure 15 shows that this reduces the stress on the reservoir since the agricultural demand has been reduced with average about 185 Mm^3, compared to the baseline scenario.

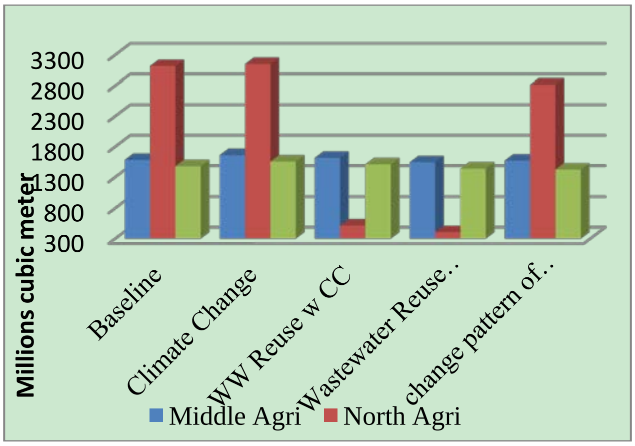

Figure 15 the unmet demand for the agriculture when applying different scenarios

This scenario indicates that saving water can be accomplished through demand reduction, when farmers adapt new crops that required less water to replace it with high-value crops that required more water.

TABLE 4 UNMET DEMAND WITHIN DIFFERENT SCENARIOS (MILLION CUBIC METERS)

	Climate Change	WW Reuse w CC	WW Reuse for N Agr	Change pattern of Agr.
Middle Agri	1660.40	1609.11	1609.11	1571.01
North Agri	3148.94	1954.66	1954.66	2814.05
South Agri	1553.94	1503.71	1503.71	1423.02
Sum	6363.28	5067.47	5067.47	5808.07

X. DISCUSSION AND CONCLUSION

In his paper we developed and calibrated a scenario model for the Jordan Valley and explored different scenarios. The baseline scenario results in Amman city having a growing unmet demand, while the agricultural sector maintains its output.

The reused TWW scenario resulted in reduced stress on freshwater resources, which could then be allocated to Amman city. The unmet water demand was reduced by 18.3 %. Climate change was simulated by reducing the inflow to the region by 23%. The reduction did not have a large influence on dam storage, but it did lead to less water for agriculture, since Amman city has higher priority to receive water. Combining an increase in TWW in agriculture with climate change suggests that TWW could compensate the negative effect of reduced water availability: we found that the unmet demand for agriculture was reduced significantly within average of 56 Mm^3. Finally, the scenario of changing cropping patterns shows that stress on water resources can be reduced considerably while maintaining the size of the agricultural area.

The calibrated WEAP model provides useful information for decision makers to evaluate various policy interventions. Future research could concentrate on further refining the spatial resolution of the model so as to provide more accurate geographical specific recommendations. Including more rural and urban areas would further improve the regional scope of water resource policies.

ACKNOWLEDGMENTS

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