SUSTAINABILITY OF BASIN LEVEL DEVELOPMENT UNDER A CHANGING CLIMATE

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ABSTRACT
The potential impacts of projected future climate change scenarios on the hydrologic response of a water-stressed Mediterranean river basin (Upper Litani River Basin in Lebanon) are quantified and assessed using the Water Evaluation and Planning (WEAP) model. Projected basin-level changes in water availability are then compared to multi-sector demands estimated under six basin-level development scenarios. The sustainability under these scenarios and the resilience of the system in the face of the projected climatic changes are then assessed in terms of a water resources index, demand reliability, demand satisfaction index, demand reliability index and the average duration of failure. The results reveal that the basin is expected to experience significant alteration in its hydrologic cycle and that current plans envisioning an increase in irrigated areas within the basin, is non-sustainable and will lead to a highly water stressed system. A conservative basin-level plan that integrates both supply- and demand-side measures is proposed in an effort to achieve a more sustainable system.
Keywords: Climate Change, Water Stress Indices, Watershed Management, WEAP

1 INTRODUCTION

Climate change has been identified as one of the main drivers of water availability in the 21st century [1, 2]. Its impacts are known to have wide ranging effects on the socio-economic, political, water [2, 3] and agricultural [3, 4] sectors jeopardizing the sustainability of environmental systems [3, 5]. The relationship between climate and water resources, in particular, is recognized with potential perturbations in surface runoff, groundwater recharge, lake levels, and water quality [3]. It is projected that climatic changes will increase the percentage of the world's population currently living in water stressed regions, from one-third to two-thirds over the next few decades [4, 6]. In the face of potential shortages, additional water resources will need to be developed to meet the future water demand. As a result, most river basins are expected to face increased pressures [6, 7]. Mediterranean basins are identified as one of the most vulnerable freshwater systems [2, 3]. In this context, social, economic and technological changes will need to be implemented to alleviate or minimize water scarcity challenges [8–11].

Unfortunately, many current national and/or regional water plans fail to appropriately account for projected climate change impacts and often disregard the importance of the regional and local context [8, 12]. This oversight stresses river systems, reducing their reliability and resilience and increasing their vulnerability and average duration of failure. To avert these shortcomings, basin level adaptation measures have to be properly formulated and their impacts assessed under future climatic conditions. In this context, future alternatives for water resources management under a changing climate were assessed at a river basin scale (the Upper Litani River Basin in Lebanon) taking into account demographic, economic, technological, and management constraints and opportunities. The efficacy of proposed alternatives was tested against a set of future climatic scenarios that represent Intergovernmental Panel on Climate Change (IPCC) defined story lines executed under several global circulation models (GCMs). Water and sustainability performance metrics [13–15] were then used for performance assessment and quantification of the combined impacts associated with

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climate change and management alternatives on the water resources system in the basin. The paper concludes with arguing the need to integrate both supply- and demand-side measures for setting a more sustainable watershed management plan.

2 METHODS

2.1 Study Area

Extending over an area of ~2,186 km^2, the Litani river basin is the most important renewable freshwater system in Lebanon, a country that is expected to receive less precipitation and experiences higher temperatures under most future climatic scenarios coupled with a projected increase in water demand. Geomorphologically, the basin is divided into two sub-basins by the Qaraoun dam. The upper part (Fig. 1), the pilot area considered in this study, stretches from the Northern Bekaa plain to the dam. It covers an area of 1,545 km^2 with a population of ~660,000 in 2010 that is expected to reach 1.45 million by 2100. The upper Litani river basin (ULRB) is also the most agricultural productive area in Lebanon, with over 800 km^2 of productive agricultural land [16], of which 290 km^2 are intensively cultivated and irrigated. Future plans aim at increasing irrigated areas to ~540 km^2 by the late 2030 early 2040.

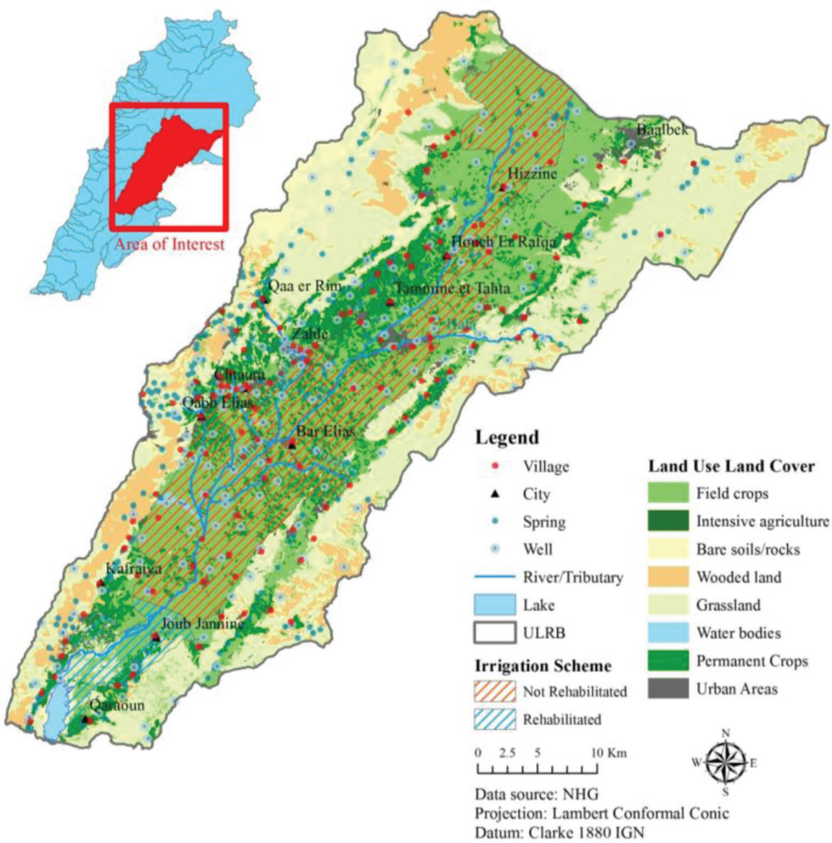

Figure 1. The upper Litani river basin with the agricultural and irrigation schemes.

Surface water resources in the ULRB are estimated at 290 MCM/year, of which 200 million cubic meter (MCM)/year are currently used. In addition, groundwater abstraction in the basin is significant (~190 MCM) and largely non-regulated. The water stored in the Qaraoun Lake, a reservoir with an estimated area of ~12 km^2 and a capacity of 220 MCM, is also used for hydropower and irrigation at a rate of 160 MCM/year [17, 18]. While at present only 15 MCM/year are used for irrigation, future plans envision using between 70 and 80 MCM/year of the reservoir's water for irrigation. The basin's water infrastructure is relatively old and inefficient, with an average supply service less than 10 hours a day and more than 50% of the transmission and distribution networks installed is more than 40 years ago. Future climatic prediction for the region foresee decreased precipitation and increased temperatures [19] resulting in lower surface runoff and groundwater recharge rates coupled with increased evapotranspiration [20]. Similarly, socio-economic pressures (population growth, shifts in agriculture practices and changes in water management) are expected to reduce the availability of water resources in the basin.

2.1.1 Future Climate Scenarios

Twenty four future climatic scenarios were used to assess the impact of climate change on the hydrology and water resources in the ULRB for the time period 2011–2100 [19]. 24 scenarios were constructed by coupling the four IPCC Special Report on Emissions Scenarios (SRES) emission scenarios (i.e. A1FI, A2, B2 and B1) with the five commonly used GCMs (i.e. Coupled Global Climate Model (CGCM2), Commonwealth Scientific and Research Organisation (CSIRO2), European Centre for Medium Range Weather Forecasts and Hamburg (ECHAM4), Hadley Centre Coupled Model (HadCM3) and Parallel Climate Model (PCM)). In addition, four ensemble scenarios were defined that averaged emission scenarios over the different GCM models [21–24]. The spatial resolution of the gridded climatic data was 0.5 degree (~50 km) [19]. Assessing the future climatic data over the study area indicated that the most pessimistic scenario is the fossil intensive ECHAM4-A1FI, while the CSIRO2-B2 (ecologically friendly) was found to be the most optimistic scenario. In this study, we present our results in terms of the four ensemble scenarios (A1FI, A2, B2 and B1) along with the most pessimistic and optimistic scenarios (ECHAM4-A1FI and CSIRO2-B2, respectively).

2.1.2 Water Resources Management Alternatives

To investigate the impacts of future climate change on the hydrology of the ULRB, six future management alternatives were defined namely, the Reference ('Do Nothing') (RA), the Non-Conservative (NCA), the Conservative Agricultural (CAA), the Management-Based Adaptation (MAA), the Structural Focused (SFA) and the Full Development (FDA). All six alternatives account for population growth in addition to different sets of proposed demand and supply-side mitigation measures. The RA represents a future with the same current water resources practices, while accounting for the increase in population and for a slight change in current agricultural practices. The NCA accounts for population growth and an expansion in agricultural practices coupled with no adaptation measures. This alternative represents mostly closely the proposed governmental plan for the basin. The CAA and the MAA account for limited expansion in agricultural practices, while considering different demand side adaptation measures. While the CAA focuses primarily on reducing agricultural water consumption by changing cropping patterns, the MAA projects a future where major losses from the supply system are reduced through enhanced connectivity and network rehabilitation. On the other hand, the SFA accounts for increases in population and agricultural practices, with emphasis on supply-side adaptation measures. Finally, the FDA assumes the implementation of a full suite of potential demand and supply-side adaptation measures at the basin level.

Table 1 summarizes the adaptation measures for each alternative with corresponding estimated costs. Table 2 outlines the key constraints and model variables that were defined for each alternative. Note that policy and nonphysical measures proposed in the alternatives were implemented in the Water Evaluation And Planning (WEAP) model [25, 26] through a reduction of areas (e.g. agricultural areas) and/or changes in the supply and return flow constraints. On the other hand, legislative and legal framework measures were accounted for by introducing constraints on permissible water abstraction rates (e.g. groundwater abstraction).

Table 1: Adaptation measures under future water resources management alternatives.

		Responses		
Alternatives	Adaptation Measure	*Increase supply*	*Demand reductions*	Cost
RA	None			
NCA	None			
CAA	Reduce agricultural water consumption (Improved Irrigation)		++++	+
	Change in type of crops		++	++
	Enhanced connectivity	+	++	+
	Improvement in agricultural technology & research		+	+
MAA	Enhanced connectivity		+++	+/++
	Network rehabilitation		+	+
	Reduced agricultural water consumption (Improved irrigation)		++	+
	Change in crop types		+	+
	Water conservation/ Sustainable water use (domestic water consumption)		++	+
SSA	Enhanced connectivity		+++	+/++
	Network rehabilitation & expansion (infrastructure/ distribution)	+++	+	++++
	Wastewater treatment	+	++	++++
	Increased water-use efficiency (Water reuse, water recycling)	+/++	+	+++
FDA	Enhanced connectivity		+++	+/++
	Network rehabilitation & expansion (infrastructure/ distribution)	+++	+	++++
	Wastewater treatment	+	++	++++
	Reduce agricultural water consumption (Improved Irrigation)		++++	+

(*Continued*)

Table 1: (*Continued*)

Alterna-tives	Adaptation Measure	Responses: *Increase supply*	Responses: *Demand reductions*	Cost
	Change in type of crops		++	++
	Improvement in agricultural technology & research		+	+
	Environmental sustainability & protection	++		++
	Increased water-use efficiency (Water reuse, water recycling)	+/++	+	+++
	Water conservation/ Sustainable water use (domestic water consumption)	+	+	+

Predicted water savings: < 10 MCM = +; 10–25 MCM = ++; 25–50 MCM = +++; > 50 MCM = ++++; Estimated implimentation costs: < 1 $/m^3$ = +; 1 – 2 $/m^3$ = ++; 2 – 3 $/m^3$ = +++; > 3 $/m^3$ = +++

Table 2: Summary of alternatives, drivers and key adaptation measures.

	Key drivers and adaptation measures
RA	• Population in basin moderately increasing ~1.45 million by 2100 • Economic development stable: water demand ~10% of urban demand by 2100 • Water consumption per capita 160 l/capita/day • Agricultural area stable (290 km^2 irrigated, 800 km^2 total agricultural lands (TAL)) • System losses 52.5%; irrigation efficiency 63% • Crop type distribution (55% mixed vegetables, 25% fruits, and 20% wheat) • Receives up to 15 MCM of water from Qaraoun Lake
NCA	• Population in basin moderately increasing ~1.45 million by 2100 • Moderate economic development: water demand 30% of urban demand by 2100 • Water consumption per capita 180 l/capita/day by 2100 • Increasing agricultural area (520 km^2 irrigated by 2040 and stabilizing; 900 km^2 TAL) • System losses 52.5%; irrigation efficiency 63% • Crop type distribution: (56% mixed vegetables, 19% fruits, and 25% wheat) • Receives up to 15 MCM of water from Qaraoun Lake
CAA	• Population growth moderately increasing ~1.45 million in 2100 • Economic development stable: water demand ~10% of total urban demand by 2100 • Water consumption per 160 l/capita/day • Increasing agricultural area (390 km^2 irrigated by 2040 and stabilizing, 800 km^2 TAL) • System losses 42.5%; irrigation efficiency 73.25% • Crop type distribution (40% vegetables, 15% fruits, and 45% wheat) • Receives up to 85 MCM of water from Qaraoun Lake

(*Continued*)

Table 2: (*Continued*)

	Key drivers and adaptation measures
MAA	• Population moderately increasing reaches ~1.45 million in 2100 • Moderate economic development: water demand 20% of total urban demand by 2100 • Water consumption per capita 140 l/capita/day • Increasing agricultural area (390 km^2 irrigated by 2040 and stabilizing, 800 km^2 TAL) • System losses 37.5%; irrigation efficiency 70% • Crop type distribution (45% vegetables, 20% fruits, and 35% wheat) • Receives up to 45 MCM of water from Qaraoun Lake
SSA	• Population moderately increasing reaches 1.45 million in 2100 • Moderate economic development: water demand 30% of total urban demand in 2100 • Water consumption per capita 180 l/capita/day by 2100 • Increasing agricultural area (390 km^2 irrigated by 2040 and stabilizing, 800 km^2 TAL) • System losses 20%; irrigation efficiency 69% • Crop type distribution (45% vegetables, 20% fruits, and 35% wheat) • Wastewater treatment and increased water-use efficiency • Receives up to 45 MCM of water from Qaraoun Lake
FDA	• Population in the basin moderately increasing reaches 1.45 million in 2100 • Moderate economic development: water demand 30% of urban demand in 2100 • Water consumption per capita 58.4 m^3/capita/year (160 l/capita/day) • Increasing agricultural area (390 km^2 irrigated by 2045 and stabilizing, 800 km^2 TAL) • System losses 20%; irrigation efficiency 73.25% • Crop type distribution: (40% vegetables, 15% fruits, and 45% wheat) • Wastewater treatment and increased water-use efficiency • Receives up to 85 MCM of water from Qaraoun Lake

2.2 Hydrological modelling, water stress indices, and performance metrics

A calibrated WEAP integrated hydrologic and water management model for the URLB [20] was used to investigate future climate impacts on water resources availability and to examine the effects of future management plans. The model generated monthly hydrologic basin responses (river flow, groundwater recharge, and evapotranspiration) that were used to define the amount of available water. These volumes were compared with demands under the various water resources management alternatives in order to determine the magnitudes of future water scarcities in the basin. The estimation of available water sources was conducted on a monthly time basis over the time period from 1961 to 2100. Seven water stress indices were used to assess the impact of management alternatives on the ULRB's water resources system:

C_R: Reliability that measures the time frequency when the system is able to supply enough water to meet the demand requirement; it is expressed in percent time;

C_{RS}: Resilience that measures the speed at which the supply system is able to recover after a failure (in %);
V_T: Time vulnerability that measures the maximum duration of system's failure in meeting its demands (in months);
V_V: Volumetric vulnerability that measures the maximum volume of the system's failure in meeting its demands (in MCM);
D_{SI}: Demand satisfaction representing reliability of volumetric supply of water (in % deficit in volume)
D_{RI}: Demand reliability that represents the total volume of supply that met the demand under a condition of no failure divided by the total water demand volume (in % deficit in volume);
F_{DI}: Failure deficiency that is the average duration of failure (in months)

More detailed discussions on the adopted metrics can be found in Hashimoto *et al.* [27], Zongxue *et al.* [28], Fowler *et al.* [29], Martin-Carrasco and Garrote [30] and Pulido-Velazquez *et al.* [31] to name a few. All indices were used to examine the reliability, resilience, demand satisfaction and reliability, and deficit vulnerability of the ULRB water sources system under the baseline (1961–2010) and future projections of climatic conditions and basin management alternatives (2011–2100).

3 RESULTS AND DISCUSSIONS

Simulation results showed that between 1961 and the mid 1990's the ULRB was able to meet almost all its demands. Starting in the mid-90's, the basin underwent significant agricultural expansion that coincided with several dry years. As such, the system experienced decreased water availability and increased water shortages. Current (averaged over 2001–2010) water demands in the basin, estimated at ~390 MCM/year, exceed the long-time average water supply of ~250 MCM/year (averaged over 1961–2010). Projected water demands under future water management alternatives were estimated independently of climatic conditions. Under the do-nothing RA management alternative, the average yearly demand reached 500 MCM/year by 2100. The increase in demand is mostly attributed to population increase. Under the NCA, the water demand was estimated at ~740 MCM/year by 2100, exceeding by far the annual renewable water resources (i.e. surface flow and recharge). Under the CAA, water demand reached 440 MCM/year by 2040, before decreasing to ~400 MCM/year by 2100. The increase in demand is instigated by the planned implementation of new irrigation schemes as well as changes in crop types between 2011 and 2040. The drop in demand is attributed to the change in crop types and a greater efficiency in agricultural water use. The MAA and SCA had average water demands of 456 and 500 MCM/year (average 2011–2100), respectively. Under these alternatives, upgrading the agricultural, distribution network, and wastewater systems were able to offset the agricultural expansion planned within the basin. Finally, under FDA, the annual water demand was estimated to range between ~420 MCM/year and 360 MCM/year between 2011 and 2100, respectively. The reduction in annual water requirement is attributed to the implementation of water saving measures as well as to the greater use of the stored water from the Qaraoun reservoir.

The available water supply in the basin under the different climate change scenarios was determined. Under ECHAM4-A1FI, the worst-case future climate change scenario, the projected average water supply, from both surface and groundwater sources, was estimated at 320 MCM/year (average 2011–2100). The mean supply reached 370 MCM/year under the most optimistic scenario, CSIRO2-B2. Meanwhile, under the ensemble scenarios the yearly water supply ranged between 337 and 345 MCM/year, with a standard deviation of ~60 MCM/year. As expected the variability between scenarios increases as time progresses.

Comparing projected water supply under future climate scenarios with the predicted demands under the defined water management alternatives provides the expected future water deficits in the ULRB. Under the RA, the impact of climate change for the first 30 years of the simulation is a deficit of ~120 MCM/year. The impact of climate change and increased demand becomes more apparent after the 2050's, whereby deficits consistently exceed 200 MCM/year. Under the NCA management alternative, the water deficit in the basin is dramatic. By 2030, the magnitude of the deficit is expected to surpass the basin's annual renewable resources. Under the CAA alternative, the proposed demand-side agricultural mitigation measures were able to reduce the water deficits to levels slightly higher than the long-term average for the basin. The water deficits under the MAA and SSA supply-side alternatives were in general very close to the deficits recorded for the RA, highlighting the limited ability of supply-side measures to reduce deficits. Note that the MAA, which incorporates some elements of demand-side mitigation measures, resulted in slightly lower deficits when compared with SSA. Under the FDA alternative, which accounts for all adaptation measures, the ULRB is projected to have minimal water shortages, ~20 MCM under the best CSIRO2-B2 climate scenario, and ~50 MCM/year under the worst ECHAM4-A1FI climate scenario, and between 28 and 35 MCM/year under the four ensemble models.

The water indicators for the ULRB were calculated for the baseline period between 1961 and 2010 as well as under future climatic scenarios (2011–2100). Between 1961 and 2010, the performance metrics were acceptable. The overall system's reliability (C_R) reached a high of ~97%, the average duration of failure (F_{DI}) of a deficient system was around 2.85 months, and it's maximum duration (V_T) was 4 months, while the system's resilience (C_{RS}) reaching 35% recovery/per month, the system demand satisfaction (D_{SI}) was around 95%, and the demand reliability (D_{RI}) reached 93%. Water stress indices for all management alternatives were calculated under the various climate change scenarios for 2011–2100 (Table 3). The results further corroborate the fact that the do nothing scenario will reduce the reliability (C_R) of the system to as low as 66% and increase the duration of system failure to around 4.2 months under the worst ECHAM4-A1FI. With the NCA the system's reliability (C_R) is not expected to go above 63% even under the most optimistic climatic scenario. In fact, under the NCA the ULRB would be able to supply the total water demand only 50% of the times. Under the CAA, the system's reliability will drop to between 73% and 88% and the duration of failure is expected to increase up to 4 months. Water reliability under the MAA and SSA were largely similar with the R_A varying between 65 and 74%. The demand satisfaction index was slightly higher for MAA, while the SSA had slightly shorter F_{DI} values and a slightly faster recovery. Under FDA, the overall system reliability ranged between 78 and 92%. The ULRB would thus be able to supply between 86 to 94% of its water demands. If the FDA mitigation measures are implemented in the URLB, it is projected that the annual water deficit would not exceed the 150 MCM/year threshold even under the driest year modeled under the worst-case climate change scenario (ECHAM4-A1F1).

Table 3: Performance metrics under all climatic scenarios and water management alternatives (2011–2100).

		ECHAM4-A1FI	Ensemble-A1FI	Ensemble-A2	Ensemble-B1	Ensemble-B2	CSIRO2-B2
RA	C_R (%)	66	69	70	71	71	74
	D_{SI}; D_{RI}	64; 52	68; 56	69; 58	70; 60	70; 60	75; 64
	C_{RS} (%)	24	26	27	27	27	30
	V_V	350	322	314	315	312	283
	F_{DI} ; V_T	4.2; 7	3.8; 7	3.7; 7	3.7; 6	3.7; 6	3.3; 5
NCA	C_R (%)	57	60	60	61	61	63
	D_{SI}; D_{RI}	44; 33	47; 36	48; 38	48; 38	48; 38	52; 41
	C_{RS} (%)	19	21	21	21	22	23
	V_V	646	627	620	620	619	587
	F_{DI} ; V_T	5.3; 8	4.8; 7	4.8; 7	4.8; 7	4.5; 7	4.3; 6
CAA	C_R (%)	73	78	80	81	81	88
	D_{SI}; D_{RI}	80; 69	84; 76	86; 78	86; 79	86; 79	91; 87
	C_{RS} (%)	25	29	29	29	30	32
	V_V	186	169	154	154	152	135
	F_{DI} ; V_T	4; 7	3.4; 6	3.4; 6	3.4; 6	3.3; 6	3.1; 5
MAA	C_R (%)	65	69	69	70	70	74
	D_{SI}, D_{RI}	69; 57	73; 62	74; 63	75; 63	75; 63	80; 70
	C_{RS} (%)	23	25	25	26	26	29
	V_V	272	257	249	249	247	212
	F_{DI} ; V_T	4.3; 7	4; 6	4; 6	3.8; 6	3.8; 6	3.4; 6
SSA	C_R (%)	66	68	68	69	69	73
	D_{SI}, D_{RI}	63; 48	66; 52	68; 53	68; 53	68; 53	72; 60
	C_{RS} (%)	24	26	26	26	26	30
	V_V	329	307	297	297	295	261
	F_{DI} ; V_T	4.2; 7	3.8; 6	3.8; 6	3.8; 6	3.8; 6	3.3; 6
FDA	C_R (%)	78	84	85	86	87	92
	D_{SI}, D_{RI}	86; 76	90; 82	91; 84	91; 85	91; 85	94; 90
	C_{RS} (%)	29	33	33	34	35	37
	V_V	148	142	141	143	142	129
	F_{DI} ; V_T	3.4; 7	3; 6	3; 5	2.9; 5	2.9; 5	2.7; 4

4 CONCLUSION

The potential impacts of future climate change on the ULRB were assessed with regards to six watershed management alternatives that incorporated different supply- and demand-side measures. The model simulations showed that the basin is highly vulnerable to projected future climate changes, even if no future development projects are implemented within the basin. The results also highlighted the risk of current plans aiming to increase agricultural areas in the basin up to 900 km^2, of which 520 km^2 would be intensively irrigated. If implemented, it will decrease the ULRB reliability to less than 63% even under the most optimistic future climatic scenario. With such a low reliability and increased vulnerabilities to the system, socio-economic hardships within the basin are expected along with an increase in water conflicts between various demand sectors. Moreover, with the total system demand exceeding supply the environmental situation in the basin –in terms of environmental flows and water quality- is expected to degrade significantly. This bleak situation is shared with other basins in the Middle East, many of which are trans-boundary river systems (Nile, Euphrates-Tigris, Orontes, Jordan and El-Kebir basins). There system failure will only strain existing precarious trans-boundary water conflicts. The future water scarcity in all basins in the Middle East are tightly linked to remediating poor water management in the agricultural sector. The model results highlighted the limitation of implementing supply-side mitigation measures alone. It is only when demand-side agricultural adaptation measures are implemented that the basin will achieve higher sustainability levels. Other adaptation measures targeting other economic sectors can help; but are ineffective alone to alleviate shortages within the basin. As such, priority across the Middle East should be given towards improving irrigation methods, exploring crops with lower water consumption, and increasing the efficiency of the distribution network.

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