Climate Change and Water Resources in Lebanon and the Middle East

E. Bou-Zeid[1] and M. El-Fadel[2]

Abstract: While the extent of human-induced global warming is inconclusive, the vulnerability of natural systems to rapid changes in climate patterns is regarded as one of the most challenging issues in recent years. Water resources are a main component of natural systems that might be affected by climate change. This paper characterizes water resources in several Middle Eastern countries and evaluates regional climate predictions for various scenarios using general circulation models. The country of Lebanon is selected as a case study for an in-depth investigation with potential impacts on the water budget and soil moisture as indicators. Adaptation measures are assessed, with a focus on no-regret actions in the context of local socioeconomic and environmental frameworks.

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Introduction

Climate change due to greenhouse gases (GHGs) has been at the forefront of current research efforts in the past decade (IPCC-WGI 1996a,b). The aim of these efforts was defined at the Earth Summit in Rio de Janeiro, Brazil as achieving ''stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climatic system.'' This statement of purpose clearly recognizes that some change is inevitable and acceptable as long as it is not considered dangerous. However, the real challenge is to predict how GHGs interfere with the climatic system and what impacts will result. In this context, several modeling approaches have been used to simulate climate conditions under increased CO_2 concentration. Since CO_2 is the most significant GHG, accounting for 70% of radiative forcing (IPCC-TGCIA 1999), all other GHGs are converted into equivalent CO_2 in accordance with their relative radiative forcing ability. The models vary from simple upwelling diffusion-energy balance models to complex general circulation models (GCMs) with atmospheric and ocean modules (AOGCMs) (IPCC-WGI 1996a). GCMs solve the equations of energy and mass transfer in the atmosphere and oceans. These media are divided into a horizontal grid with a typical resolution of 2–4° latitude by 2–4° longitude, and 10–20 layers in the vertical direction. Winds, ocean currents, exchanges of heat, moisture and momentum between the two components, and several other processes are simulated. GCMs attempt to predict future climatic conditions under increased atmospheric radiative forcing. They are validated using sets of past climate data to predict current climate conditions. However, the intrinsic complexity of climate systems has hindered the development of a coherent and comprehensive set of future scenarios that can be safely relied upon (IPCC-WGI 1996a,b). Many aspects, critical to climate modeling, are still not fully understood including cloud physics, aerosol effects, and atmosphere-ocean interaction, among other processes (IPCC-WGI 1996a; *Impacts* 1999).

Another critical factor hindering the development of accurate predictions for future climate is the uncertainty inherent in estimating GHG emissions and concentrations. The Intergovernmental Panel for Climate Change (IPCC) developed several emission scenarios, investigating high, average, and low GHG releases. IS92a (updated in 1995 to IS95a) is one such scenario that assumes average emission prospects. Note that IS92a is the IPCC scenario that predicts GHG emission under average development and growth projections, assuming no emission mitigation policies are implemented. IS92a predicts an increase of equivalent CO_2 concentrations close to 1%/year. Recent emissions have been below the levels predicted by IS92a. However, this is largely attributed to a slowdown in economic activity in countries with economies in transition, leading to reduced energy and fossil fuel use. Hence, this slowdown might be only temporary. Other scenarios have been developed to consider the effect of stable CO_2 concentrations, such as $2\times CO_2$ (2×reference CO_2 concentrations), $4\times CO_2$, S450, S550, and so on. Reference CO_2 could be preindustrial levels or 1990 levels. S450 and S550 are stable at 450 or 550 ppm. Concentrations of GHGs stabilize after reaching fixed levels, the time needed to reach these levels is important in view of the thermal inertia of the oceans. In addition to GHG concentrations, several other factors are important for climate modeling, such as aerosol concentrations. The localized cooling effect of aerosols is considered an important aspect that cannot be neglected in climate change models (IPCC-WGII 1997; *Impacts* 1999; IPCC-WGI 1996a). However, similar to GHGs, aerosol concentration predictions are highly uncertain. To account for these uncertainties, ranges rather than determinate values are used. GCMs are run for several emission scenarios and results are assessed.

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Table 1. Some Impacts on Water Resources Expected with Changing Climate

Resources	Major impacted components	Potential effects
Hydrologic resources[a]	• Precipitation	• Soil moisture changes
	• Evaporation	• Reduced groundwater recharge
	• Transpiration	• Water shortages or surpluses
	• Runoff	• Dam failure due to floods
	• Recharge	• Dam storage loss due to sedimentation
Water quality[a]	• Water temperature	• Changes in chemical quality
	• Water salinity	• Changes in biological quality
	• Pollutant concentrations	• Changes in thermal quality
	• Fauna and flora	
Aquatic systems[a]	• Streamflows	• Droughts or floods
	• Erosion and sedimentation	• Dam failure due to floods
	• Water levels in surface water bodies	• Dam storage loss due to sedimentation
	• Water levels in aquifers	
	• Water fluxes in subsurface	
Water supply[b]	• Water demand per capita	• Water demand increase beyond projected levels
	• Agricultural water demand	
Water management systems[b]	• Streamflows	• Reduced water supply
	• Water levels in surface water bodies	• Changing loads on water treatment systems
	• Water levels in aquifers	• Changing hydropower production potential

[a]Biophysical resources.

[b]Socioeconomic resources.

A shortcoming of GCMs is their coarse grid and large scales relative to hydrological systems. Coupling of regional circulation models (RCMs) or local area models to GCMs minimizes the limitations and enhances the reliability of the results (IPCC-WGI 1996a; *Impacts* 1999). RCMs solve the same conservation equations as GCMs; however, RCMs model smaller zones and have higher resolutions, allowing the inclusion of small-scale details such as topography. Regional models typically overlay subgrids in GCM cells and reproduce the distribution of average GCM results in these cells. Efforts are being exerted to create fully coupled interactive GCMs-RCMs where data are also transmitted from RCMs to GCMs (IPCC-WGI 1996).

Despite uncertainties, GCMs depict certain trends that are useful in analyzing vulnerability and setting guidelines for potential adaptation measures. GCM simulations generally indicate increasing global temperatures, leading to a more active hydrologic cycle. An increase in the hydrologic cycle activity denotes increasing global evaporation and precipitation. For the Middle East, GCM simulations indicate higher future temperatures that will increase evapotranspiration and changes in climate patterns that might reduce rainfall in the region as a whole (IPCC-DCC 1999; IPCC-WGI 1999a). In contrast, a few other recent simulations including the effect of aerosols in the atmosphere indicate a potential for lower temperatures in the Middle East, which may increase rainfall and water availability (Jones et al. 1997). The present paper evaluates climate change scenarios for the Middle East, with Lebanon as a case study. For this purpose, simulations from several GCMs were used and a water balance model was applied to assess several indicators, including actual evapotranspiration, surplus, soil moisture deficit, and evapotranspiration deficit. Adaptation measures are also addressed in the context of regional characteristics.

Climate Change and Water Resources

Vulnerability of water systems and their sensitivity to climate change have been an active research topic in the last decade (Arnell 1996; *Impacts* 1999). In view of the uncertainties associated with climate and hydrologic models, the benefits of developing quantified predictions remain controversial (IPCC-WGII 1996). Several approaches can be used to compile results of different analyses and scenarios and produce aggregate estimates of potential changes in biophysical characteristics of a basin. Bayesian techniques are helpful in developing impact assessment studies and explaining results. Such techniques rely on the combination of diverse sources of information (model output, subjective opinions, etc.) in a single theoretical framework that results in an inference or decision rather than an output that needs further analysis (Hobbs 1997). Other approaches use indicators and graphical methods, which in general are more appealing to policymakers because they rely on plotting the available information and presenting a visual tool that assists in decision making (Lane et al. 1999).

Water resources management systems are very adaptive by nature (or through institutional intervention), and the usual variations in climatic and socioeconomic conditions have provided water managers with experiences that help them cope with potential changes in climate patterns (Strzepek 1998). However, the high rate of climate change and its cumulative effect might pose serious problems. The biophysical and socioeconomic impacts on water resources expected with a potentially changing climate are summarized in Table I. Note that, in many situations, changes in the variability and distribution of some patterns are more important and detrimental than changes in mean levels (Noda and Tokiota 1989). For example, increased temperature extremes and floods/droughts associated with sharper precipitation patterns could lead to an increase in epidemic and waterborne disease infections (Patz 1999).

It is generally accepted that increased global temperatures will inevitably lead to changes in the hydrologic cycle. This is attributed to increased atmospheric water vapor and enhanced poleward water vapor transport (IPCC-TGCIA 1999). However, vast regions may still experience reduced precipitation. The increase in temperature leading to higher evaporation and the expected increase in precipitation event intensity would further re-

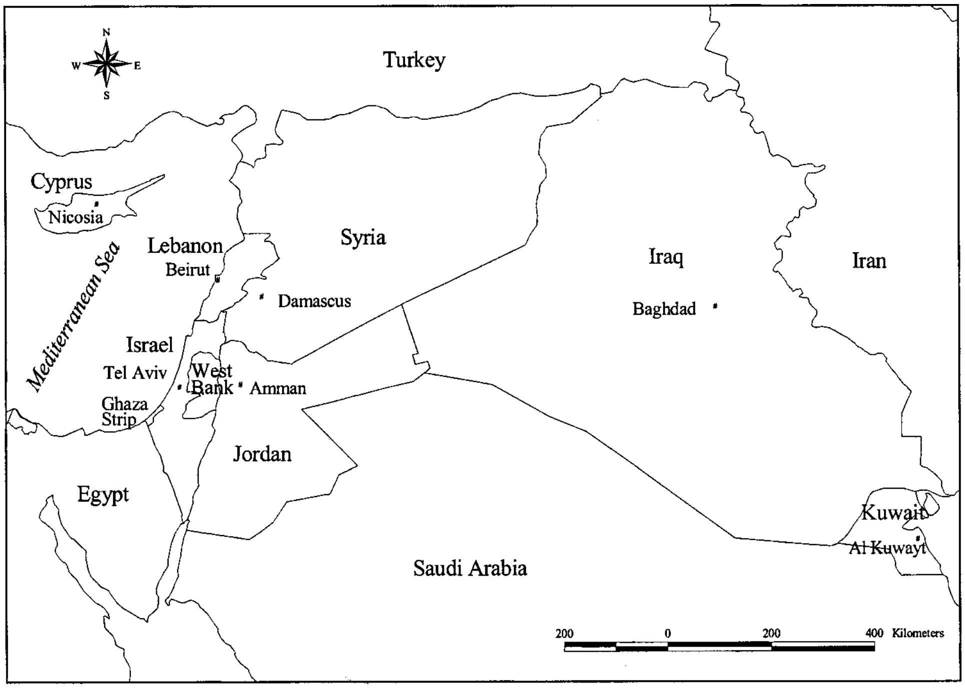

Fig. 1. Map of Middle Eastern countries considered in this study

duce available water in regions where precipitation is reduced or unchanged. General findings related to the climate change effect on rainfall, water availability, and the hydrologic cycle include the following:

- Intermonthly variability for temperatures will likely remain unchanged (tropical regions) or decrease (midlatitudes in the northern hemisphere) (Meehl et al. 1994; IPCC-TGCIA 1999).
- Large changes in the frequency of extreme events can be triggered by a small change in the mean climate or climate variability. Changes in variability are more detrimental than similar changes in mean levels (Whetton et al. 1993; Hennessey and Pittock 1995; Arnell 1996; IPCC-TGCIA 1999). This is particularly true for small and medium-size watersheds (*Impacts* 1999).
- Regions where net warming occurs will observe an increase in high temperature extremes and a decrease in low temperature extremes (Whetton et al. 1993; Hennessey and Pittock 1995),
- Several models suggest increased precipitation intensity leading to more floods and longer drought periods (Noda and Tokiota 1989; Gordon et al. 1992, 1999b).
- Soil moisture will decrease, due mainly to increased evapotranspiration, inducing an increase in agricultural water demand and changes in the flora of nonirrigated regions (*Climate* 1996a; IPCC-WGII 1996b; *Impacts* 1999).
- Total runoff will increase unevenly worldwide (UKMO 1997; *Impacts* 1999).
- Impact on rivers depends strongly on current climate, physiographic properties, and land use. Catchments subjected to the same climate change may have completely different responses (Arnell 1996).
- Seasonal streamflow timing patterns will be modified—particularly where the snowfall and snowmelt contribution to streamflow is significant (*Impacts* 1999).
- Moderate differences in scenarios can produce large differences in results for river flow models because hydrologic systems tend to amplify differences between scenarios (Arnell 1996). This applies especially in arid and semiarid regions (IPCC-WGII 1997).

Water Resources in Lebanon and Middle East

The borders of the Middle East are not well established. The boundaries of this region change with changing topics. A different approach in defining the area is used in politics, geography, history, environment, economics, and so on. For the scope of this paper, the countries that have significantly interconnected water resources and that do not yet rely heavily on desalination techniques are considered—that is, Lebanon, Syria, Iraq, Israel, Jordan, and the Palestinian Authority (West Bank and Gaza Strip) (Fig. 1). Turkey is the source of a significant amount of water flowing into Iraq and Syria; however, this country is not addressed in this study, due to climatic and hydrologic differences with the countries under consideration.

The Middle East and North Africa, with water resources of less than 1,000 m^3 per capita in nine out of 14 countries, is the part of the world where water scarcity is the most severe and precarious (Postel 1993; Berkoff 1994, ESCWA 1996, 1999). Water shortage and uneven distribution of the water supply are exacerbated by the rapid demographic and economic development in the region (Fig. 2 and Table 2), increasing water demand at a relatively high pace. Iraq is the only other country in the Middle East that appears to have sufficient water resources at present. However, Iraq is at the disadvantage of procuring more than two-thirds of its water resources as river flows from Turkey (Berkoff 1994).

Because of population growth, it is expected that by 2025 the average annual renewable water resources for the Middle East would have fallen to 667 m^3 per capita, compared to a world

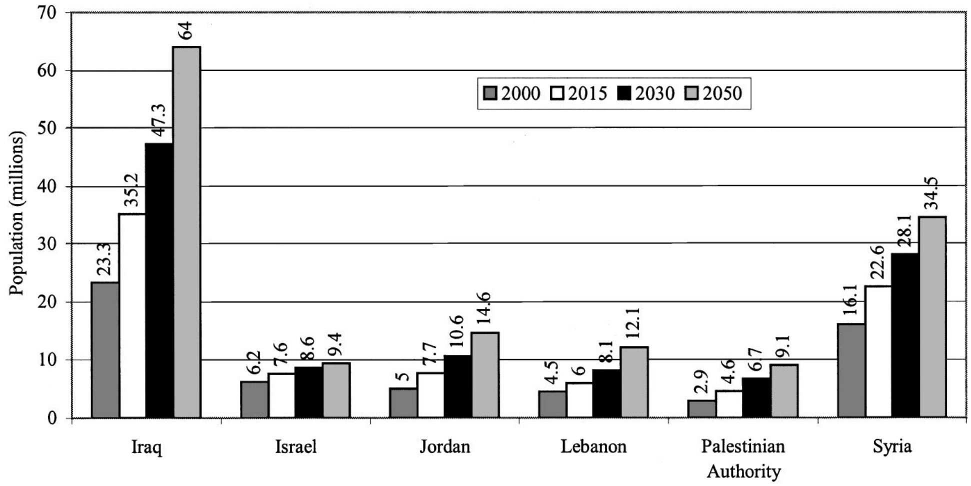

Fig. 2. Population projections (Berkoff 1994, ESCWA 1999, FAO 1999, El-Fadel et al. 2000)

average of 4,780 m^3 per capita (Berkoff 1994). Projections indicate significant water shortages in the future for most countries in the region (Table 3). Only Iraq would have adequate resources to cover its demands; however, recent Turkish projects on the Euphrates and Tigris Rivers threaten to reduce Iraq's supplies significantly. Table 3 depicts the baseline conditions, neglecting the effects of potential climate change. These estimates do not account for potential increased capacity through desalination or wastewater reuse. The ranges presented depict varying assumptions of demographic growth, water use variation, water resources management reform, and likewise.

Table 4 depicts water demand growth for the countries under study. Note that agricultural demand accounts for 84% (30–88% for the individual countries) of the water demand in the region. Furthermore, if Middle Eastern countries continue to tap into groundwater aquifers at a nonsustainable rate and do not develop alternative nonconventional water resources (such as the use of surplus winter runoff, seawater or brackish water desalination, wastewater reclamation, rainfall enhancement by seeding clouds with silver iodide crystals, etc.), adverse impacts on water availability and quality will result, even without climate change effects.

Climate Change Impacts on Water Resources in Middle East

It is often assumed that since the Middle East region has very scarce water resources, the impact of climate change would be negligible (IPCC-WGII 1996). However, as noted before, water resources in the region are under a heavy and increasing stress. Any alteration in climatic patterns that would increase temperatures and reduce rainfall would greatly exacerbate existing difficulties. The general approach used for assessing the impacts on hydrologic regimes is to obtain climate data (representing various assumptions concerning projection period, GHG growth scenarios, etc.) from GCMs and RCMs and use them as input to basin hydrologic models. However, if long-term data on rainfall-runoff correlation and basin water balance are not available, complex hydrologic models should be avoided (IPCC-WGI 1996b; *Impacts* 1999; Strzepek 1998). Such data are unfortunately missing or unavailable in almost all of the countries under study (Lonergan and Brooks 1994, Water 2000). While data are available for some major basins, data collection programs are recent and do not have the time span that allows reliable statistical correlations of inputs (precipitation, runon, etc.) and outputs (runoff, evaporation, etc.) to be developed for extreme conditions. In this study, potential climate change impacts are evaluated using GCM simulations. Subsequently, a water balance model is used for two representative regions in Lebanon to assess likely modifications in the hydrologic cycle.

Several GCMs have been used to model the future climate for the whole planet under varying scenarios. Recent efforts focused on setting standard scenarios and time frames to ensure comparability of results from different GCM simulations (IPCC-WGI 1996a; 1997; Strzepek 1998). The relative success of GCMs in reproducing global weather patterns from past data is not nec-

Table 2. Socioeconomic Indicators (*Encyclopædia britannica* 1999; FAO 1999; The World Bank 1999)

Country	Area (km^2)	Urban population (% of total)	GNP in 1998 (billions of U.S. dollars)	GNP per Capita 1998 (U.S. dollars)	GNP per Capita Growth 1999–2003	GDP growth 1999–2003	Access to safe drinking water (% of population)
Iraq	438,320	76	—[c]	540	−9.0	−6.0	77
Israel[a]	20,700	91	95.2	15,940	-0.3	2.0	99
Jordan	89,210	73	6.9	1,520	0.4	3.2	98
Lebanon	10,452	89	15.0	3,560	1.7	3.5	94
Palestinian Authority[b]	6,263	—[c]	—[c]	—[c]	—[c]	—[c]	—[c]
Syria	185,180	54	15.6	1,020	2.4	4.8	88

[a]Area controlled by Israel before 1967.

[b]West Bank and Gaza Strip.

[c]Not available.

Table 3. Annual Water Resources in Some Middle Eastern Countries (Berkoff 1994; Shuval 1994; FAO 1997; ESCWA 1999, Alatout 2000; Amery 2000; El-Fadel et al. 2000; Lithwick 2000; Shannang and Al-Adwan 2000)

Country	Average annual rainfall (mm)	Use of desalinated water and reclaimed waste water (% of total withdrawal)	Total renewable water resources (billion m^3)	Current and Projected Renewable Water Resources[b]		
				1997	2015 (m^3/capita)	2025
Iraq	154	—[a]	62.85–100.00	2,963–4,628	1,832–2,938	1,359–2,000
Israel	630	11.56	1.50–2.57	280–435	190–356	140–311
Jordan	94	5.32	0.75–1.35	168–229	78–133	70–91
Lebanon	827	0.16	2.00–3.94	766–1,287	336–979	262–809
Palestinian Authority	350	1.08	0.20–0.22	72–92	43–56	34–36
Syria	252	2.56	15.00–21.48	1,160–1,438	759–948	535–609

[a]Not available.

[b]The level below which a country is considered water poor varies between different agencies and experts, but is consistently around 1,000 m^3/capita/year.

essarily an assurance that they will correctly predict the future climate even at the global scale.

In this study, climate change projections in the Middle East, which are calculated by four different GCMs (Table 5) for the same set of assumptions (IS92a scenario), are compared. Both greenhouse gases and sulfur aerosols are accounted for in the GCMs, and the projections available are for the 2020s climate conditions in comparison to the period of 1961–1990. Table 5 illustrates the wide variations in the reported predictions of the various models (warming at CO_2 concentrations doubling time and $2\times CO_2$ sensitivity). These variations can be attributed to the following:

- The different approaches used in the models to simulate meteorological processes,
- The different flux correction terms used to calibrate the models to reproduce the current climate, and
- The different sets of historic data used to calibrate and validate the models.

Warming at CO_2 concentrations doubling time (for the same emission scenario) varies by more than 100% between the ECHAM4 model (1.3°C) and the CGCM model (2.7°C). Therefore, large discrepancies between model predictions are also expected for the Middle East region.

The temperature change during the winter (January, February, and March) and the summer (June, July, and August), and the rainfall change during the wet season (October to April) as calculated by the different models for the countries under study are summarized in Table 6. These results show minor changes in mean precipitation for the region, while temperatures are projected to increase in all seasons. Mean summer temperatures, already high in the region, will rise significantly (0.8–2.1°C). Areas bordering the Mediterranean (Lebanon, Israel, Palestinian Authority, and coastal Syria) would be the least affected. However, groundwater aquifers in these areas will be under the hazard of increased seawater intrusion due to higher sea levels.

The discrepancies between predictions of different models reach a maximum of 1.3°C for Syria during the summer. However, the trend is clearly toward increasing mean temperatures. This will increase the irrigation water demand due to higher evaporation. Extreme temperatures are predicted to increase more than mean temperature values. Increased temperature and evapotranspiration coupled with constant precipitation are highly associated with desertification. Mean winter temperatures will also increase; however, the rise is lower than for the summer season. Higher winter temperatures will enhance evapotranspiration and reduce potential groundwater recharge. If the increased runoff due to sharper precipitation patterns is also considered, the net effect will be a reduction in groundwater recharge and hence in the baseline renewable water resources (Table 3).

These results are a compilation of simulations from several GCMs, and represent intermediate GHG emission scenarios (IS92a). GHG emissions have followed the IS92a prediction until now, and this is expected to last. However, even if emissions uncertainties are disregarded, the GCMs might still have considerable errors correlated with uncertainties in climate modeling under known atmospheric GHG concentrations. Hence, the results are best guesses of a likely climate change in the region.

It is noteworthy that while most models predicted an increase in temperature, few reported an opposite trend. One particular study that coupled a nested regional model for the Middle East

Table 4. Current Economic and Projected Water Demand (Million m^3) (Berkoff 1994; ESCWA 1999; FAO 1999; MFA 1999; El-Fadel et al. 2000)

Country	Current and Projected Total Water Demand		Projected Breakdown for 2025 by Sectors		
	2000	2025	Domestic	Agriculture	Industrial
Iraq	54,972	74,310	4,750	66,000	3,560
Israel	1,960	3,116	997	1,906	206
Jordan	1,257	1,760	700	900	160
Lebanon	1,650	3,069	876	1,500	693
Palestinian Authority	495	1,290	800	420	70
Syria	17,130	23,555	2,825	19,430	1,300

Table 5. Description of General Circulation Models and Scenarios used in this Study (IPCC-WGII 1997)

Component	ECHAM4	HadCM2	CGCM1	GFDL
AGCM[a] (latitude×longitude)	2.8°×2.8°	2.5°×3.75°	3.7°×3.7°	4.5°×7.5°
OGCM[b] (latitude×longitude)	2.8°×2.8°	2.5°×3.75°	1.8°×1.8°	4.5°×3.75°
Flux correction[c]	Monthly mean heat	Monthly mean heat	Heat	Monthly mean heat
Flux correction[c]	Fresh water	Fresh water	Fresh water	Fresh water
Flux correction[c]	Stress	Stress	—	—
CO_2, historic	1860–1989	1860–1989	1890–1989	1766–1989
CO_2, IS92a[d]	1990–2049	1990–2099	1990–2100	1990–2065
SO_4, historic	1860–1989	1860–1989	1860–1989	1766–1989
SO_4, IS92a[d]	1990–2049	1990–2099	1990–2100	1990–2065
Warming (°C) at CO_2 doubling time[e]	1.3	1.7	2.7	2.3
$2\times CO_2$ sensitivity[f]	2.6	2.5	3.5	3.7

[a]Atmospheric general circulation model.

[b]Oceanic general circulation model.

[c]Used to adjust for defectiveness of model to correctly simulate current climate.

[d]~1% increase/year.

[e]Global-mean temperature due to doubling of effective CO_2 at doubling time (thermal inertia delays equilibrium).

[f]Global-mean temperature response to doubling of effective CO_2 at equilibrium time.

and southern Europe to a GCM predicted a decrease in temperature for the region ranging from 0° to 1°C, due to doubling CO_2 levels (Jones et al. 1997). This was attributed to the sulfur aerosols cooling effect.

Lebanon Case Study

With the background presented above on potential climate change impacts on Middle Eastern countries, Lebanon is selected as a case study where an assessment is conducted to evaluate the vulnerability of Lebanese water resources to potential climate change. Global warming is suspected to trigger adverse environmental consequences, including coastal zones flooding and desertification. Both flooding and desertification are likely to affect the country, since it is located at the border of desert regions and more than 60% of its economic activity lies in a narrow coastal plain along the Mediterranean Sea (ERM 1995). Water resources in the country are believed to be particularly vulnerable to increased temperatures and alterations in precipitation patterns (UNDP 1999).

Lebanon has high water resources per capita relative to other countries in the region; however, it will still be unable to meet its local demand by 2025 (Tables 3 and 7). This reality is in contradiction to the long-held view that Lebanon is water rich and that it can, and should, share its excess water resources with its neigh-

Table 6. Climate Change Parameters (IPCC-DCC 1999a)

Country	HadCM2	GFDL-R15	CGCM	Echam4	Maximum
(a) January–March Mean Temperature Increase (°C)					
Iraq	0.9	1.7	1.6	1.1	1.7
Israel	0.6	1.2	1.2	1	1.2
Jordan	0.9	1.8	1.3	1.1	1.8
Lebanon	0.6	1.2	1.3	1	1.3
Palestine	0.6	1.2	1.3	1	1.3
Syria	0.8	1.7	1.3	1.1	1.7
(b) June–August Mean Temperature Increase (°C)					
Iraq	0.9	2.1	1.5	1.5	2.1
Israel	0.8	1.8	0.9	1.4	1.8
Jordan	0.9	2.1	0.8	1.2	2.1
Lebanon	0.8	1.8	0.9	1.4	1.8
Palestine	0.8	1.8	0.9	1.2	1.8
Syria	0.8	2.1	0.8	1.2	2.1
(c) October–April Mean Rainfall Change (mm/day)					
Iraq	0	0	0	0	0
Israel	0	−0.1	0	0	−0.1
Jordan	0	0	0	0	0
Lebanon	0	−0.1	0	0	−0.1
Palestine	0	−0.1	0	0	−0.1
Syria	0	0	0	0	0

Note: Values are for 2020s relative to the 1961–1990 period.

Table 7. Population and Water Demand Projections for Lebanon (El-Fadel et al. 2000)

Projection year	Population (millions)	Water Demand (Million m^3/Year)			
		Domestic	Industrial	Irrigation	Total
2010	5.5	452	445	1,000	1,897
2015	6.0	532	516	1,200	2,248
2020	6.7	641	598	1,350	2,589
2025	7.6	780	693	1,500	2,973
2030	8.1	876	804	1,600	3,280

bors (Kolars and Naff 1993; Berkoff 1994). In addition, the country has numerous difficulties in managing its water resources after a long period of civil unrest (1975–1990) that left damaged infrastructure and resources. Moreover, reliable hydrologic data are greatly needed, since almost all water resources inventories rely on previous studies and no reliable climate data are available at a countrywide scale. Population censuses and water demand studies are also lacking (El-Fadel et al. 2000). Fig. 3 depicts Lebanese rivers, water basins, and two locations selected for a water balance analysis. Table 8 summarizes the corresponding annual water balance.

The orography of Lebanon plays a major role in determining the climate of the country, and will still be important under changing climate conditions. The water deficit is especially acute in the Bekaa Valley (Fig. 3), where potential evapotranspiration exceeds 70% of precipitation (NCRS 1998). Salt-water intrusion near coastal areas is also precarious, due to overpumping of groundwater. Chloride (Cl^-) measurements detected a tenfold increase in Beirut groundwater between 1970 and 1985 (Khair et al. 1994). Estimates of likely changes in climate variables for Lebanon for the 2020s are depicted in Table 9, where data are compiled from the results presented in Table 6.

A water balance model (WATBAL) was used to assess the significance of these changes. The model is an "end-of-month" balance of monthly precipitation, evapotranspiration, drainage, and soil water storage change (Star 1999). It was applied at two locations in Lebanon. The first is Ksara, in the Bekaa (inland) Valley, and the second is along the Mediterranean coast near Beirut (Fig. 3). Four scenarios were examined. The first two scenarios simulate varying increases in temperature with stable precipitation (mild-hot and hot). The last two scenarios reexamine the impact of the same temperature increases with a 0.1 mm/day reduction in precipitation. Climate change data used in the scenarios are presented in Table 10.

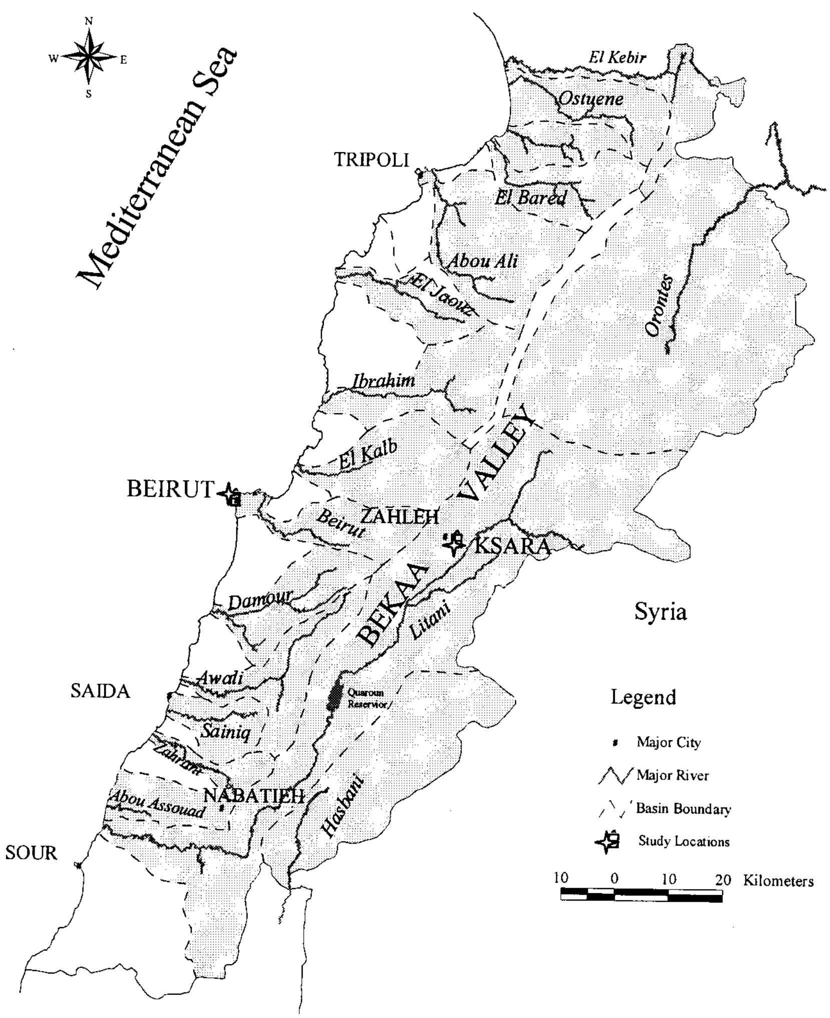

Fig. 3. Rivers and water basins of Lebanon

Table 8. Current Annual Water Balance for Lebanon (El-Fadel et al. 2000)

Component	Yearly average values (million m^3)	
Precipitation		8,600
Surface water evapotranspiration losses (assumed to be 50% of precipitation)		−4,300
Surface water flows to neighboring countries		
• Flow to Syria, Orontes River	−415	
• Flow to Syria, Al-Kabir River	−95	
• Flow to Israel, Hasbani River	−160	
• Subtotal		−670
Groundwater flow		
• Unexploitable groundwater or losses to sea	−880	
• Losses to neighboring countries	−150	
• Subtotal		−1,030
Net potential surface and groundwater available		2,600
Net exploitable surface and groundwater		2,000

Baseline simulations were conducted for the 1960–1990 period conditions and for the modified conditions under the four changing climate scenarios. The impacts on the actual evapotranspiration, evapotranspiration deficit, surplus, and soil moisture deficit were evaluated. These variables are defined in Eqs. (1)–(3)

$$\mathrm{ETD}=\mathrm{AET}-\mathrm{PET} \quad (1)$$

$$\mathrm{SUR}=P-\mathrm{AET}-\Delta\mathrm{SM} \quad (2)$$

$$\mathrm{SMD}=\mathrm{AWC}-\mathrm{SM} \quad (3)$$

where ETD=evapotranspiration deficit (mm); AET=actual evapotranspiration (mm); PET=potential evapotranspiration (mm); SUR=water surplus (mm); P=precipitation (mm); ΔSM =soil moisture change (mm); SMD=soil moisture deficit (mm); AWC=available water capacity (mm); SM=soil moisture (mm).

PET is estimated from insolation rather than temperature. Temperature change effects are included indirectly through the latent heat of vaporization and during the computation of AET. The insolation values are calculated using a statistical relationship between solar radiation at the top of the atmosphere and that received at the surface (insolation). Surface solar radiation measurements should be available for the site under consideration. Precipitation (plus any snowmelt) is evaporated at the PET rate. If the air temperature is 0°C, then PET equals zero and the precipitation (snowfall) accumulates as snowpack. If PET is greater than the precipitation (+ snowmelt), the unsatisfied part of the evapotranspiration demand is transferred to the water stored in the soil. The evapotranspirative withdrawal of soil water may take place at the PET rate or at a reduced rate, the AET rate, depending on a relationship determined by the moisture content and the AWC (Star 1999). When evapotranspiration occurs but is less than PET, it is calculated from PET and temperature data.

Data for model calibration were limited to PET data from Ksara. Model parameters and input (solar radiation and soil type) were adjusted to reproduce observed data. With this limited calibration process, the simulations are expected to be associated with a high degree of uncertainty with respect to future water balances; however, it will be adequate for a comparative analysis. This type of analysis reduces uncertainties correlated with partial model calibration.

Model simulation results are depicted in Fig. 4 for Beirut and in Fig. 5 for Ksara. Evaporation increases at the two sites for all scenarios. However, the maximum increase in evaporation is observed with the "hot" scenario (33 mm/year or 6.6% for Beirut, and 18 mm/year or 6.1% for Ksara). Evaporation in the two dry scenarios is lower than for the other two scenarios. This is attributed to the reduction in precipitation, leading to a reduction in soil moisture and water available for evaporation.

The soil moisture deficit increase in Beirut, under changing climate, ranges from 13 mm/year or 1.5% (mild-hot) to 25 mm/year or 3% (dry and hot). The increase for a single month may reach up to 26% (dry and hot scenario in April). The impact at Ksara is greater, with a 24–43 mm/year (3–6%) increase in the soil moisture deficit and a peak 140% increase for dry and hot conditions in April. The soil moisture deficit is correlated with irrigation demand in agricultural areas. Evidently, Ksara, which lies in the agricultural and relatively dry Bekaa Valley, is more affected than Beirut, which is located along the west coast (Fig. 3). The results indicate a potential increase in irrigation demand in the Bekaa Valley by up to 6% if the dry and hot scenario is considered (assuming irrigation will aim at fulfilling the soil moisture deficit). The domestic water demand is also expected to increase, due to increased temperatures.

The results also illustrate that surplus water, which ultimately

Table 9. Change of Climate Variables for Lebanon in 2020s Relative to 1961–1990 (IPCC-DCC 1999)

Variable	Period	Unit	Change
Winter (JFM) mean temperature increase	Winter (JFM)	°C	0.8
Summer (JJA) mean temperature increase	Summer (JJA)	°C	1.2
October–April mean rainfall change	Wet season (October–April)	mm/day	0
Max T for hottest month	July	°C	2.0
Min T for hottest month	July	°C	1.2
Cloud cover change	Winter (JFM)	%	0
Cloud cover change	Summer (JJA)	%	1
Diurnal temperature range	All year	°C	0

Table 10. Change of Climate Variables in Four Simulated Scenarios for Lebanon

Scenario	Average temperature change in winter (JFM)	Average temperature change in summer (JJA)	Precipitation change (mm/day)
mild-hot	0.5	1	0
hot	1.5	2	0
dry and mild-hot	0.5	1	−0.1
dry and hot	1.5	2	−0.1

produces runoff or percolates and reaches water bodies, is reduced by 11–34 mm/year (3.5–11%) for Ksara and 21–49 mm/year (6.5–15%) for Beirut. Since surplus is the main source of water for surface water bodies and groundwater aquifers, this reduction will directly influence available water resources in the country. The reduction in available water is expected to be roughly proportional to the reduction in surplus water. Therefore, the net usable surface water and groundwater resources as defined in Table 8 (2,000 million m^3/year) might be reduced by 5–15%, depending on the scenario.

These potential impacts might be exacerbated by the alteration in flow regimes in Lebanese rivers that are fed by snowmelt. They

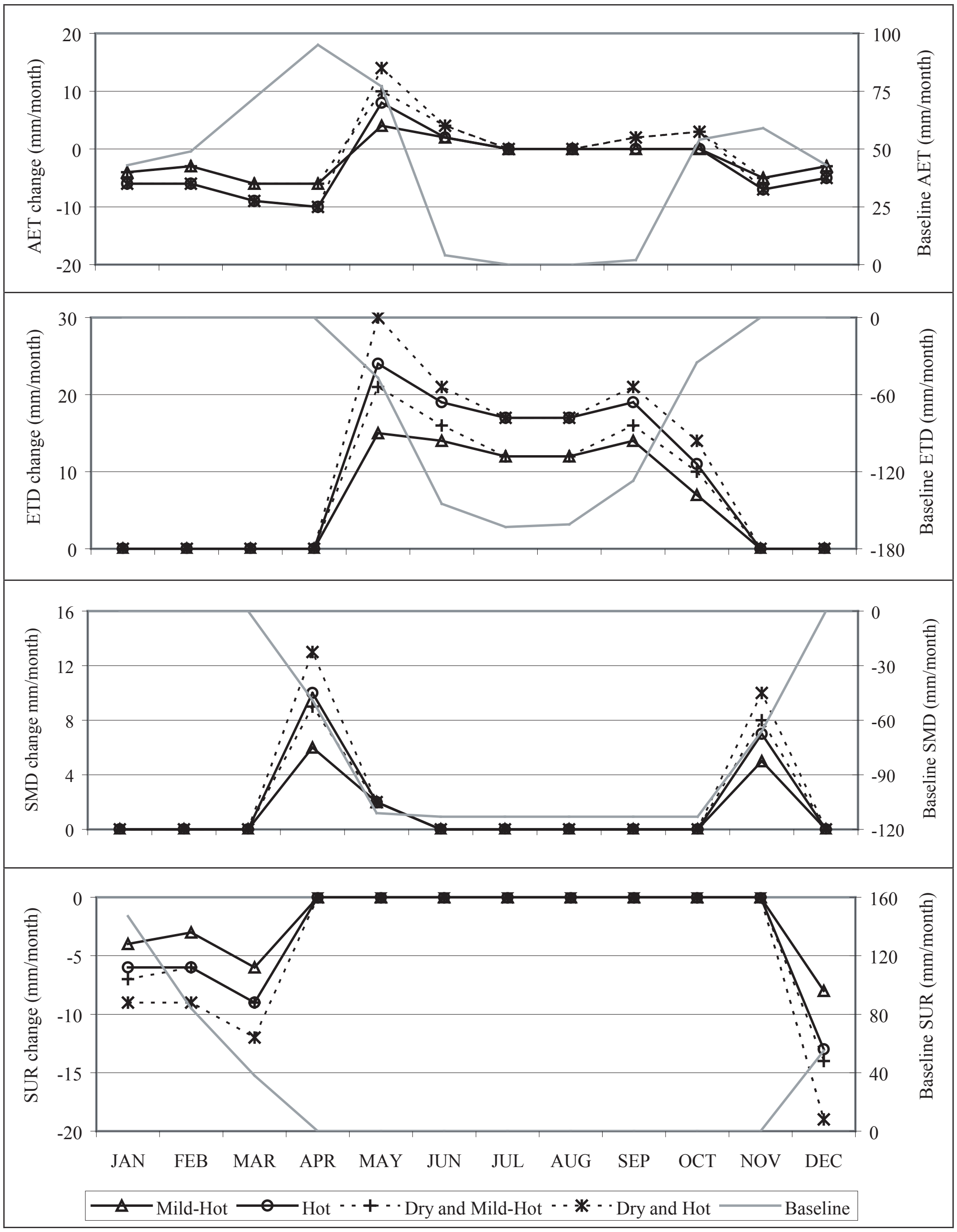

Fig. 4. Climate change impact on water balance parameters in Beirut, Lebanon. Baseline results are plotted as absolute values on the right-hand side vertical axis. Scenario results are plotted as changes from baseline values (scenario−baseline) on the left-hand side vertical axis. AET=actual evapotranspiration, ETD=evapotranspiration deficit, SMD=soil moisture deficit, and SUR=water surplus.

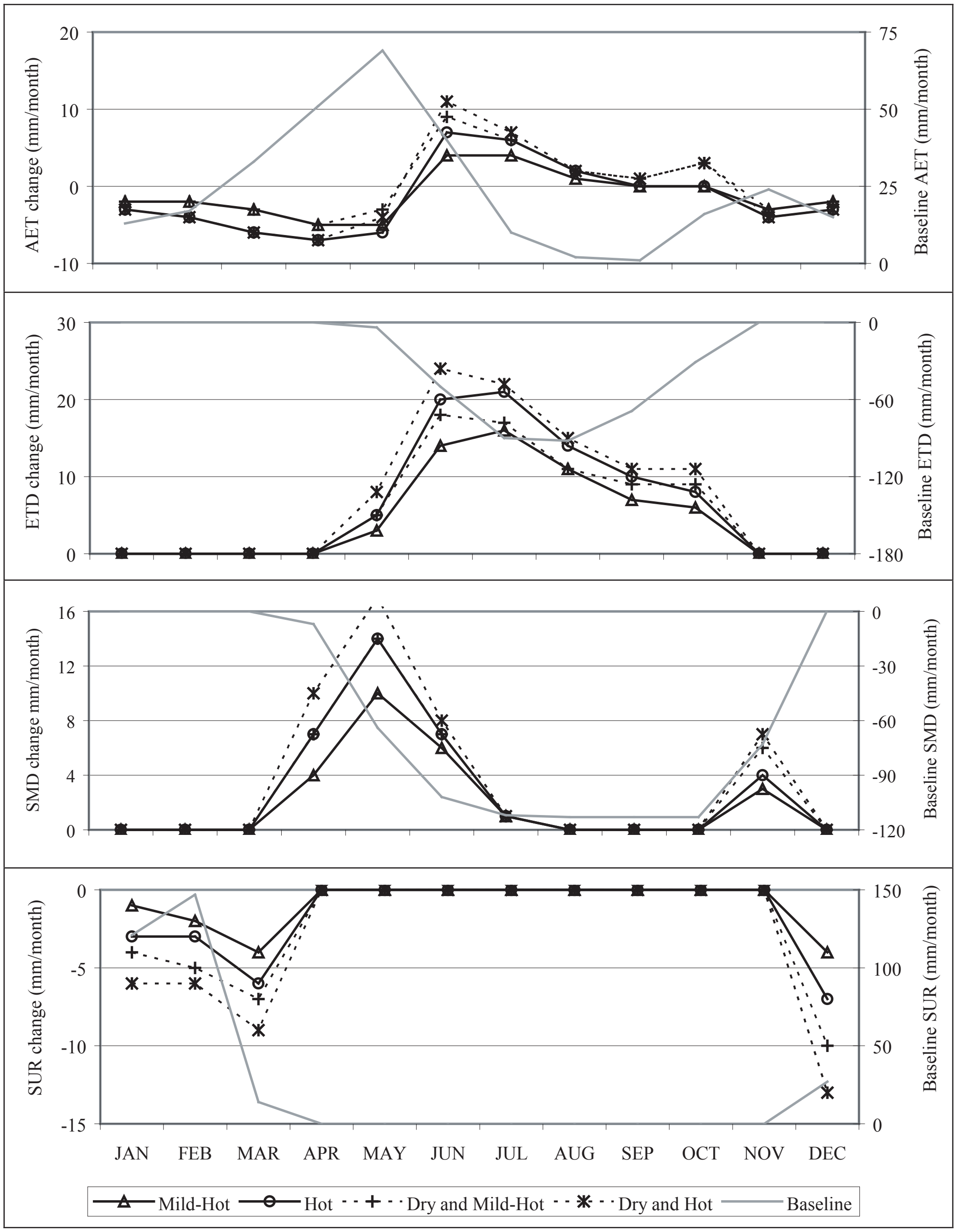

Fig. 5. Climate change impact on water balance parameters in Ksara, Lebanon. Baseline results are plotted as absolute values on the right-hand side vertical axis. Scenario results are plotted as changes from baseline values (scenario−baseline) on the left-hand side vertical axis. AET=actual evapotranspiration, ETD=evapotranspiration deficit, SMD=soil moisture deficit, and SUR=water surplus.

will have increased flow in the winter and reduced flow in the spring due to higher temperatures and early snowmelt, leaving the soils drier at the beginning of summer.

Note that the predominant geologic formations in Lebanon consist of fractured karstic limestone, which allows rapid percolation of rainfall (El-Fadel et al. 2000). This would alleviate the potential impacts of floods and reduced groundwater recharge due to more intense precipitation.

Adaptation Measures

When adaptation measures are designed or implemented before climate change, they must be flexible enough to perform their designated objectives under a wide variety of future climate conditions (Smith 1996). Measures that apply to Lebanon as well as other Middle Eastern countries are discussed in light of the expected increasing stress on water resources in the study region and the potential adverse impacts of climate change. In addition to the climate change stress on water resources, water shortages will be exacerbated by population and economic growth. In fact, the baseline scenario predicts a drop in per capita water resources of around 50% for the region by 2025. Therefore, most adaptation measures can be qualified as no-regret options. That is, they would be beneficial regardless of climate change impacts. Moreover, these measures will improve the adaptability of water resources systems to the natural variability in climate patterns (Conway and Hulme 1996).

These adaptation measures are mainly centered on new water resources and conservation efforts. At a regional level, Israel has adopted aggressive and novel approaches for developing nonconventional resources. Its experience can be helpful for other neighboring countries, in view of the similarity of ecological conditions. The main adaptation measures and nonconventional sources

Table 11. Technical Adaptation Measures and Nonconventional Water Resources

Adaptation measure	Potential benefits	Best uses	Cost [U.S. dollars/ $(m^3 \cdot day^{-1})$] (ESCWA 1999)
Conservation	Curbs water demand increase	Domestic, industrial, agricultural demand reduction	Cost could be negative if pricing policies are adopted to reduce demand
Use of surplus winter runoff	Collectable runoff can constitute up to 10% of rainfall.	Irrigation, aquifer recharge	—[a]
Wastewater reclamation	All collected wastewater can be reused.	Irrigation, aquifer recharge	0.5–1.5
Seawater/brackish water desalination	Unlimited water supply	Domestic, industrial	0.07–1.5
Rainfall enhancement by seeding clouds with silver iodide crystals	Can increase precipitation by up to 15% in arid regions	Irrigation, Aquifer recharge	—[a]
Use of submarine springs	Submarine springs with significant flows are located along Lebanese coastal waters (Ayoub et al. 2000)	Domestic, industrial, agricultural use, aquifer recharge	—[a]

[a]Not available.

of water that can be exploited in the future are summarized in Table 11. Adoption of any particular adaptation measure will need capital investment, institutional reforms, and capacity building. Institutional reforms should aim at strengthening institutions, removing market distortions, correcting market failure to reflect environmental damage or resource depletion, and promoting public awareness and involvement. Capacity building would be of crucial importance for monitoring and mitigating the impacts on water quality.

Another important aspect to be investigated is the potential increase in precipitation intensity, as indicated by some studies (Noda and Tokiota 1989; Gordon et al. 1992; IPCC-WGI 1996b; IPCC-TGCIA 1999). New hydraulic structures may be needed to contain higher river flows. Statistical methods currently used to calculate peak flows would need updating. Dams are especially vulnerable to increased precipitation intensity, which is likely to result in higher runoff intensity as well. This would put more structural stress on the dam and would result in rapid storage loss due to increased sedimentation (McCully 1996). In addition to technical adaptation measures, improvement of management systems (coordinating use of river basins, interbasin transfer, etc.) and development of drought or flood contingency planning are essential to minimize the climate change impact on water resources.

Limitations

While the analysis provides a prediction of the potential climate change impact on water resources in the Middle East and Lebanon, the simulated results can be correlated with several limitations as follows:

- Climate change scenarios for the region have large uncertainties and discrepancies between the different GCMs. For instance, predictions for the Nile river flow in Egypt vary from a 30% increase (GISS model) to a 78% decrease (GFDL model) for the same scenario depicting $2\times CO_2$ conditions (Strzepek and Yates 1996).
- A given change in climate will produce different responses in the basins of the Middle East, depending on the hydrologic characteristics of each basin.
- Lack of data about basin characteristics and lack of accurate water balance data hinder the use of advanced hydrologic models. A simple water balance model was used in this study.
- Changes in vegetation, soils, and vegetation water use efficiency are not accounted for in the water balance model, which affects model calibration.
- Baseline predictions are unsure in view of the uncertainty in forecasting socioeconomic, legislative, and water management conditions.

Conclusion

The potential impacts of climate change on water resources were assessed for the Middle East region in the 2020s, with Lebanon as a case study. Simulations of climate change predictions from several GCMs were used to evaluate impacts on water resources in Lebanon. Climate change is expected to further exacerbate existing water shortages. Although precipitation was not predicted to decrease, temperature increases of 0.6–2.1°C would impact the water balance and reduce available resources. Lebanon was selected for an in-depth investigation using several indicators, including actual evapotranspiration, evapotranspiration deficit, surplus, and soil moisture deficit. Maximums of a 15% decrease in available water and a 6% increase in agricultural demand were projected by the year 2020.

Adaptation measures are necessary in view of an increased water demand and potential decrease in available water. Most adaptation measures are no-regret options that attempt to develop nonconventional sources of water that can be exploited in the future, including the use of surplus winter runoff, wastewater reclamation, seawater and brackish water desalination, rainfall enhancement by seeding clouds with silver iodide crystals, and exploitation of submarine springs. Conservation measures, as well as institutional reforms and capacity building, are also needed. The indirect impact of climate change on hydraulic structures should not be underestimated in view of potential increases in precipitation intensities and modifications in river flow patterns.

Similar hydrologic impacts might have different socioeconomic consequences, depending on region-specific characteristics. In the context of the Middle East, different configurations of water resources systems might affect the magnitude of potential adverse effects, such as the reduction of the gross domestic product, future population distribution, workforce shifts to alternative economic sectors, and so forth. To assess the socioeconomic impacts of climate change, numerous models have been proposed, ranging from macroeconomic to sectoral, general equilibrium, and partial equilibrium (Strzepek et al. 1996). While the assessment of these impacts at a local level is needed, a national or regional scope should be considered in assessing the socioeconomic impacts of changes in water resources, power consumption, land use, and other parameters affected by climate change.

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