Water for Food and Energy Security:

An assessment of the impacts of water scarcity on agricultural production and electricity generation in the Middle East and North Africa

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Background Paper for the World Bank Study:

The Water-Energy-Food Nexus in the Middle East and North Africa : Scenarios for a Sustainable Future

Public Disclosure Authorized

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A. BACKGROUND: WATER-ENERGY-FOOD NEXUS IN THE MENA REGION

The interdependency between water, energy and food (WEF) is growing in importance as demand for each of these vital resources' security increases. Several regions of the world are already experiencing WEF security challenges, which adversely affect sustainable economic growth (Bazilian et al. 2011). In addition, there is already evidence of the effects of climate change on the availability and demand for water, energy and food. At the same time, scarcity in either water, energy or food is caused not only by physical factors, but there are also social, political and economic issues at play that effect the allocation, availability, and use of these resources.

In the Middle East and North Africa (MENA) region, this nexus between water, energy and food is particularly important for the region's sustainability and continued growth. Countries in this region (Algeria, Bahrain, Djibouti, Egypt, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Libya, Morocco, West Bank and Gaza, Oman, Qatar, Saudi Arabia, Syrian Arab Republic, Tunisia, United Arab Emirates, Yemen) are arid to semiarid, with many areas already facing water stress and a highly variable precipitation rate due to their geographic and climatic conditions. Although to date governments in the region have been in general successful in satisfying the needs of the population through ambitious dam building and groundwater provision systems, reduction in leakages, conservation, desalination, reuse and water transfers, per capita supply are declining due to growing population, increased urbanization, extended irrigated agriculture and highly water intensive crops together with the development of the industrial and the tourism sectors. This decline in per capita supply has increasingly pushed some countries in the region to think of ambitious desalination plans to supply water to coastal cities and agricultural areas, and to explore the possibility of large transfers of water from less arid parts of the region. Some examples of such plans are the Peace Water Pipeline and the Manavgat River Project explored the feasibility to move water from Turkey to its southern neighbors; the Ras Al Khair Desalination Plant is able to move water from the Persian Gulf to Riyadh City; and the Great Man-Made River is a network of pipes that supplies water to the Sahara in Libya, from the Nubian Sandstone Aquifer System. These options (desalination, reuse and water transfers) require relatively larger amounts of energy, mainly electricity, and significant capital investment.

Climate historical data on rainfall amounts in the region show a negative trend at national and regional scales. Average annual runoff is expected to decrease in the future due to climate change impacts and temperatures are expected to increase. High evapotranspiration and soil infiltration rates in the region reduce soil moisture and consequently increase irrigation requirements that typically surpass 80 percent of total water withdrawals in most countries (Verner, 2012).

The agriculture sector in countries of the MENA region consumes a large share of water. Moving forward, the allocation of water to agriculture will likely face increased competition from high-value uses in the industrial and urban sectors; consider the economic returns of water used for irrigation for different crops, which differ significantly among Arab countries (**Figure 1**). Managing water in the region will benefit from the inclusion of agriculture within a nexus strategy that involves all sectors. This approach will be particularly important given that the agriculture sector is the largest employer in many countries of the region and contributes significantly, yet decreasingly, to meeting food requirements (Verner, 2012). For instance, countries can optimize their return on water by choosing different crop mixes, which will lead to different returns on the agricultural water used. Also worth considering is the fact that the cost of producing crops will continue to rise in significant parts of the region, as fossil (non-renewable) groundwater resources are depleted and groundwater levels sink. Currently, wells require deep drilling, and the cost per cubic meter is increasing.

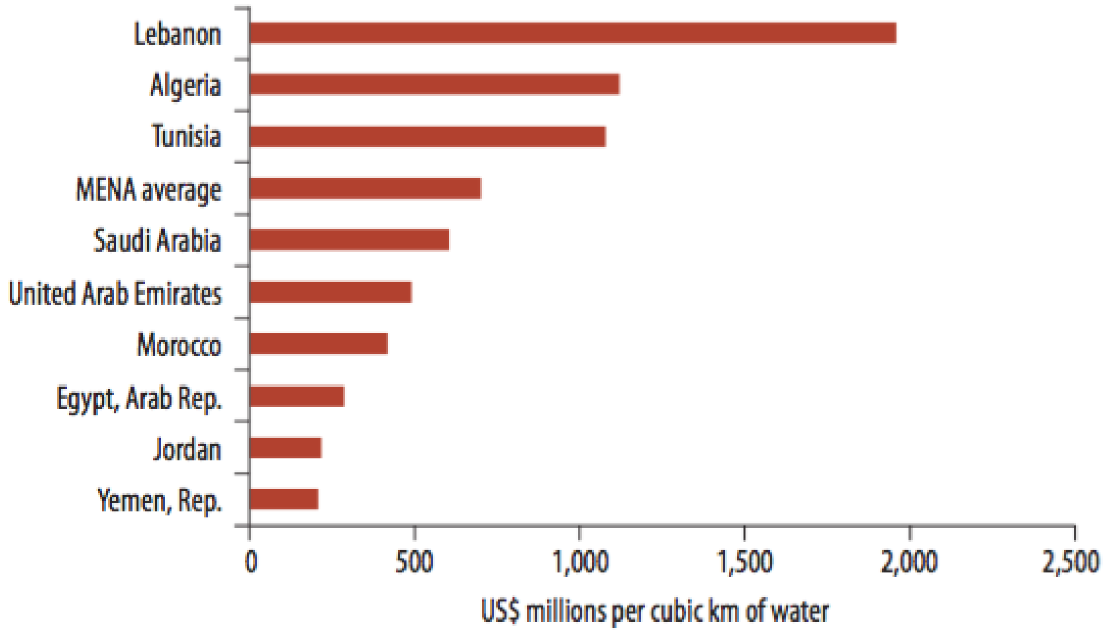


Figure 1: Agriculture value added GDP per cubic kilometer of water used in agriculture (Bucknall, 2007).

On the energy side, the region is heavily reliant on fossil fuels (coal, oil and gas) to generate electricity and, in some countries, to generate non-conventional water supplies. The dependency on fossil fuels is frequently complemented with energy imports, implying that the energy sector could face serious challenges in the near future. To address this issue, some countries in the region have launched renewable energy development programs to diversify their energy sources and to achieve objectives of energy security and environmental sustainability. While the large-scale implementation of renewables such as solar energy can have a positive impact on greenhouse gas emissions and can improve energy security, it could negatively impact water resources availability if such resources are not taken into account in the planning stages. Due to the lower efficiency of solar thermal plants compared to conventional fossil fuel power plants, larger amounts of water are required for cooling purposes. Moreover, due to their radiation needs, solar plants are usually located in the most arid areas, where water is usually a scarce resource. Therefore, since water is needed for electricity generation, energy policy choices that focus on more water-efficient electricity generation technologies can have a positive impact on the water resources of a country and impact the development of the region as a whole.

Managing the WEF nexus in the region and satisfying the future water needs of all sectors has become a strategic challenge for the MENA region in the coming years. In some parts of the region, the combined effects of population growth, increasing hydrological variability and climate change may result in increased reliance on relatively energy-intensive water supply options. At the same time, agriculture is expected to continue to pose major pressures on the region's diminishing water supplies. The WEF nexus poses not only challenges for sustainability in the MENA region, but also for the region's food, energy and water security, and improving its social, economic and political stability.

B. STUDY OBJECTIVES

The objective of this project was to develop and illustrate an analytical framework – based on the Global Change Assessment Model (GCAM) – that can be used by the World Bank in its dialog with MENA countries to help assess long-term integrated (nexus) scenarios for water, energy and food activities in the region. This report summarizes that effort. It places focus on (i) an analysis of the current status of water resources in the region using an integrated resource (nexus) modeling approach; (ii) scenario analyses focused on water scarcity and potential impacts on the energy and food sectors in the region; and (iii) recommendations for further analysis that can inform policy making at the national level, and contribute to ongoing efforts towards integrated planning at the regional level, such as those discussions taking place in the Gulf Cooperation Council (GCC) countries (e.g., see **Figure 2**, IRENA, 2015).

This work can support strategies to identify synergies to meet sectoral needs in a manner consistent with regional goals of environmental sustainability, WEF security and socioeconomic development. The results of this analysis can be used to incorporate nexus approaches in the formulation of planning practices and provide strategic recommendations for investments in the region. This work can contribute to building integrated planning capabilities in MENA countries and help flag any potential constraints and opportunities that may arise from an integrated long-term view at water, energy and food needs in the region**.** Climate change impacts are also incorporated in this exercise in order to understand how potential changes in climate variability and trends might affect WEF sector development planning.

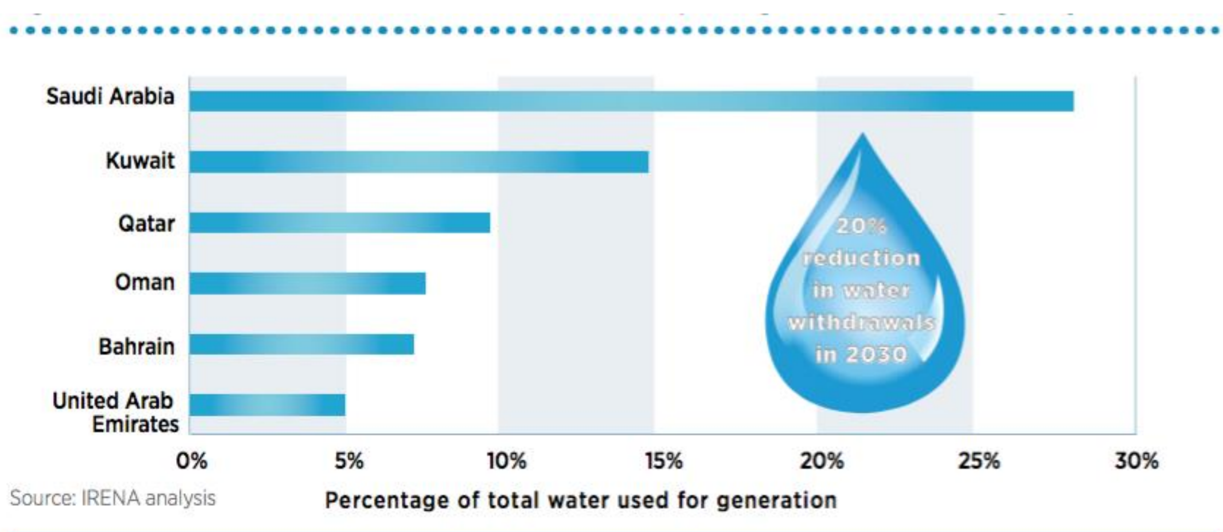


Figure 2: Potential for reduction in water withdrawals for power generation in GCC countries through 2030 by shifting to renewables.

C. OVERVIEW OF RESEARCH TASKS

Using the analytical capability developed for this project, the remainder of the report describes three main research tasks:

Task 1: Physical Assessment of Climate Impacts on Water Scarcity in the MENA Region
This task employs multiple general circulation models (GCMs) in a "reference climate change" scenario to assess the level of uncertainty propagating from climate models on water scarcity through the MENA region. Three climate models that span the range of uncertainty (wet, dry, and normal) are selected. This allows for a comparison between the uncertainties surrounding climate models and their impacts. Results from this task provide a physical basis to assess the impacts of climate change induced water scarcity on the WEF nexus in the region.

Task 2: Socioeconomic Scenario Analysis of Water Scarcity in the MENA Region
This task provides an assessment of different socioeconomic development pathways on water security throughout the MENA region. To do so, it uses the socioeconomic development scenarios from the Shared Socioeconomic Pathways (SSPs[1]). This scenario analysis shows how socioeconomic development trajectories might affect water demands and consequently water scarcity in different countries of the region. This task helps to assess the relative effects of global socioeconomics and technological trends as compared to the effects of climate change (Task 1).

Task 3: Scenario-Based WEF Nexus Analysis in the MENA Region
This task builds on Task 1 and Task 2 to explore the implications for the food-energy-water nexus of limited water supplies in the context of varying climatological conditions (Task 1) and varying socioeconomic conditions (Task 2) The analyses quantifies changes in the supply and demand of water throughout the region, shedding light on infrastructure needs, costs of policies and associated investment needs. Scenarios that span the sources of uncertainty associated with the estimated water availability (e.g., water transfers, groundwater) are investigated.

[1] e.g., See O'Neill et al. 2015, The roads ahead: narratives for shared socioeconomic pathways describing world futures in the 21st century, Global Environmental Change, doi:10.1016/j.gloenvcha.2015.01.004

D. METHODOLOGY

D.1. The Global Change Assessment Model (GCAM)

D.1.1. Overview of GCAM

Integrated Assessment Models (IAM) provide a general modeling framework for exploring the relationships between water, climate, land and energy (nexus) through an interwoven understanding of the physical, economic and institutional constraints of water resources issues and consideration of climate-related impacts on management and decision-making process in water supply, energy generation and food production.

The Global Change Assessment Model (GCAM) is an IAM for exploring consequences and responses to global change. Climate change is a global issue that impacts all regions of the world and all sectors of the global economy. Thus, any responses to the threat of climate change, such as policies or international agreements to limit greenhouse gas emissions, can have wide ranging consequences throughout the energy system as well as on water resources, energy generation, food production, land use and land cover. IAMs endeavor to represent all world regions and all sectors of the economy in an economic framework in order to explore interactions between sectors and understand the potential ramifications of climate change mitigation actions.

GCAM has been built and populated with global and detailed datasets for over 20 years, and is extensively used to explore climate change mitigation and adaptation policies. A key advantage of GCAM over some other IAMs is that it is a Representative Concentration Pathway (RCP)-class model. This means it can be used to simulate scenarios, policies, and emission targets from various sources including the Intergovernmental Panel on Climate Change (IPCC).

GCAM solves for partial market equilibrium of water, energy and food at discrete time steps. It employs representations of the economy, energy sector, land use and water resources linked to climate models that can be used to explore climate adaptation and mitigation policies including carbon taxes, carbon trading, regulations, deployment of energy technologies and spatial representations of food production, particularly agriculture (**Figure 3**). Regional population and labor productivity growth assumptions drive the energy and land-use systems employing numerous technology options to produce, transform, and provide energy services as well as to produce agriculture and forest products, and to determine land use and land cover. Using a run period extending from 1990 – 2100 at 5 year intervals (or 1-yr intervals for higher temporal resolution), GCAM has been used to explore the potential role of emerging energy supply technologies and the greenhouse gas consequences of specific policy measures or energy technology adoption. Outputs of GCAM include projections of future energy supply and demand and the resulting greenhouse gas emissions, radiative forcing and climate effects of 16 greenhouse gases, aerosols and short-lived species at 0.5×0.5 degree resolution, contingent on assumptions about future population, economy, technology, and climate mitigation policy. On the water side, six major water use sectors are considered: agricultural irrigation, municipal water supply, primary resource extraction (energy/mining), livestock production, electricity generation and industrial manufacturing.

GCAM is a publicly available, open source modeling tool, developed and maintained by the Pacific Northwest National Laboratory, part of the US Department of Energy. Further details about GCAM can also be found on its dedicated website.

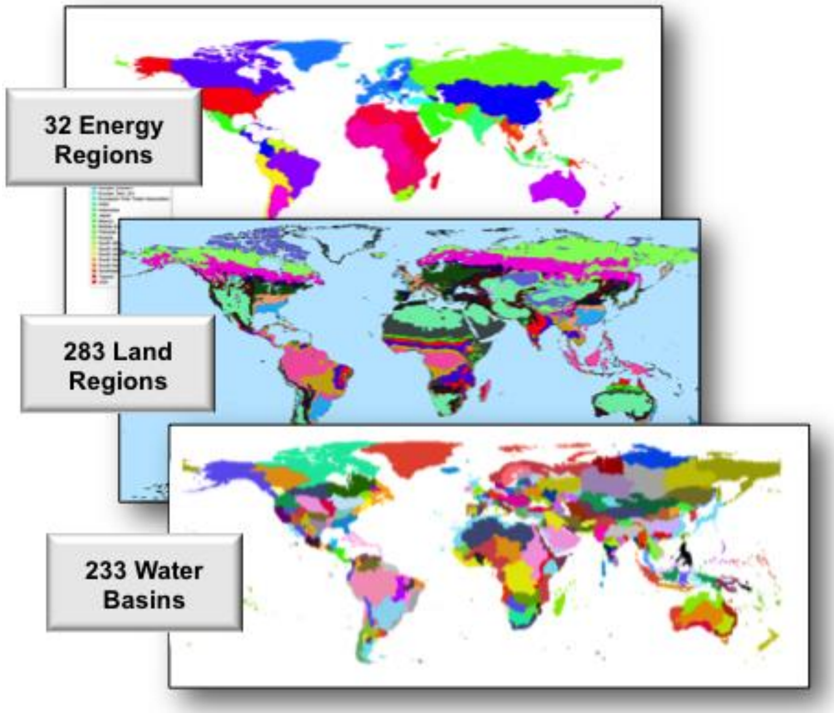


Figure 3: GCAM links Economic, Energy, Land-use, Water, and Climate systems

D.1.2. Water Demands in GCAM

GCAM tracks annual demand for water in multiple sectors (e.g., land/food, energy, as well as subsectors therein) at several spatial scales (Hejazi et al. 2014a,b). Agricultural water demand is calculated in the land/food module of GCAM, and it is based on georeferenced land use and crop type, with derivations for twelve crop commodity classes at sub-regional scales (Chaturvedi et al. 2013). Industrial water demands are also georeferenced and calculated for a wide range of technologies in GCAM's energy production and transformation sectors (Davies et al. 2013; Kyle et al. 2013), with the remainder of industrial water use assigned to manufacturing, modeled in an aggregate representation. Municipal estimates of water use are determined at a regional scale as a function of GDP per capita, water price, and a technological-change parameter (Hejazi et al. 2013). The industrial and municipal sectors are also represented at the regional scale, with the agricultural sector further disaggregated into as many as 18 agro-ecological zones (AEZs) within each region. Base-year water demands—both gross withdrawals and net consumptive use—are assigned to specific modeled activities such that bottom-up estimates of water demand intensities of specific technologies and practices are consistent with top-down regional and sectoral estimates of water use. Historical water demand data compiled from the FAO Aquastat database are summarized in **Table 1**, and GCAM total water withdrawal estimates are comparable to the FAO estimates as shown in **Figure 4**. The present study also accounts for in-stream water demands for uses such as ecosystem services, navigation, and recreation. This amount of water is termed *environmental flow requirement* and is estimated as a percentage (e.g. 10%, can be varied by the model user) of the long-term mean monthly natural streamflow following the work of Voisin et al. (2013).

Table 1: Historical water demand data compiled from the FAO Aquastat database.

	North Africa							
	1975	1980	1985	1990	1995	2000	2005	2010
Ag withdrawal(10^9 m3/yr)	53.4	58.2	63.7	70.2	69.4	79.5	86.9	94.4
Ind withdrawal(10^9 m3/yr)	4.3	4.7	5.6	5.6	5.9	5.9	6.2	6.6
Muni withdrawal(10^9 m3/yr)	4.3	4.7	5.4	6.0	7.4	10.7	10.6	10.5
Tot withdrawal(10^9 m3/yr)	62.0	67.6	74.7	81.8	82.7	96.0	103.8	111.5
fresh surf withdrawal(10^9 m3/yr)	50.6	54.0	56.8	59.3	63.2	64.8	61.5	59.6
fresh GW withdrawal(10^9 m3/yr)	11.4	13.1	15.7	18.6	19.1	19.9	18.7	18.0
Tot fresh withdrawal(10^9 m3/yr)	62.0	67.0	72.5	77.9	82.4	84.7	80.1	77.6
Desal produced(10^9 m3/yr)	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.2
	Middle East							
	1975	1980	1985	1990	1995	2000	2005	2010
Ag withdrawal(10^9 m3/yr)	97.0	111.6	125.3	138.6	160.6	179.4	194.0	209.9
Ind withdrawal(10^9 m3/yr)	1.4	1.6	1.7	4.0	8.1	12.1	14.4	16.2
Muni withdrawal(10^9 m3/yr)	5.9	7.5	9.1	11.1	14.3	15.9	18.3	19.8
Tot withdrawal(10^9 m3/yr)	104.4	120.7	136.1	153.7	183.0	207.3	226.7	246.0
fresh surf withdrawal(10^9 m3/yr)	27.5	32.4	36.6	41.2	48.7	53.8	56.6	59.5
fresh GW withdrawal(10^9 m3/yr)	76.1	87.4	97.8	109.7	132.0	150.5	163.0	175.4
Tot fresh withdrawal(10^9 m3/yr)	103.6	119.7	134.4	150.8	180.7	204.3	219.7	234.9
Desal produced(10^9 m3/yr)	0.0	0.1	0.5	1.5	1.6	1.9	3.2	3.2

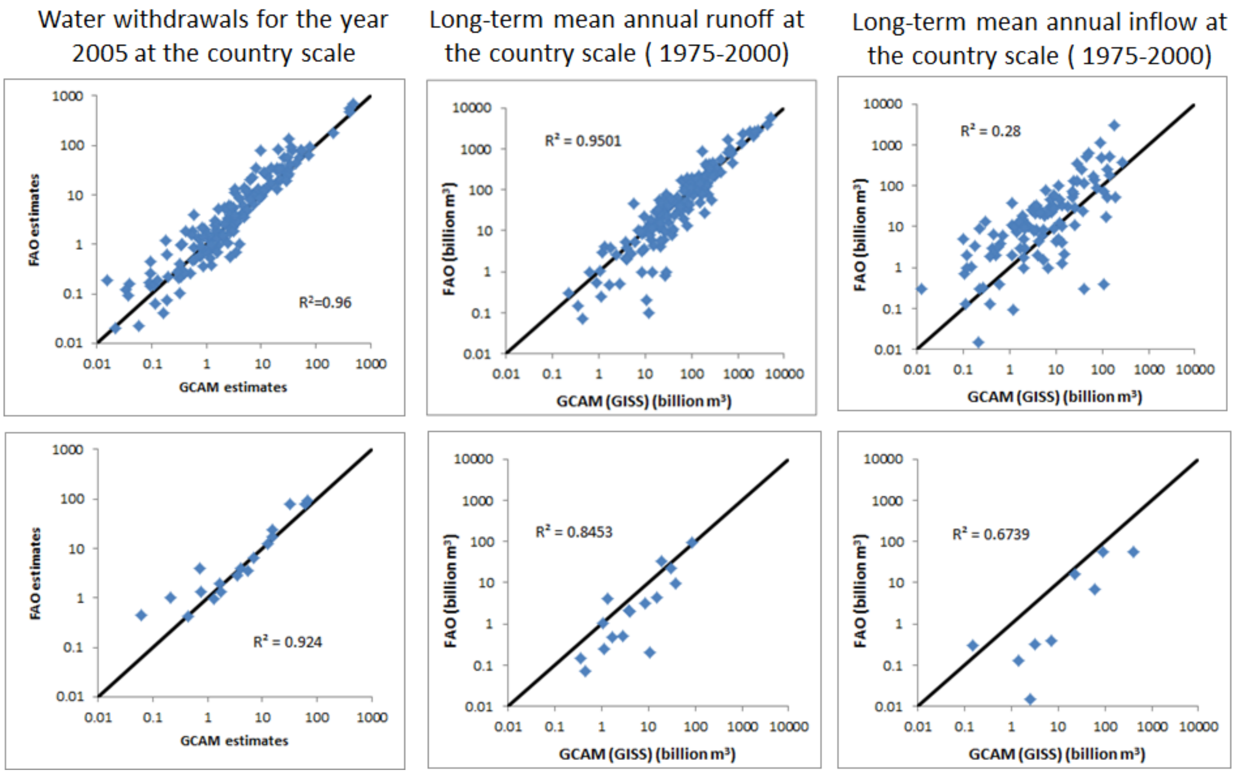


Figure 4: Comparison of water withdrawal, runoff, and inflow results against FAO estimates for all countries (top panel,) and the MENA countries specifically (bottom panel); only countries with values in the FAO Aquastat database are shown.

D.1.3. Renewable Water Resources in GCAM (Surface and Groundwater)

On the supply side, GCAM currently uses a global hydrologic model for water supply that is based on a gridded monthly water balance model with a resolution of 0.5°x0.5°. The GCAM hydrology model (see Hejazi et al. 2014a,b) requires gridded monthly precipitation, temperature, and maximum soil water storage capacity (a function of land cover) values, which are used to compute monthly evapotranspiration and runoff, and the soil moisture retained in the soil column. The GCAM hydrologic model has been evaluated against observational data for streamflow and results of other global hydrologic models, and is used to provide water supply estimates globally at the grid scale through the end of the 21st century (Hejazi et al. 2014b, also see Figure 5). GCAM also includes a spatial river routing component – a modified representation of the River Transport Model (RTM) that employs a cell-to-cell routing scheme with a linear advection formula to simulate monthly natural streamflow (Zhou et al., 2015). Moreover, the GCAM hydrologic model provides estimates of renewable water resources for each of its model grids, which capture the maximum naturally-available annual water volumes in each basin around the world.

Some of this runoff flows too quickly to saline water bodies for capture, or occurs in remote areas where there is no potential human use. Thus, almost all recent studies have assessed water scarcity conditions using water scarcity indices such as that of Falkenmark (1989), which compares total water demand to the total available amount of renewable water, and defines water-scarce regions as those in which total water demand is greater than 40% of total water availability. In this study, we define the volume of renewable water resources accessible for human use as:

$$QA_i^t = max\ (\ 0\ , min\ (\ QT_i^t - EFR_i\ , QB_i^t - EFR_i\ +\ RS_i\ )\ ) \qquad (1)$$

where QA_i^t, QT_i^t, and QB_i^t are the annual volumes of accessible renewable water, natural streamflow and baseflow, respectively, in basin i and year t; EFR_i is the environmental flow requirement for each basin, and RS_i is total reservoir storage capacity in each basin i in year 2005 (Kim et al., 2016). All volumes are measured in $km^3\ yr^{-1}$. According to the GRanD database (Lehner et al. 2011), the total reservoir storage volume globally is approximately 6,100 $km^3\ yr^{-1}$; their geographic locations are then used to compute the total reservoir storage capacity in each basin. As explained previously, EFR_i is a percentage of the monthly average streamflow for each basin. Baseflow is computed as a fraction of annual streamflow following the estimates of Beck et al. (2013). The hydrological model in GCAM does not currently calculate groundwater recharge separately; thus, accessible water calculated includes renewable surface and groundwater available through recharge.

In regions where the total water demands exceed the total accessible flow of renewable water (surface and groundwater), non-renewable groundwater and desalinated water are also available for use. However, long-term use of non-renewable groundwater is unsustainable and desalination of brackish and saline water is costly. The total water availability in each basin, including renewable water (surface and groundwater), non-renewable groundwater, and brackish and saline water, is estimated for calibration purposes to match current usage shares in the base year along with the associated cost of moving or treating water for human consumption.

D.1.4. Non-Renewable Groundwater Supplies in GCAM

The first step to calculating the volume of economically accessible groundwater in GCAM is quantifying the volume of groundwater present. This is estimated through:

$$V_{wd} = bA\phi \qquad (2)$$

Where V_{wd} is the volume of water drained (m^3), b is the saturated thickness (m), A is the areal extent of the aquifer (m^2), and ϕ is the porosity. This calculation is applied to the major aquifer systems of the region. To achieve this, a combination of data resources are used for this purpose. A map of the groundwater resources of the world from the Worldwide Hydrogeological Mapping and Assessment Programme (WHYMAP) is used to delineate the areal extents for aquifers of interest (**Figure 5**; high resolution map available from the WHYMAP site).

The digital WHYMAP is georeferenced and digitizing the various colored regions (i.e. blue for major groundwater regions, green for complex hydrogeological structures, and shading based on recharge). This areal map is then overlaid with detailed porosity and permeability datasets from Gleeson et al. (2014), aquifer thickness estimates from DeGraaf et al. (2015), and a depth to groundwater map from Fan et al. (2013). It should be noted that no global aquifer thickness map exists based on direct hydrogeologic data. To cope with this obstacle, DeGraaf et al. (2015) followed from the proposed use of global data sets of surface lithology and elevation for aquifer parameterization (Sutanudjaja et al. 2011; DeGraaf et al. 2015). DeGraaf et al. (2015) acknowledge discrepancies between their modeled and observed calibration data in mountainous terrains. No aquifer thickness is provided in cases where the discrepancies are large. We assume an average of 200 m for these cases; this value represents a mid-point in the reported range (DeGraaf et al., 2015).

Based on groundwater volumes, GCAM uses a framework for cost analyses of groundwater production from storage that estimates the volume of accessible groundwater and unit costs over time as a function of several key variables. Costs are broken down between capital costs of well installation and maintenance and recurring electricity costs associated with water production.

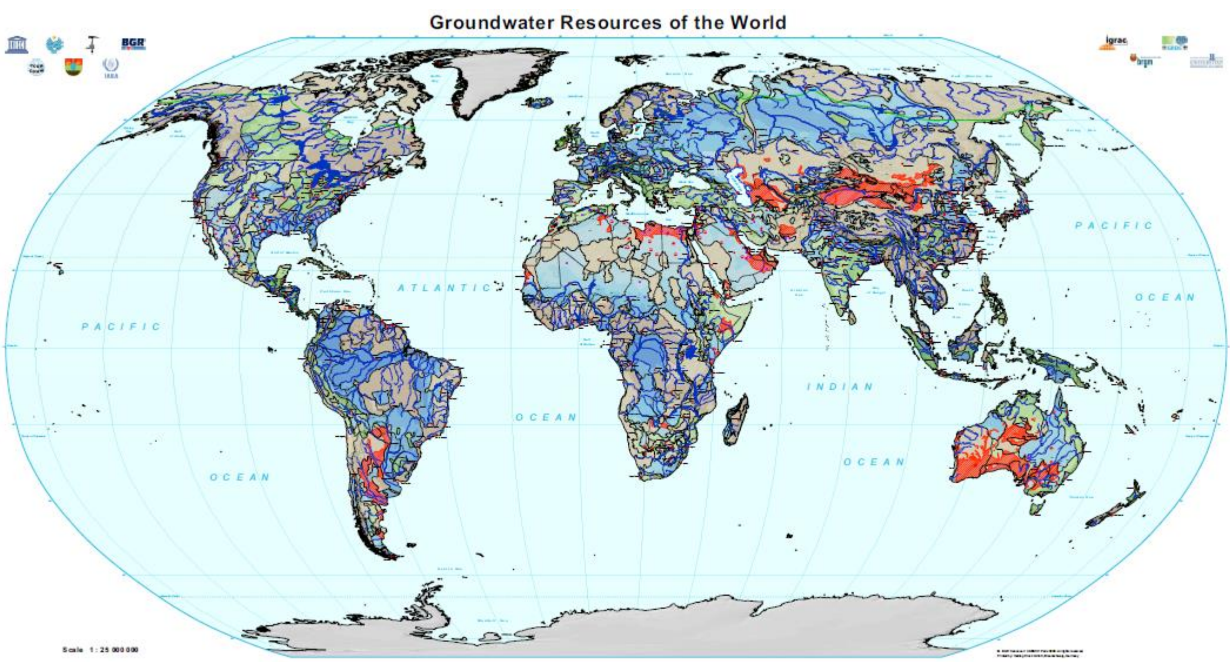
This analysis follows the methods of Naggar (2003). The annual unit cost of water (USD/m^3) is:

$$C_W = C_T / V_p \quad (3)$$

Where V_p is the volume of water produced per year, and C_T is the total annual cost (USD/yr).

$$C_T = C_C + C_M + C_E \quad (4)$$

C_C is annual capital cost of the well, C_M is the annual maintenance and labor fees, and C_E is the recurring cost of electricity (USD/yr). The annual maintenance and labor fees, C_M, are assumed to be a percentage (e.g., 7%, adjustable by the model user) of the initial capital cost (Naggar, 2003).



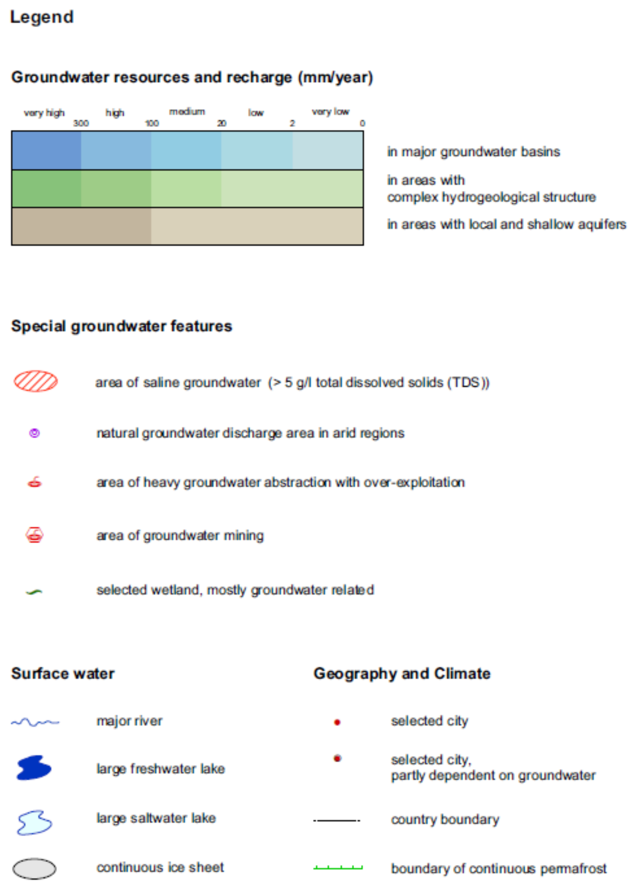


Figure 5: Global database of groundwater aquifers (WHYMAP), used to delineate groundwater systems in the MENA region.

The capital recovery factor is used to calculate the annual capital cost of the well (C_C) (Beakley et al., 1986; Naggar, 2003).

$$C_C = C_I(1+i)^n \times \frac{i}{(1+i)^n - 1} \tag{5}$$

Where C_I is the initial capital cost (USD), C_C is the annual capital cost (USD/yr), i is the rate of interest (-), and n is the lifetime of the well (yr). The initial capital cost is taken as the average cost of drilling a groundwater well; assumed to be \$82/m for simpler geologic conditions and \$160/m for more complex geologies. The interest rate is assumed to be 0.10 (Naggar, 2003).

The recurring cost of electricity (C_E) depends on the power required to lift a unit volume of water from depth to surface and the efficiency of the pumping system (pump and motor) (Naggar, 2003).

$$C_E = \left(\frac{\gamma QH}{1{,}000\eta}\right) t_A\, e_r \tag{6}$$

Where the grouped term $\left(\frac{\gamma QH}{1{,}000\eta}\right)$ is the power (kW), where γ is the specific weight of water (N/m^3), Q is the well yield (m^3/s), H is the total head (m), η is the pump efficiency (-); t_A is the annual operating time (hr/yr); e_r is the energy cost per Kilowatt-hour (USD/kWh). Hence, $V_p = Q \times t_A$ (m^3/yr).

To calculate the annual cost of electricity, the drawdown relative to the pumping rate must be provided. The assumption in GCAM is that we are depleting groundwater aquifers beyond the natural recharge over the pumping period. This type of production considers groundwater as a nonrenewable resource, as it will not be replaced on a human timescale. As a first step towards building groundwater unit cost curves, we calculate analytical solutions to groundwater pumping in homogeneous closed systems (as opposed to building detailed heterogeneous numerical models). These systems are treated as "closed systems" in the sense that there is no recharge entering the units from horizontal flow paths. This allows for conservative estimates of the volume of water accessible by pumping in a depletable reservoir. We refer to these closed systems as hydrologic units, where each major aquifer is broken into equally sized hydrologic units depending upon the regional hydrogeologic properties. A transient Theis solution is performed to calculate the drawdown in the production well, assuming one production well in each hydrologic unit (Theis, 1935).

$$s = \frac{Q}{4\pi T} W(u) \tag{7}$$

Where s is the drawdown (m), Q is the well discharge rate (m^3/s), T is the transmissivity (m^2/s), and $W(u)$ is the Well function (exponential integral). The Well function may be approximated by:

$$W(u) = -0.577216 - \ln(u) + u - \frac{u^2}{2 \times 2!} + \frac{u^3}{3 \times 3!} - \frac{u^4}{4 \times 4!} + \cdots \tag{8}$$

$$u = \frac{r^2 S}{4Tt} \tag{9}$$

and r is the radial distance from the well to the observation point (m), S is the storativity, and t is the production time.

The Theis solution assumes an aquifer of infinitely acting areal extent. To adapt this analytical solution to a closed system, we impose imaginary pumping wells, or image wells, about the main production well. This method (Ferris et al., 1962) exploits the symmetry of the cone of depression to create the effect of a drainage divide between the production well and the image wells. A drainage divide is hydraulically similar to an impermeable boundary in that they both do not allow for flow into or out of the hydrologic unit. An example with one image well is shown in **Figure 6** (Ferris et al., 1962). In our case, the real production well is bounded on all sides. This requires a more complex network of image wells extending out to infinity, similar to that seen in Ferris et al. 1962 (**Figure 7**).

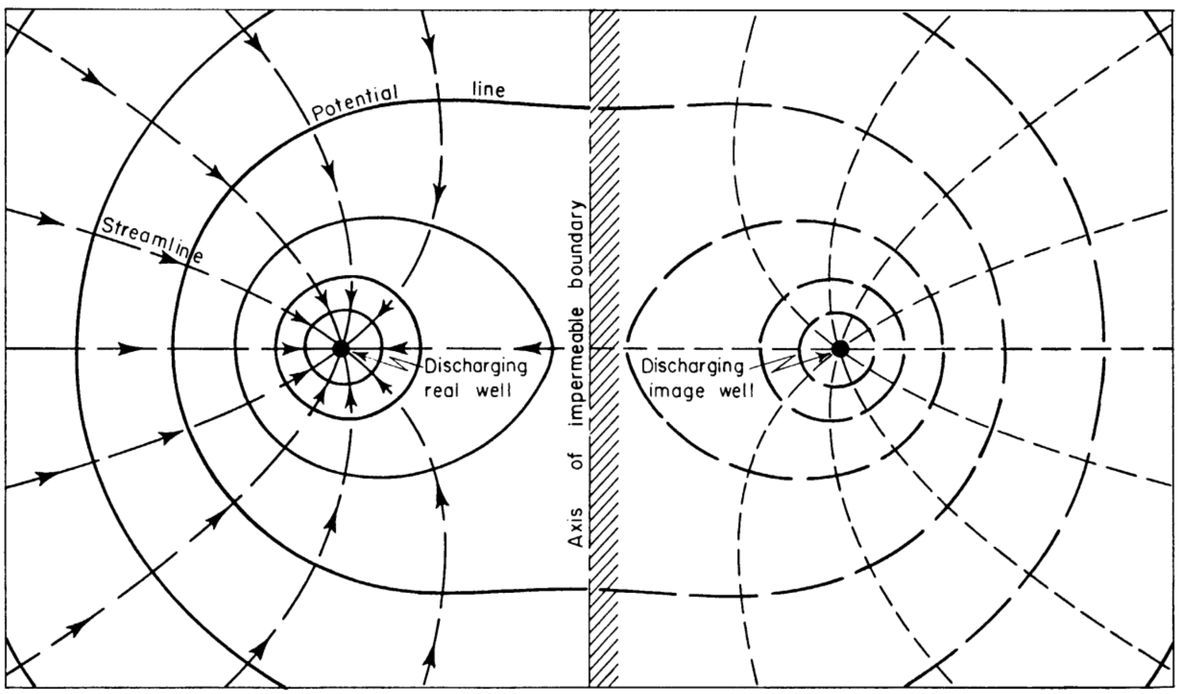


Figure 6: Flow net showing stream lines and potential line in the vicinity of a discharging well near a no flow boundary. Image from Ferris et al. (1962).

The algorithm implemented to build the network of image wells computes radial observation distances and as seen in Equation (13).

$$r_{o(x,y)} = ((x r_i)^2 + (y r_i)^2)^{0.5} \tag{10}$$

Where r_o is the observation radius of the image well at point (x,y), r_i is the radial distance to the closest image well, and x and y are unitless counters, as opposed to distances. **Figure 8** displays the wedge of image wells generated by this algorithm.

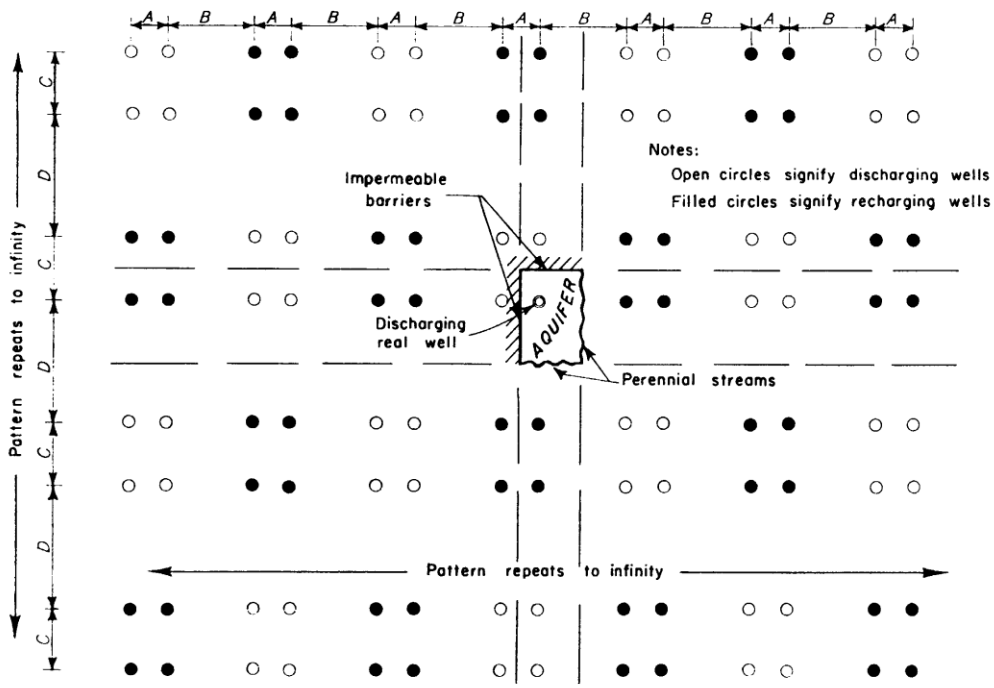


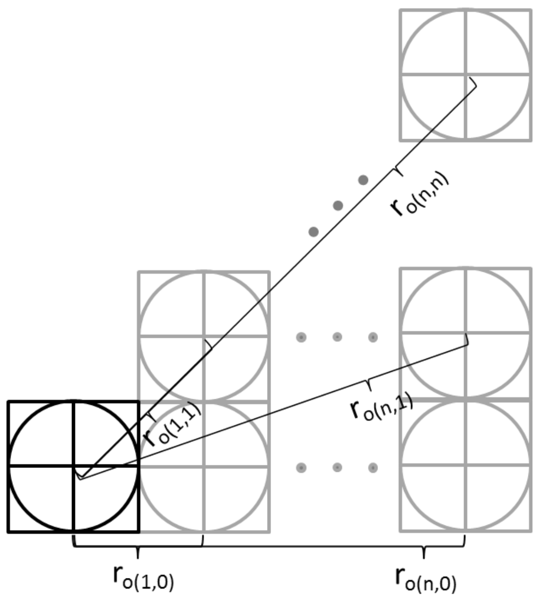
Figure 7: Image well network for a discharging well bounded by 2 no flow no boundaries and 2 perennial streams. Figure from Ferris et al. (1962).

The radii calculated by the algorithm are then used in Equations (10)-(12) to calculate the contribution to drawdown at the production well due to the wedge of image wells. The symmetry of the system about the production well is exploited by multiplying the sum of the contributed drawdowns by a factor of 8 (**Figure 9**).

To avoid double counting shared boundary image wells, shown in red in Figure 8, the algorithm specifics that

$$s = \frac{s}{2} \quad for\ x = y\ or\ y = 0 \tag{11}$$

For each hydrologic unit, the initial radius, $r_{o(1,0)}$, is back-calculated from Equation (10). This requires the definitions of well yield (Q), annual operation time (t_A), the lifetime of the well in years (n), the saturated thickness of the aquifer reduced by the well screen length (b), and the storativity (S). The hydrogeologic properties are set from the same data sources discussed earlier (Gleeson et al., 2014; DeGraaf et al., 2015). Optimistic assumptions are made for the first example set to establish an upper bound to the amount of accessible groundwater. Following from this logic, in the absence of a detailed storativity database, the porosity is taken as an initial estimate. The lifetime of the well is set to 20 years (Naggar, 2003) and the annual operating time is taken to be the full year. An optimal well yield is calculated for each hydrologic unit based on the hydrogeologic properties. This calculation follows an iterative procedure about Equation (12).



$$r_{o(1,0)}=((1\times r_i)^2+(0\times r_i)^2)^{0.5}$$
$$r_{o(1,1)}=((1\times r_i)^2+(1\times r_i)^2)^{0.5}$$
$$\vdots$$
$$r_{o(1,n)}=((1\times r_i)^2+(n\times r_i)^2)^{0.5}$$
$$r_{o(2,0)}=((2\times r_i)^2+(0\times r_i)^2)^{0.5}$$
$$r_{o(2,1)}=((2\times r_i)^2+(1\times r_i)^2)^{0.5}$$
$$\vdots$$
$$r_{o(2,n)}=((2\times r_i)^2+(n\times r_i)^2)^{0.5}$$
$$\vdots$$
$$r_{o(n,n)}=((n\times r_i)^2+(n\times r_i)^2)^{0.5}$$

Figure 8: Image well location algorithm. The black well is the production well and gray wells are imaginary wells.

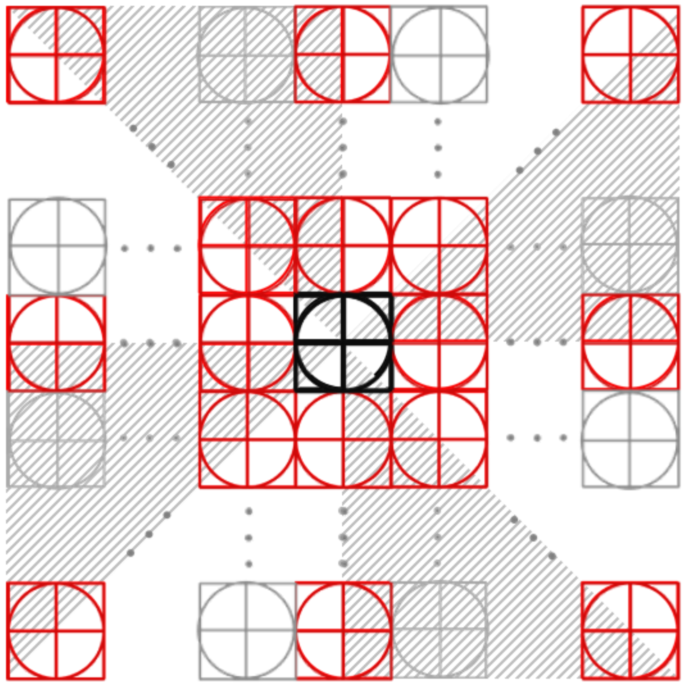


Figure 9: Image well symmetry about the pumping well.

The well yield iterative procedure begins with an initial Q estimate and calculates the anticipated drawdown, s, over 20 years. The drawdown is then compared to the maximum operational drawdown, s_{max}. The maximum operational drawdown is assumed to the depth to the top of the screened production interval, which is ~30% of the aquifer thickness by rule of thumb. A cubic function is used to increment the well yield up or down to move closer to the optimal drawdown (s_{max}).

$$Q_{new} = \quad Q_{current}\left(\frac{s_{max}}{s_{current}}\right)^3 \qquad for\ abs(s_{max} - s) > err \tag{12}$$

The desired error tolerance is specified by the model user (e.g., err = 0.1 m).

D.1.5. Water allocation in GCAM

GCAM allocates water among competing water users and solves for an inferred value of water in each of the 235 basins globally for each time period. The supply-demand equilibrium solution for water is simultaneously solved with all other goods and services in GCAM (e.g., energy, agriculture, land) to ensure internal consistency of WEF nexus calculations for any given time period. The three sources of water at the basin scale – accessible renewable water, non-renewable groundwater, and desalinated water – are nested within a logit structure and compete for the share of water supply; desalinated water is assumed to be available for non-irrigation purposes only. The logit formula is shown in Equation (13) (Clarke and Edmonds 1993; Wise et al. 2014).

$$S_i = \frac{(\gamma_i \Pi_i)^{\varphi}}{\sum_{j=1}^{3}(\gamma_j \Pi_j)^{\varphi}} \tag{13}$$

where Π_i is the cost of option i, γ_i is a scalar parameter, φ is the logit exponent, and $j=1,2,3$ is used to denote the three sources of water (accessible renewable water, non-renewable groundwater and desalinated water). Commonly used to describe consumer choice, the logit approach is used here to determine the share of water from each source to meet water demands in each basin. Accessible renewable water is assumed to be the lowest cost option relative to non-renewable groundwater or desalination, and is utilized prior to more expensive options. When accessible renewable water supply is insufficient to meet total water demands in any given basin, however, the water price in that basin rises until higher cost options provide additional supplies. Changes in the water price propagates throughout the system and leads to changes in the costs of all goods and services that require water inputs, particularly agricultural goods, with corresponding readjustment of their demands. Given the large differential in water cost between the agricultural sectors and other end-uses, GCAM assumes a subsidy of a factor of one hundredth on the price of irrigation – a value consistent with the study of Sağlam (2013), who reports that the agricultural sector pays substantially less than industry and households with a ratio around 1%. If such a subsidy is ignored, GCAM cannot reproduce the estimated crop productions in the base year calibration because crop production is unprofitable with the associated water costs (Kim et al., 2016).

D.2. Constructing GCAM-MENA

A primary portion of this project was the development of a new analytical capability based on GCAM, but with regional detail for the MENA region. The GCAM model developed for the MENA region is hereinafter referred to as ***GCAM-MENA.*** GCAM-MENA was developed specifically to analyze water-energy-food nexus issues in the MENA region at the country level of spatial resolution. For this purpose, the 2 geopolitical regions in the existing GCAM model (North Africa and Middle East) were further divided into 15 geopolitical regions in the MENA region (see **Figure 10**).

This effort of breaking out the MENA into 15 unique geopolitical regions in GCAM required a substantial data compilation and rearrangement effort to ensure the ability of the model to balance demands and supplies for all sectors over the calibration years at the country level. For example, several datasets used in GCAM were missing entries for some of the MENA countries (e.g., Bahrain). And many MENA countries had missing values in these input datasets especially over historical years. To overcome these issues, we had to aggregate some of these countries together (e.g., Arabian Peninsula), and to carefully estimate some of the missing energy and land entries to ensure that markets for all tracked commodities are cleared in all historical time periods for all 15 MENA regions.

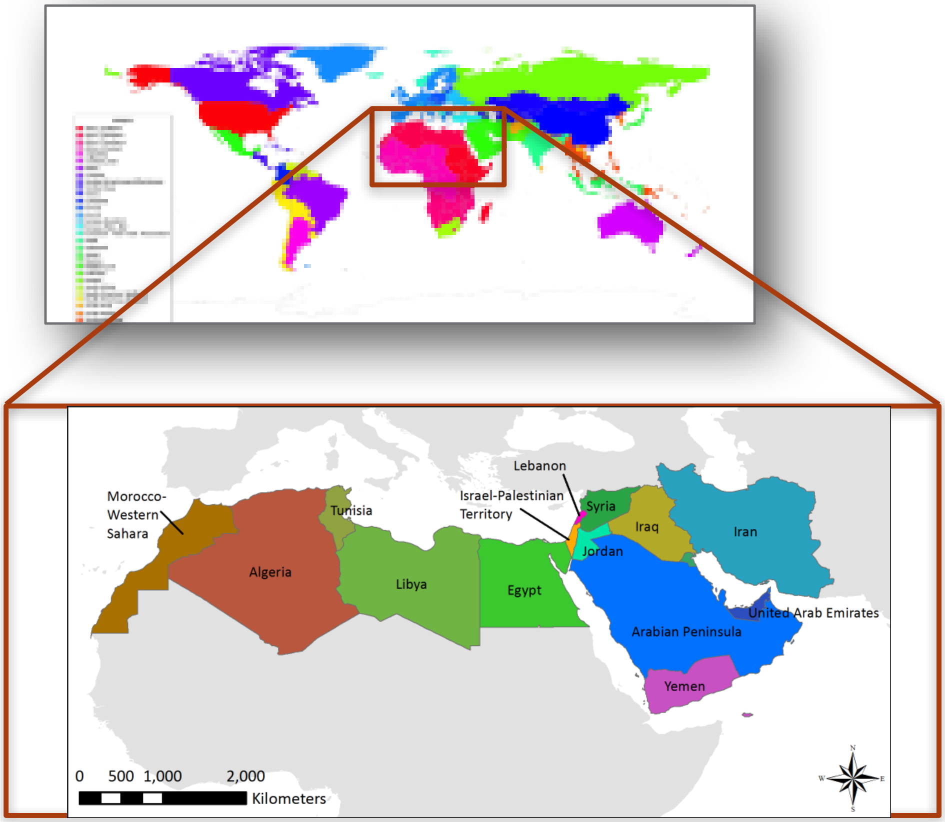


Figure 10: Telescoping approach implemented in the GCAM-MENA model (15 regions).

Through the physically-based approach of estimating groundwater resources, we have applied the framework that defines a cost function for groundwater throughout the MENA region to establish groundwater resource curves for each of the 15 MENA regions. **Figure 11** shows the total groundwater volume (in term of depth) that is available at any given grid (using Equation 5). We then calculate the groundwater cost as well for each one of the grids (**Figure 12**), using Equations (3)-(12) at the grid level. By combining these two spatial distributions, we can construct the groundwater resource curves for each of the MENA regions (Northern Africa and Middle East), as shown in **Figure 13**, aggregated at the country level. These resource curves account for environmental flow requirements, which are deducted from the total renewable water resources calculation. Note, with the cost function rooted in the physics of the system, we have the flexibility to consider various capital cost scenarios. In the current formulation, the cost is only reflecting the cost of electricity required to pump water from the ground plus groundwater well drilling and installation. We started with these parameters because they are both based on the depth of the well, which is a parameter of the analytical groundwater flow solution. There are other known costs (the cost of the pump, water treatment, and transport) that are not used in the analytical solution but can be easily added in to the cost computation developed in this work.

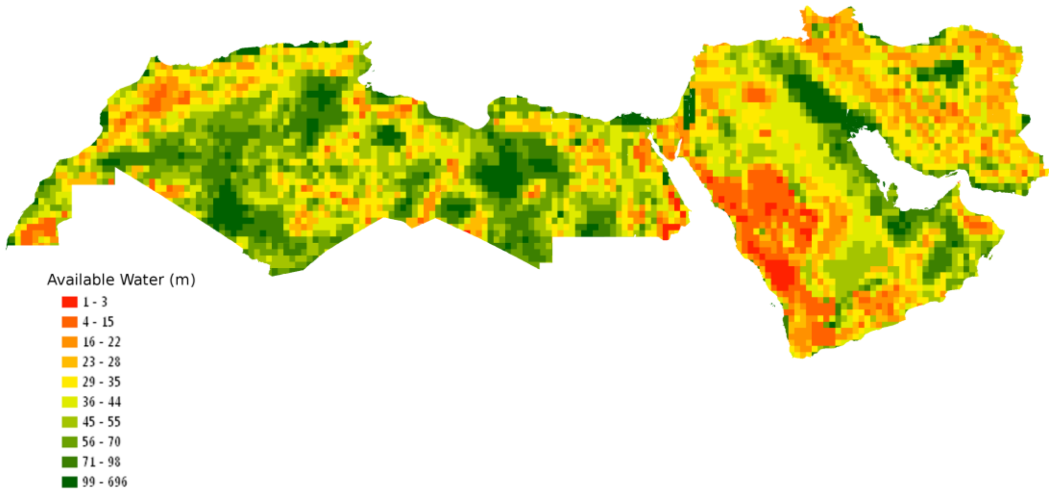


Figure 11: Spatial distribution of estimated total available groundwater (expressed as depth of water column), values calculated using Equation (5). This is the total available groundwater underground, some of which may not be actually available for abstraction given limits of water pumps.

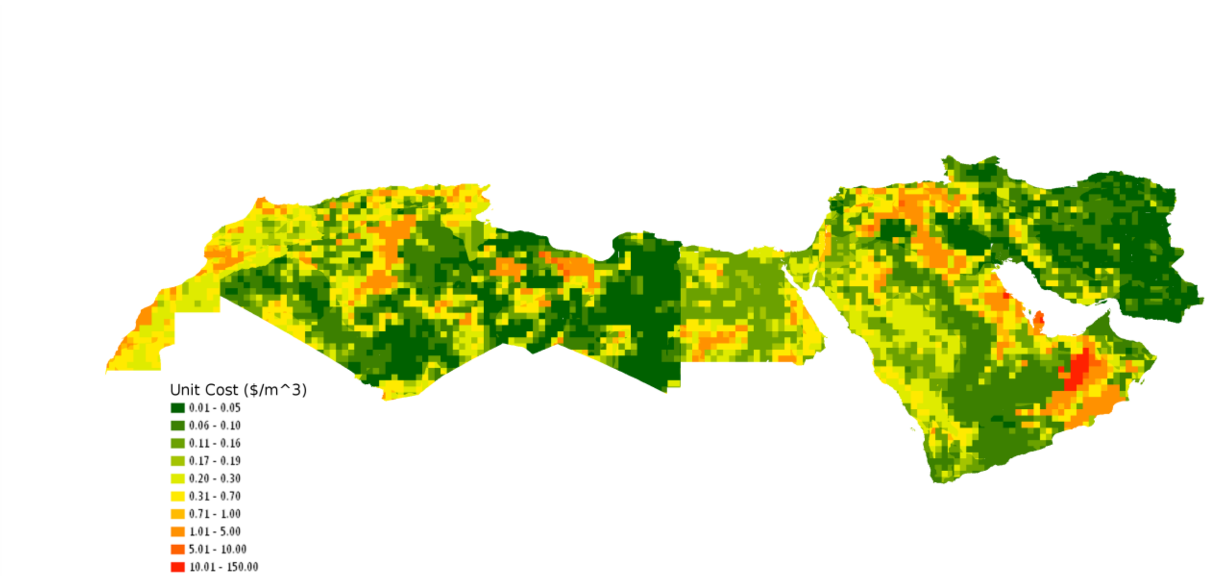


Figure 12: Estimated total groundwater cost ($/m^3) for each grid in MENA region.

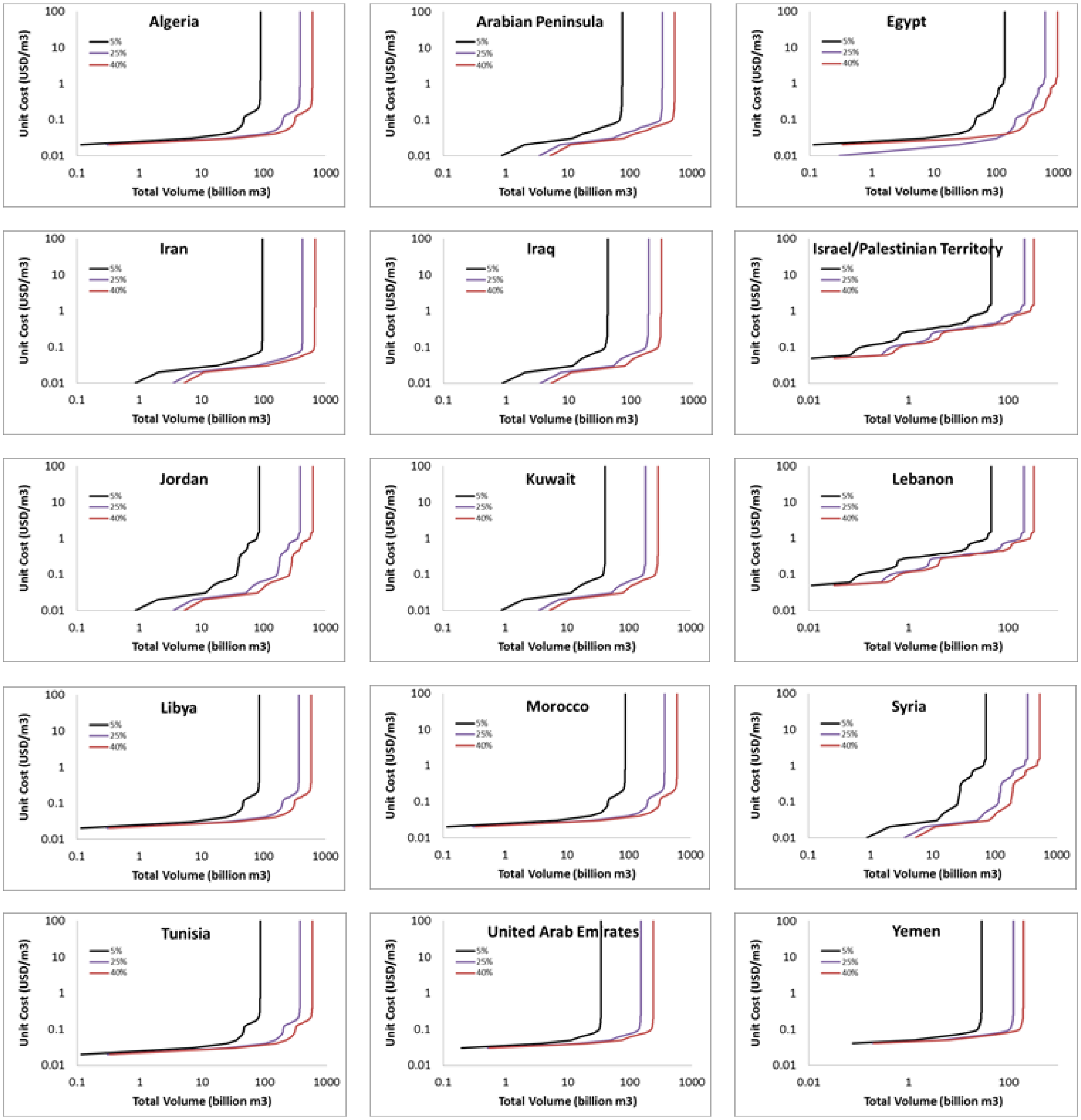


Figure 13: Groundwater resource curves for countries of the MENA region, with defined maximum threshold amounts of groundwater of 5, 25 and 40 percent of available groundwater that can be economically exploited without causing environmental degradation.

D.3. Analytical Methodologies

D.3.1. Water Scarcity Index

A key analytical element of this project is the development of water scarcity measures. For this purpose, a water scarcity index (WSI) can be calculated (annually) at the country scale using Equation (17).

$$WSI = \frac{Demands}{Runoff + Inflow} \qquad (14)$$

Runoff is the total internally generated runoff within a country. The total inflow into each country is calculated as the sum of available surface runoff (internally generated within the country) and groundwater resources; groundwater data was obtained from the FAO's Aquastat database. A modified version of the WSI can also be calculated that includes non-conventional water sources such as desalination in the denominator of Equation (14).

D.3.2. Estimating Economic Impacts (focus on agriculture)

The effects of climate change, mitigation activities, and adaptation strategies all have the potential to impact multiple aspects of the economy in both direct and indirect ways. Although some regions may experience positive impacts for some economic sectors, the distribution of impacts will vary across countries and the economic burden will not be evenly distributed. Adaptation may lessen negative impacts in some sectors, but in some cases, these strategies may have unintended consequences on other parts of the economy. Finally, economic impacts can have a long-term, cumulative nature, so that seemingly short-term events may have longer-lasting impacts on economic growth. For these reasons, the economic impacts of climate change can be most effectively analyzed with an integrated modeling approach. In this section, we describe how GCAM can be used to estimate the economic effects of climate change and adaptation strategies, using an example of a water-constrained agricultural sector and the use of different irrigation technologies to adapt.

There are multiple time scales on which physical and economic impacts and damages may occur. Agricultural production and revenues may be affected by severe weather over the course of one or several years, while in the longer term, changing climatic conditions may cause shifts in productive growing regions. The effects of these impacts will differ both in economic value, broader macroeconomic consequences, and effective adaptation options. Therefore, multiple methods of analysis are required including Integrated Assessment modeling to analyze intersectoral changes, finer resolution sectoral models (e.g., hydrological or agricultural), and post modeling economic valuation. Below we present a general methodology that can be used to conduct research on the broader economic costs and benefits of different adaptation methods, using irrigation technologies as an example. Analysis can focus on either (or both) the effects of both long-term, changing precipitation patterns and short-term, extreme drought events.

Climate change will affect the agricultural sector directly, through changing temperature and precipitation patterns and more frequent extreme weather events. These changes may result in improved yields in some regions and lower yields in others (Rosenzweig et al., 2014). In our example, we focus on water-constrained agricultural production, where yields are lower due to insufficient soil moisture. In this scenario, total yields decrease and prices increase (**Figure 14a**).

Due to the inelastic nature of food demand, price increases may more than offset production losses for producers, because $P_1 * Q_1 > P_0 * Q_0$ (Dorward, 2012). Depending on the regional distribution of impacts, a net importing country such as those in the MENA region may experience either positive or negative changes in the value of net imports. In some cases, although the quantity of agricultural exports may decrease/increase, the value of those exports may increase/decrease (Hertel, 2016; Nelson et al., 2014): $P_1 * (Q_{1_{prod}} - Q_{1_{cons}}) > P_0 * (Q_{0_{prod}} - Q_{0_{cons}})$.

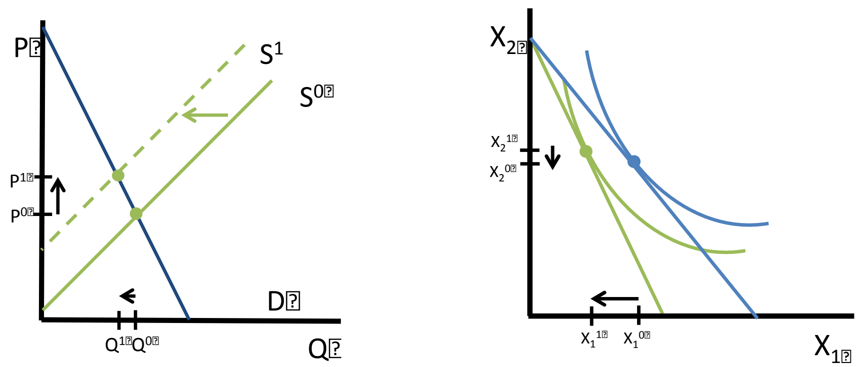


Figure 14: Framework to estimate the economic impacts on agricultural sector (a) food demand-price relationship & the effects of decreasing yields, (b) the effect of price increase on food consumption.

The total economic effect of these changes is more complicated and can be ambiguous when multiple aspects of economic welfare are considered. Even when agricultural producers and net exports increase, all groups will face higher food prices. **Figure 14b** shows the effect on consumption when the price of good 1 increases. Total consumption decreases; consumers are worse off. However, diverse consumption patterns and relative yield impacts may result in very different patterns of impacts across countries. Because agricultural products are generally globally traded goods, modeling the impacts of climate change on a specific region requires a global assessment.

Through this approach, GCAM can be used to estimate the impacts on net value of agricultural commodities:

$$Net = \left(P_1 * (Q_{1_{prod}} - Q_{1_{cons}})\right) - \left(P_0 * (Q_{0_{prod}} - Q_{0_{cons}})\right). \qquad (15)$$

GCAM outputs can be combined with econometrically derived relationships between producer and consumer prices to estimate the effects on consumer expenditures (Cui et al., 2016). The changes in consumption and prices can be used to analyze proxies of individual welfare, such as consumers' food costs, changes in household expenditure patterns, and nutritional outcomes, which are closely linked with consumption patterns (Campbell et al., 2010; Iannotti et al., 2012; Torlesse et al. 2003).

D.3.3. Investment and Adaptation Costs

Impacts are only one part of the story, however. When farmers face long-term changes in weather patterns, they will change their behavior to adapt to the new circumstances. Adaptation to water scarcity may occur through multiple channels, such as planting different crops or more drought-resistant varieties and increasing use of irrigation. The adaptive responses will tend to reduce the negative impacts of water scarcity, but they also have the potential to affect the wider economy through interactions with energy, manufacturing, or other economic sectors. The net impact on an economy of any given adaptation response cannot be known without modeling the global system.

Understanding the potential impacts forms a basis on which to model the costs and benefits of various adaptation strategies. For example, increased investment in irrigation may help to reduce the negative impact on yields, but will also increase production costs, which will depend greatly on the supply of water and demand in other sectors (e.g., water for cooling thermoelectric power plants). The costs and benefits of the same irrigation technology varies among countries.

In a scenario where water is a constraining factor, the relative costs and benefits in terms of production, prices, and net trade flows can be modeled in GCAM. For instance, the capital investment and operating costs of sprinkle, drip, flood, and micro-irrigation can be used to estimate production costs under these technologies and their impact on macroeconomic metrics. Analysis can also be conducted on the costs of different water supply options, such as using non-renewable groundwater or desalinization plants (Hussain & Bhattarai, 2004). As a starting point for this analysis, we assume a given unit cost of (e.g., $1.0/m^3) for desalination plants with a life time of 30 years following the work of Parkinson et al. (2016). The work also relies on the previous work of Immerzeel et al. (2011) and Droogers et al. (2012). The value of this unit cost can be varied by the model user (and can be varied over time) to simulate the impacts of changing technology and/or energy prices associated with desalination technologies.

E. SCENARIO DEVELOPMENT

This analysis in this study is built on exploration of scenarios. As discussed in Section C, the scenarios in this study cover three key dimensions: (1) climate impacts, (2) socioeconomics pathways, and (3) limitations on water supplies. These three areas are discussed in the remainder of this section.

E.1. Climate Scenarios

Representative Concentration Pathways (RCPs) are four greenhouse gas concentration (not emissions) trajectories adopted by the IPCC for its fifth Assessment Report (AR5) in 2014 [Moss et al. 2008]. RCPs supersede the Special Report on Emissions Scenarios (SRES) projections published in 2000. These pathways are used for climate modeling and research. They describe four possible climate futures, all of which are considered possible depending on how much greenhouse gases are emitted in the years to come. The four RCPs: RCP2.6, RCP4.5, RCP6.0, and RCP8.5, are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (increases of +2.6, +4.5, +6.0, and +8.5 W/m^2, respectively) [Weyant et al. 2009].

The RCPs are consistent with a wide range of possible changes in future anthropogenic GHG emissions. RCP2.6 assumes that global annual GHG emissions (measured in CO_2-equivalents) peak between 2010-2020, with emissions declining substantially thereafter. Emissions in RCP4.5

peak around 2040, then decline. In RCP6.0, emissions peak around 2080, then decline. In RCP8.5, emissions continue to rise throughout the 21st century.

For the purposes of this study, a “no climate policy” reference scenario (RCP6.0) has been implemented in GCAM to reflect “reference” or baseline efforts towards climate mitigation. Moreover, three different GCMs were selected to represent wet, average and dry conditions in the region in an effort to provide a robust envelope of impacts of climate change on water resources and the corresponding analysis of results (see **Figure 15**).

The Community Climate System Model (CCSM) is a GCM developed by the University Corporation for Atmospheric Research (UCAR). The coupled components include an atmospheric model (Community Atmosphere Model), a land-surface model (Community Land Model), an ocean model (Parallel Ocean Program), and a sea ice model (Community Sea Ice Model) [e.g., Hoffman 2006].

The Goddard Institute for Space Studies (GISS) GCM is primarily aimed at the development of coupled atmosphere-ocean models for simulating Earth's climate system. Primary emphasis is placed on investigation of climate sensitivity —globally and regionally, including the climate system's response to diverse forcings such as solar variability, volcanoes, anthropogenic and natural emissions of greenhouse gases and aerosols, paleoclimate changes, etc. A major focus of GISS GCM simulations is to study the human impact on the climate as well as the effects of a changing climate on society and the environment. The GISS GCM is featured in the IPCC (AR5 as well as past reports), and over 50 TB of climate model results have been publicly archived for the CMIP5. This project has included simulations for the historic period, future simulations out to 2300, and past simulations for the last 1000 years, the last glacial maximum and the mid-Holocene.

The FIO Earth System Model (FIO-ESM) is a GCM developed by the First Institute of Oceanography in China. It includes the ocean surface wave model besides the atmosphere, ocean, land and ice components, and is coupled with the fully global carbon cycle process and its interactions with the climate system. The historical simulation of the global carbon cycle is following the CMIP5 (Climate Model Inter-comparison Project, phase 5) long-term experiments design and the simulation results are used to evaluate the performance of the model including the atmosphere, ocean, land surface and biogeochemical process of ocean and terrestrial ecosystem.

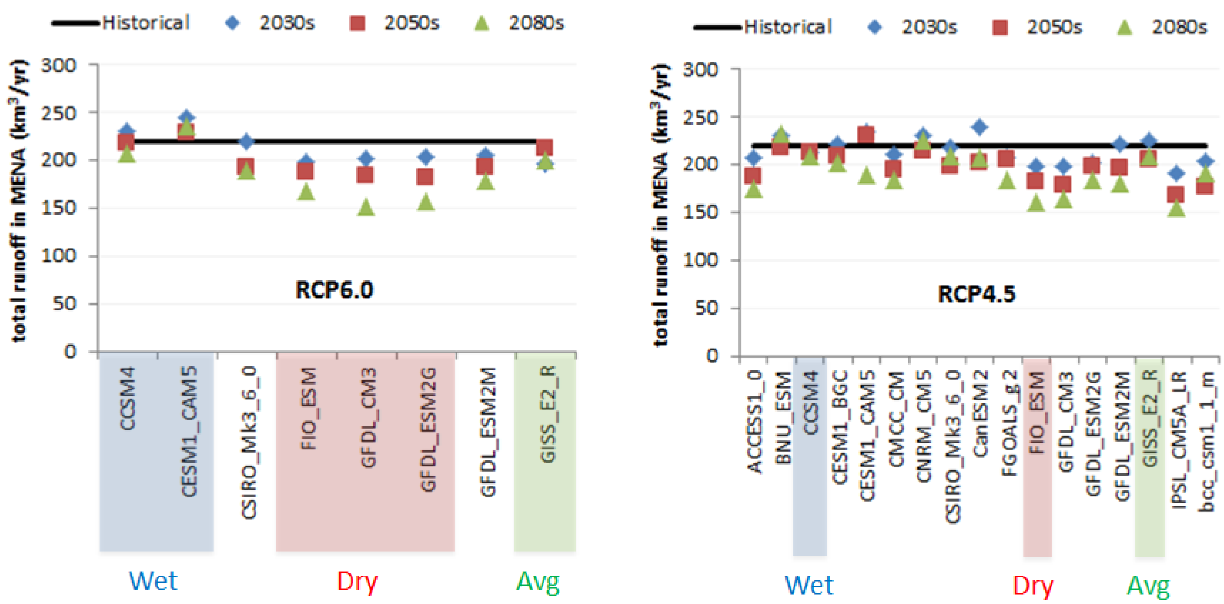


Figure 15: Influence of climate scenarios (RCP) on total runoff in the MENA region, as simulated by a range of global climate models.

E.2. Socioeconomic Development Scenarios

Long-term scenarios play an important role in research on global environmental change. The climate change research community has developed new scenarios integrating future changes in climate and society to investigate climate impacts as well as options for mitigation and adaptation. One component of these new scenarios is a set of alternative futures of societal development known as the Shared Socioeconomic Pathways (SSPs). The conceptual framework for the design and use of the SSPs calls for the development of global pathways describing the future evolution of key aspects of society that would together imply a range of challenges for mitigating and adapting to climate change.

O'Neill et al. [2015] present the "SSP narratives", a set of five qualitative descriptions of future changes in demographics, human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources. We describe the methods used to develop the narratives as well as how these pathways are hypothesized to produce particular combinations of challenges to mitigation and adaptation. Development of the narratives drew on expert opinion to identify key determinants of these challenges that were essential to incorporate in the narratives, and combine these elements in the narratives in a manner consistent with their interrelationships. The narratives are intended as a description of plausible future conditions at the level of large world regions that can serve as a basis for integrated scenarios of emissions and land use, as well as climate impact, adaptation and vulnerability analyses.

Within the conceptual framework for integrated scenarios, the SSPs are designed to span a relevant range of uncertainty in societal futures. Unlike most global scenario exercises, the relevant uncertainty space that the SSPs are intended to span is defined primarily by the nature of the outcomes, rather than the inputs or elements that lead to these outcomes. Therefore, the SSP outcomes are specific combinations of socioeconomic challenges to mitigation and socioeconomic challenges to adaptation. That is, the SSPs are intended to describe worlds in which societal trends result in making mitigation of, or adaptation to, climate change harder or easier, without explicitly considering climate change itself. **Table 2** summarizes the SSP implementation in GCAM. Note, water technology storylines and assumptions are not part of the SSP scenarios; water is considered indirectly in the SSPs through agricultural and energy water use.

Table 2: Shared Assessment Pathways (SSPs) assumptions as implemented in GCAM

		SSP1	SSP2	SSP3	SSP4			SSP5
					High Income	Medium Income	Low Income	
Socioeconomics	Population in 2100	6.9 billion	9 billion	12.7 billion	0.9 billion	2.0 billion	6.4 billion	7.4 billion
	GDP per capita in 2100	$46,306	$33,307	$12,092	$123,244	$30,937	$7,388	$83,496
Fossil Resources (Technological Change/Acceptance)	Coal	Med/Low	Med/Med	High/High	Med/Low	Med/Med	Med/High	High/High
	Conventional Gas & Oil	Med/Med	Med/Med	Med/Med	High/Low	High/Low	High/Low	High/High
	Unconventional Oil	Low/Med	Med/Med	Med/Med	Med/Low	Med/Low	Med/Low	High/High
Electricity (Technology Cost)	Nuclear	High	Med	High	Low	Low	Low	Med
	Renewables	Low	Med	High	Low	Low	Low	Med
	CCS	High	Med	Med	Low	Low	Low	Low
Fuel Preference	Renewables	High	Med	Med	High	High	High	Med
	Traditional Biomass	Low	Low	High	Low	Low	High	Low
Energy Demand (Service Demands)	Buildings	Low	Med	Low	High	Med	Low	High
	Transportation	Low	Med	Low	High	Med	Low	High
	Industry	Low	Med	Low	High	Med	Low	High
Agriculture & Land Use	Food Demand	High	Med	Low	High	Med	Low	High
	Meat Demand	Low	Med	High	Med	Med	Med	High
	Productivity Growth	High	Med	Low	High	Med	Low	High
	Trade	Global	Global	Global	Regional	Regional	Local	Global
	SPA* Policy				Afforestation	Limited afforestation	No land policy	
Pollutant Emissions	Emissions Factors	Low	Med	High	High	High	High	Low

E.3. Water Resources Management Scenarios

In this study, we pose a two illustrative examples of water resources management scenarios to better understand the implications of different water management approaches on water scarcity, energy and food in the MENA region. The purpose of this analysis is to provide a sample of the types of water management measures that can be employed and their implications throughout the region. Both of these scenarios incorporate RCP6.0 for climate and SSP2 for socioeconomic development.

UnlimitedWater: This scenario assumes unlimited water resources where all sectors within the economy can achieve all their water demands with no water constraints. This serves as a benchmarking scenario and to quantify the projected changes in the water and agricultural sectors under no water constraints.

LimitedWater (includes Adaptation): This scenario focuses on constraining the water demands to the available water resources (renewable surface and groundwater, non-renewable groundwater resources, desalinated water) within each river basin. In this scenario, we employ the new developed methodology to estimate the amount economically available groundwater and constructing marginal cost resources curves as explained in Equations (2) through (12).

This scenario also incorporates adaptation measures to be deployed as a means to mitigate the water scarcity problem. More specifically, the expansion of desalination and more efficient irrigation technologies are included as adaptation measures. This is done to shed light on the level of necessary adaptation to close the water gap in the region and the associated investment costs that are associated with those measures. Also, by comparing this scenario to the UnlimitedWater scenario, we can estimate the economic impacts associated with limitations in water on the economy of the region.

F. RESULTS

Task 1: Physical Assessment of Climate Impacts on Water Scarcity in the MENA Region

Results for runoff, water demand and WSI are shown in Figures 16-18. Tables 3-5 summarize the numerical results of total annual runoff, demand, and water scarcity values at both the aggregate regional (i.e., North Africa and Middle East) and country scales. These results illustrate four key trends for water scarcity in the MENA region.

First, *the region overall has scarce renewable water resources availability*; this result is consistent with numerous studies of water availability in the region. These results appear to be robust based on the 3 GCMs used (see **Table 3** and **Figure 16**). Some exceptions to this are found in the northern fringes of Morocco, Algeria, Tunisia, Libya, Egypt, Israel, Jordan, Lebanon, Syria, Iraq and pockets in northwest Iran, where some relatively larger values of runoff, yet still characteristic of arid zones, are found.

Second, *water scarcity increases over time in the region*; this is reasonable to expect given increased pressure in water resources (increased demand) as a result of population growth, development and other factors (see **Table 4** and **Figure 17**).

Third, *water scarcity is dominated by water demands* rather than by the climate-influenced water availability (surface and groundwater). The WSI results is fairly consistent among the 3 climate models used (see **Table 5**). This is an important finding that suggests that the human influence, rather than that posed by climate, drives water scarcity in the region.

Fourth, it appears that *moderate and higher values of water scarcity in the region advance significantly within the next few decades*, and particularly towards the second half of the century (see Table 5 and **Figure 18**).

Table 3: Total annual runoff (billion m^3/year) based on 3 GCMs

Subregion	GCM Name	2015	2050
North Africa	CCSM	88	75
	GISS	76	70
	FIO	98	73
Middle East	CCSM	128	165
	GISS	127	134
	FIO	124	114

Table 4: Estimated total annual water demand (billion m^3/year)

Subregion	Scenario	2015	2050
North Africa	Ref	146	233
Middle East	Ref	230	371

Table 5: Water scarcity index values at the country scale using three GCMs

		2015			2050		
	Country Name	CCSM	GISS	FIO	CCSM	GISS	FIO
North Africa	Algeria	0.3	0.3	0.3	0.7	0.6	0.6
	Egypt	1.3	1.7	1.7	2.5	2.8	2.5
	Libya	0.3	0.6	0.6	0.9	1.4	0.9
	Morocco	0.8	0.8	0.5	1.1	1.4	1.4
	Tunisia	0.6	0.7	0.6	1.4	1.4	1.4
Middle East	United Arab Emirates	5.1	4.5	2.5	8.6	5.1	4.2
	Bahrain	---	---	---	---	---	---
	Iran, Islamic Republic of	1.2	1.3	1.3	1.4	1.8	2.0
	Iraq	0.7	0.7	0.7	0.9	1.0	1.4
	Israel	1.5	2.5	2.7	2.5	3.6	3.7
	Jordan	1.1	1.5	1.9	1.6	2.2	2.1
	Kuwait	0.8	2.5	0.8	0.9	2.1	3.0
	Lebanon	1.7	2.4	3.7	4.0	4.0	3.9
	Oman	0.9	0.5	0.4	2.0	2.5	2.0
	West Bank and Gaza	1.0	1.6	2.3	1.8	3.4	2.2
	Qatar	4.6	1.8	1.0	1.6	3.8	4.5
	Saudi Arabia	4.7	6.3	3.3	6.1	10.7	14.6
	Syrian Arab Republic	0.8	0.7	0.8	1.2	1.2	1.5
	Yemen	2.3	1.7	1.8	6.3	4.0	7.9

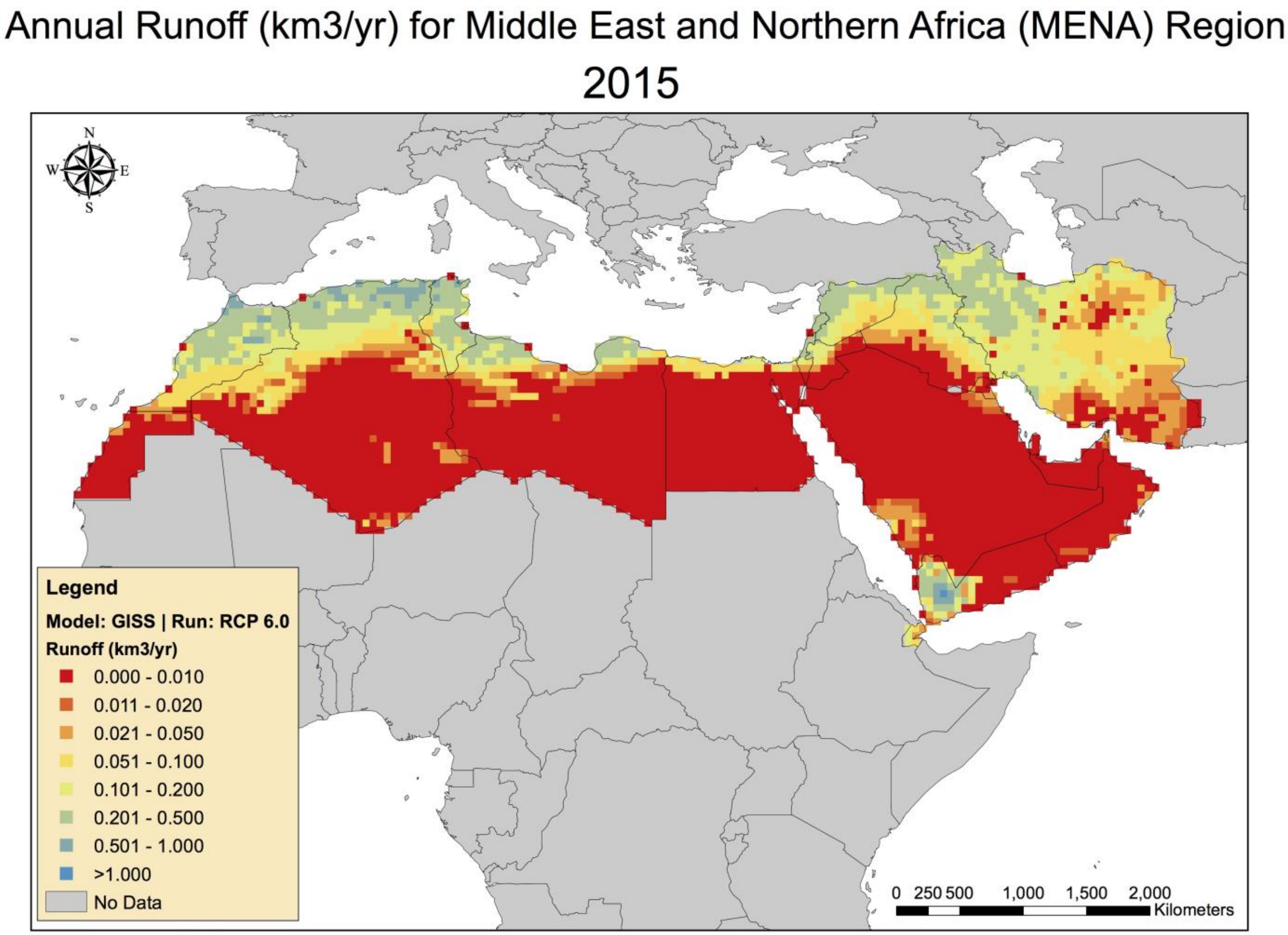


Figure 16: Estimated total annual runoff in the MENA region, year 2015 from the GISS Model under the RCP 6.0 (reference) climate scenario.

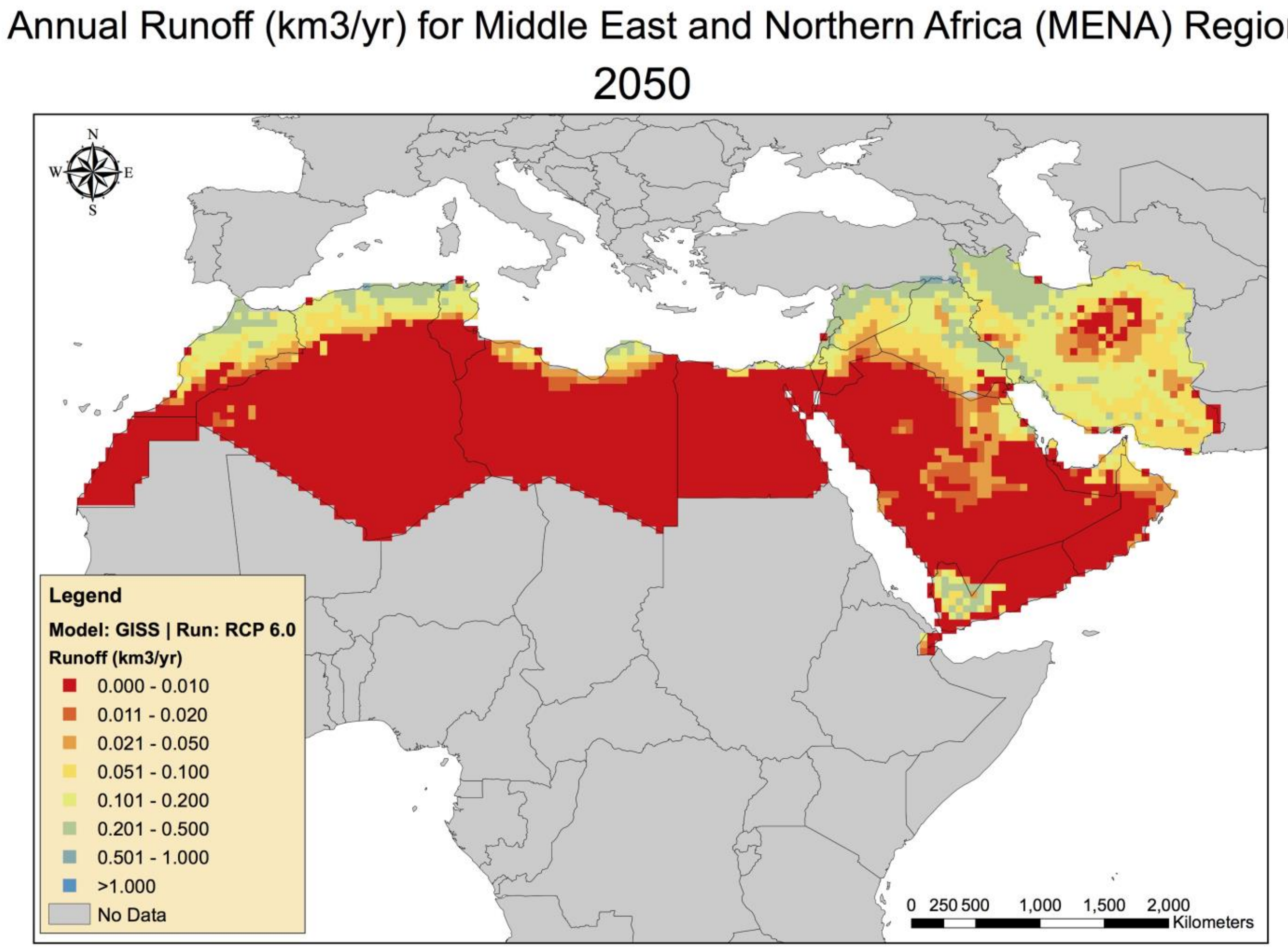


Figure 16 (cont): Estimated total annual runoff in the MENA region, year 2050 from the GISS Model under the RCP 6.0 (reference) climate scenario.

Water Demand (km^3/yr) for the Middle East and North Africa (MENA) Region

2015

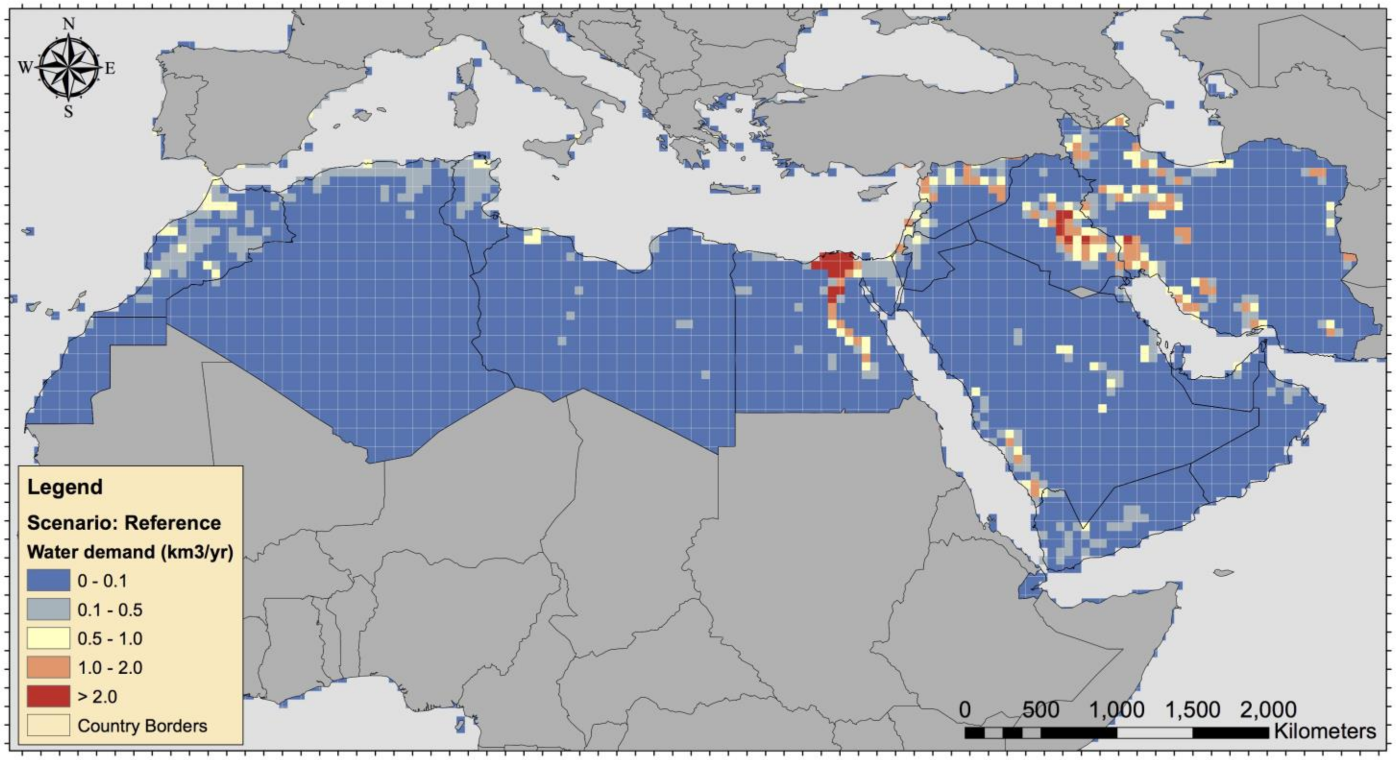


Figure 17: Estimated total annual water demand in the MENA region, year 2015 in the Ref scenario. Water demand estimates are made using population, land use (including urbanization), agricultural (FAO) and major energy demand (IEA) locations using the methodology described in Hejazi et al. (2013ab, 2014).

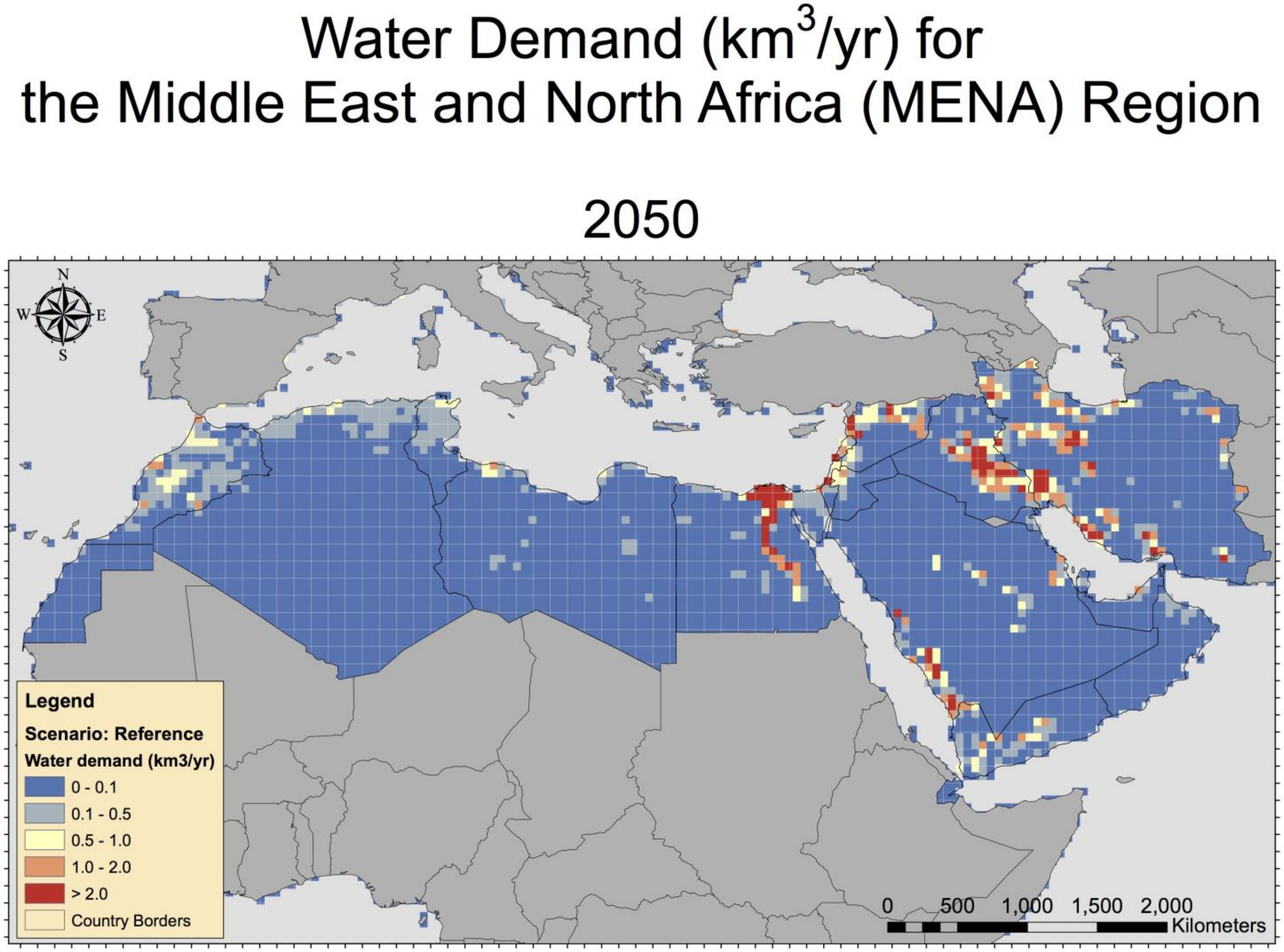


Figure 17 (cont): Estimated total annual water demand in the MENA region, year 2050 in the Ref scenario. Water demand estimates are made using population, land use (including urbanization), agricultural (FAO) and major energy demand (IEA) locations using the methodology described in Hejazi et al. (2013ab, 2014).

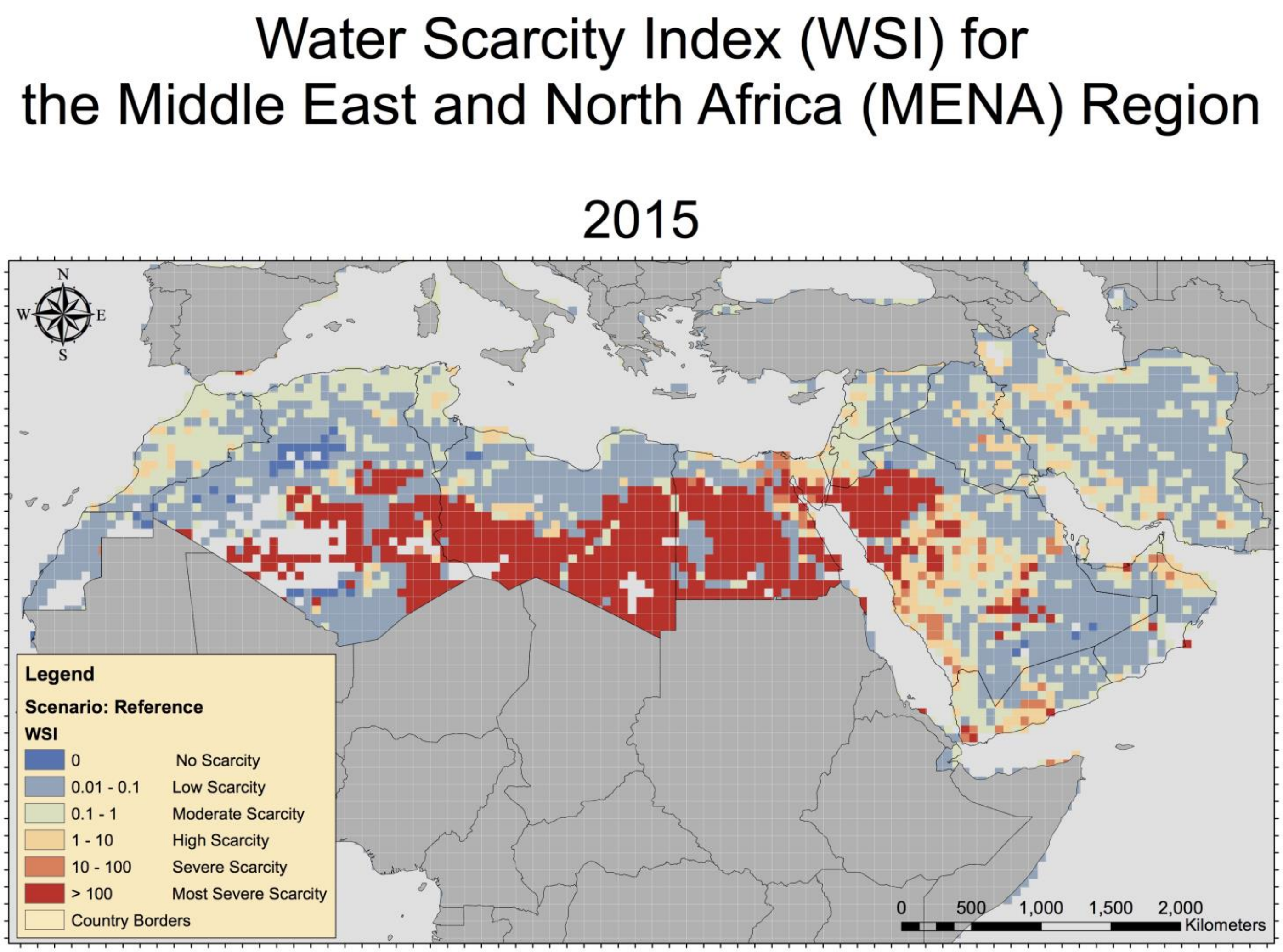


Figure 18: Estimated WSI in the MENA region, year 2015 based on the Ref scenario for water demands and the GISS climate model for runoff under the RCP6.0 (reference) climate scenario.

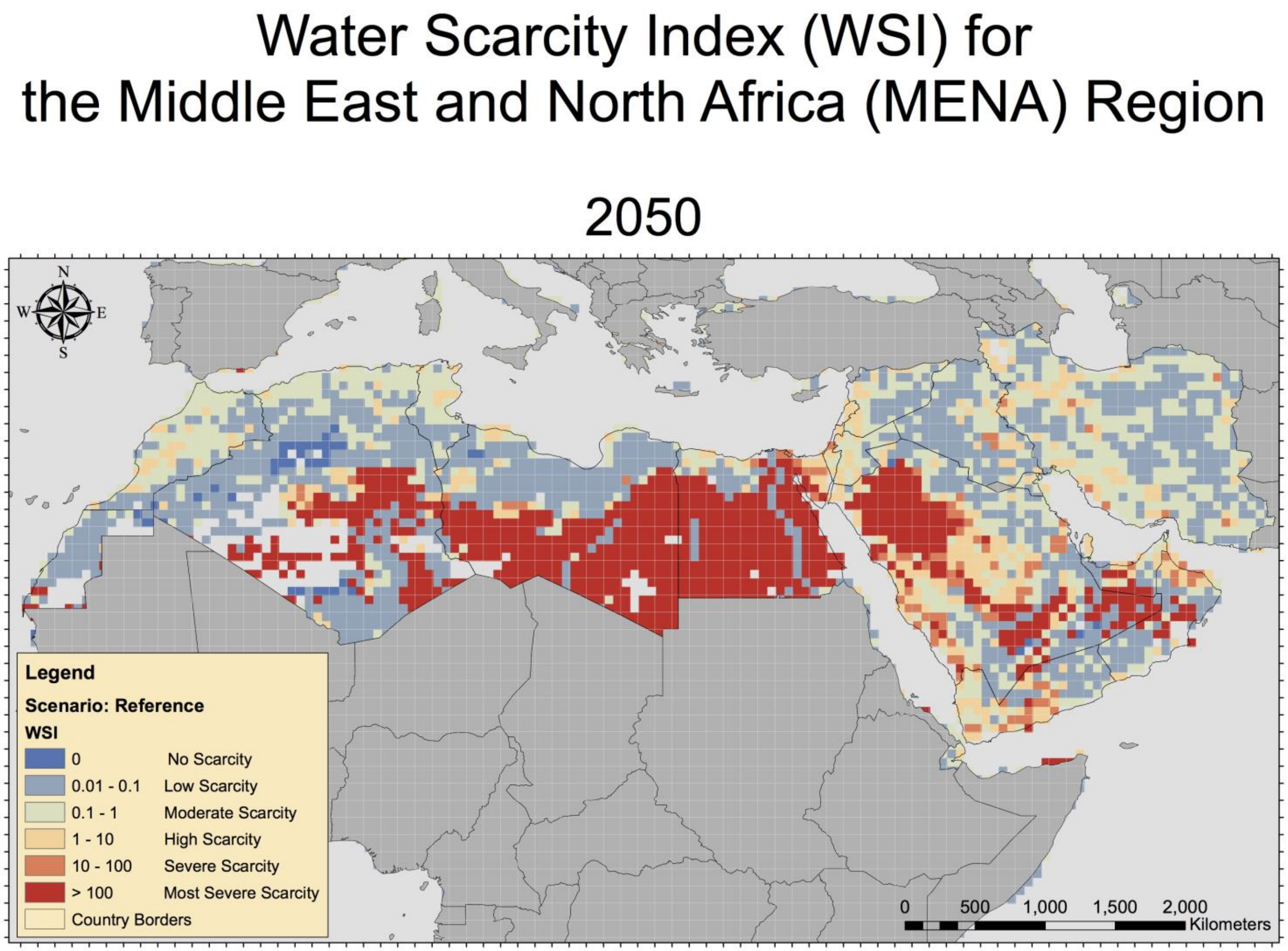


Figure 18 (cont): Estimated WSI in the MENA region, year 2050 based on the Ref scenario for water demands and the GISS climate model for runoff under the RCP6.0 (reference) climate scenario.

Task 2: Socioeconomic Scenario Analysis in the MENA Region

By implementing the SSP scenarios in GCAM including the assumptions discussed in Table 2, we simulate the water withdrawals associated with each of 5 SSPs (**Figure 19, Figure 20**). Not surprisingly, water demands are lowest in SSP4 and generally highest in SSP5, although they increase substantially by the end of the century in SSP5.

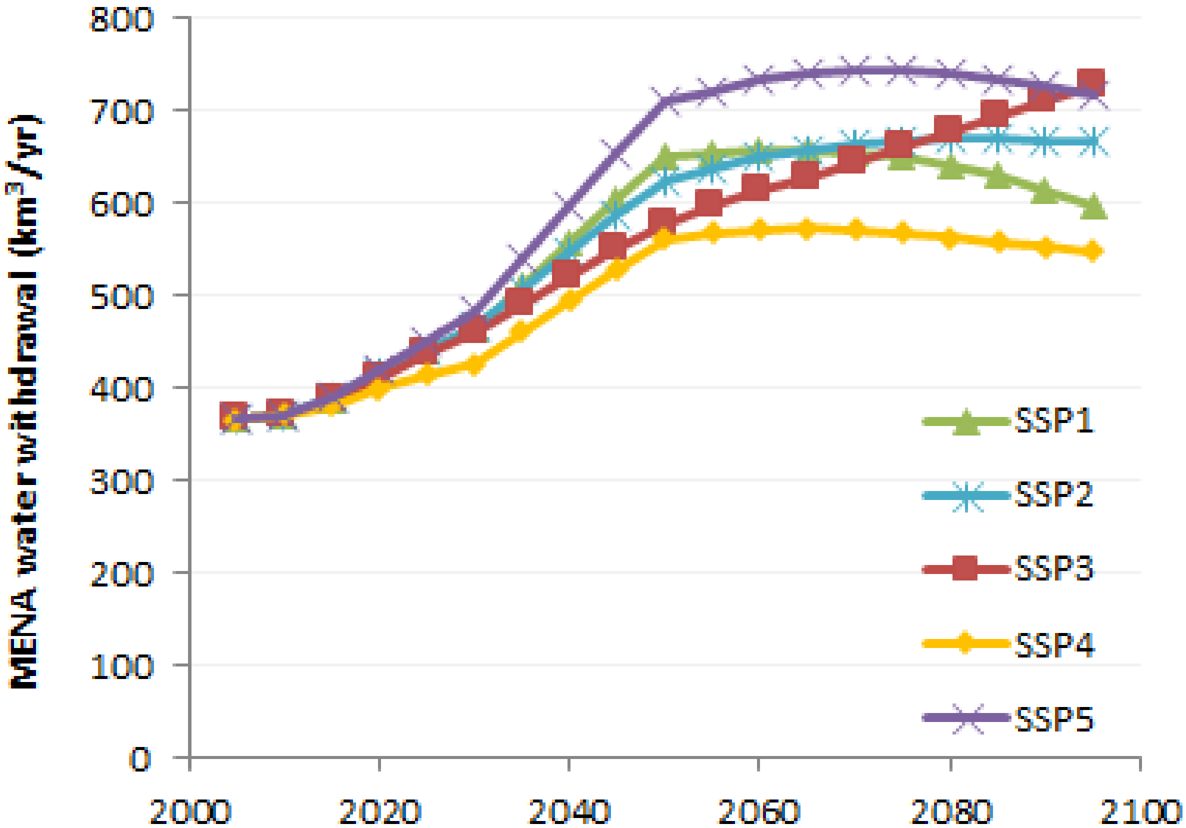


Figure 19: Total annual water withdrawal in the MENA region under each of the SSPs; water demand is not constrained.

Figure 23 shows the water scarcity map for the years 2050 and 2100, and for one GCM (GISS). The results from the two other GCMs look similar to the results driven by the GISS model. Note, in all of these scenarios water is not constrained, and as such the total water withdrawal can exceed the total amount of runoff in a region. There are 15 scenarios for each country (5 SSPs x 3 GCMs). **Table 6** summarizes the range of water scarcity values for each of the countries in the MENA region.

Almost all MENA countries have a WSI of greater than one, which implies that the total projected water demand exceeds the total amount of runoff in that country. This means that a large fraction water demand cannot be met with runoff, which may lead to investments on non-conventional sources (e.g., desalinization, and non-renewable groundwater), efficiency and reallocation or, as in the case of Yemen, to massive overexploitation of unrenewable groundwater resources.

The highest WSI values in the MENA region are generally associated with countries located in the Arabian Peninsula region such as Saudi Arabia, United Arab Emirates, and Qatar. This is mainly due to the lack of surface water resources (no rivers or lakes), combined with high per capita income, and population growth projections; i.e., extremely low renewable water resources with relatively high water demands. Many of these countries are also relatively young in term of their population age distribution and have high fertility rates, compounding future water scarcity challenges. Some of these countries are already heavily dependent on non-traditional water sources such as desalination to meet most of their current demands. Note, existing desalination capacities and fossil groundwater reserves are not included in our definition of WSI.

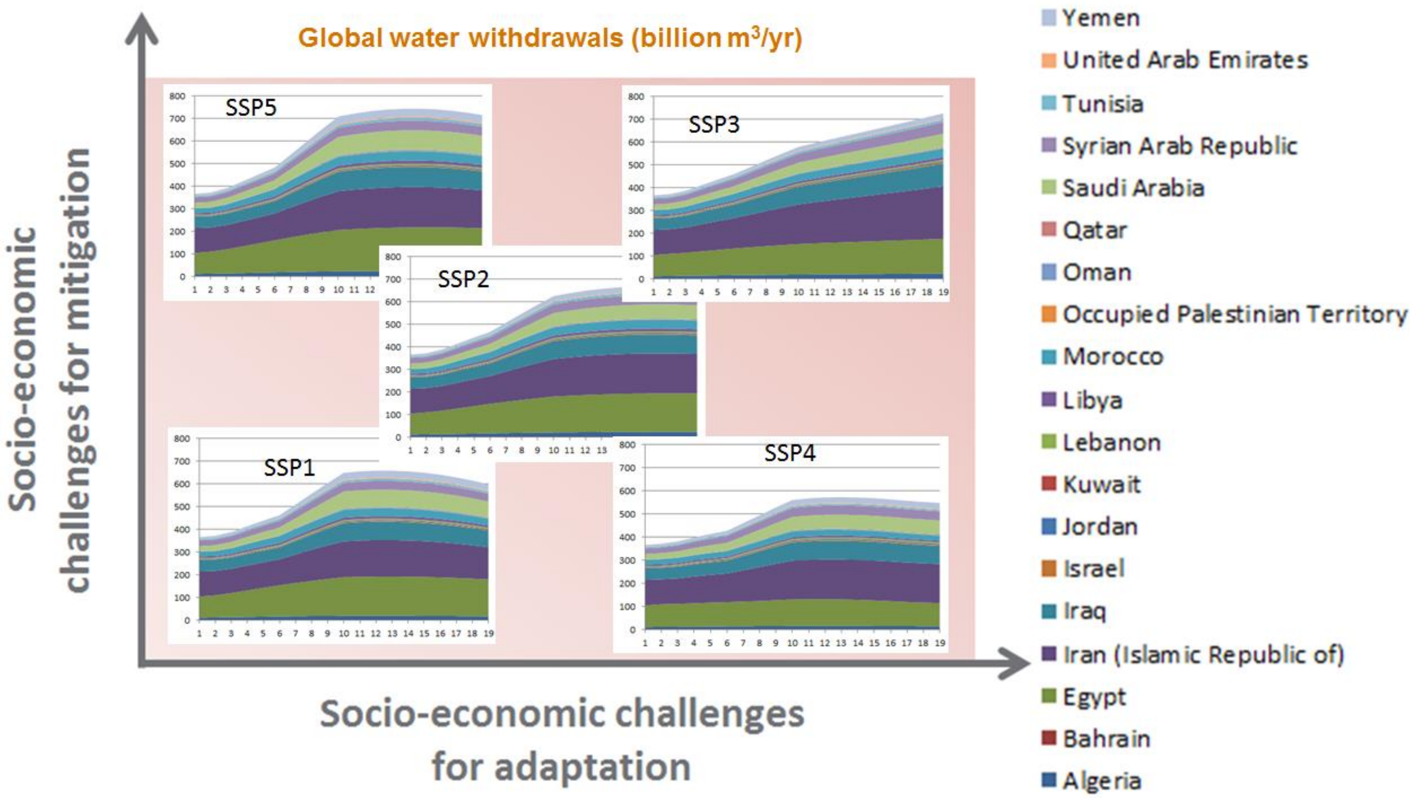


Figure 20: Total annual water withdrawal at the MENA region under each of the SSPs; water demand is not constrained.

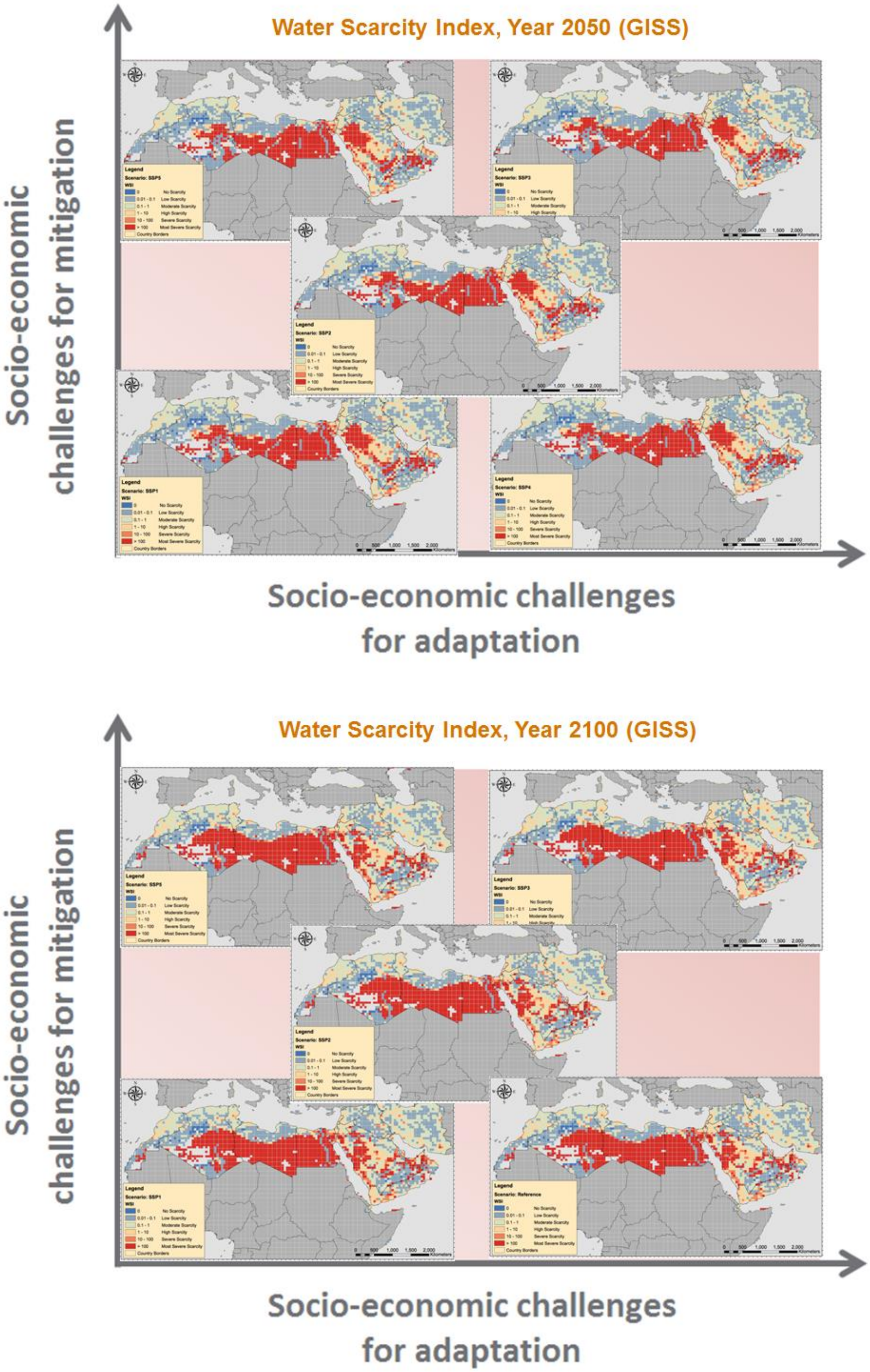


Figure 21: Water Scarcity Index (WSI) in the MENA region under each of the SSPs for the years 2050, and 2100 using the GISS model under RCP6.0 (reference) climate scenario; water demand is not constrained.

Table 6: Range of water scarcity index values at the country scale using 3 GCMs and all the SSPs using climate scenario RCP6.0 (reference).

	Country Name	2015	2050	2100
North Africa	Algeria	0.3-0.4	0.5-0.8	0.4-0.7
	Egypt	1.4-1.8	1.9-3.1	1.6-3.2
	Libya	0.4-0.7	0.6-1.4	0.5-1.2
	Morocco	0.6-0.8	0.8-1.5	0.8-2.3
	Tunisia	0.7-0.8	1.1-1.5	0.7-1.5
Middle East	United Arab Emirates	2.6-5.4	3.5-12.7	3.4-19.2
	Bahrain	---	---	---
	Iran, Islamic Republic of	1.2-1.3	1.4-2.2	2.0-2.9
	Iraq	0.6-0.7	1.0-1.5	1.1-1.8
	Israel	1.5-2.7	2.3-3.8	3.1-5.3
	Jordan	1.1-1.9	1.6-2.4	2.2-4.0
	Kuwait	0.9-2.9	0.9-3.5	1.7-3.6
	Lebanon	1.7-3.7	3.7-4.4	4.2-8.5
	Oman	0.4-1.0	1.7-3.6	1.2-3.1
	West Bank and Gaza	1.1-2.4	1.7-3.6	2.6-4.9
	Qatar	1.1-5.2	1.6-5.3	3.2-19.2
	Saudi Arabia	3.4-6.5	5.3-20.8	11.1-20.1
	Syrian Arab Republic	0.7-0.8	1.2-1.6	1.4-1.9
	Yemen	1.8-2.5	3.4-11.5	3.7-20.6

Task 3: Limited Water Supply Scenario Analysis and WEF Nexus in the MENA Region
The scenarios in Task 2 explored water scarcity in the MENA region under the assumption that there are no limits to water demand. We found that water withdrawals frequently exceeded runoff in MENA countries, which is a clear symptom of unsustainable water use. In this task, we explore potential responses to limited water. In particular, we investigate the two water resources management scenarios: *UnlimitedWater* and *LimitedWater*, as discussed in Section E.3. As noted, these scenarios are based on the SSP2 assumptions for socioeconomics and RCP6.0 (reference) for climate using the GISS climate model.

Figure 22 and **Figure 23** illustrate the impact of constraining water withdrawals to the amount of water available at the basin level (LimitedWater scenario) in comparison to unconstrained water withdrawal (UnlimitedWater scenario). Water demands drop when constraining water in GCAM since water demands in the MENA region would exceed available resources if assumed unlimited. In some regions, the implications of limits on water availability can be particularly extreme. This is especially evident in regions such as Arabian Peninsula where water demands already far exceed the limited runoff, and a sizable portion of the groundwater resource has been depleted over the past several decades, leaving them to the expensive desalination option. The impact is much larger in countries with existing low levels of water availability such as Saudi Arabia and Yemen, and less pronounced in countries such as Algeria, Morocco, Egypt and Tunisia which have pockets of somewhat higher water availability (e.g., see Figure 16).

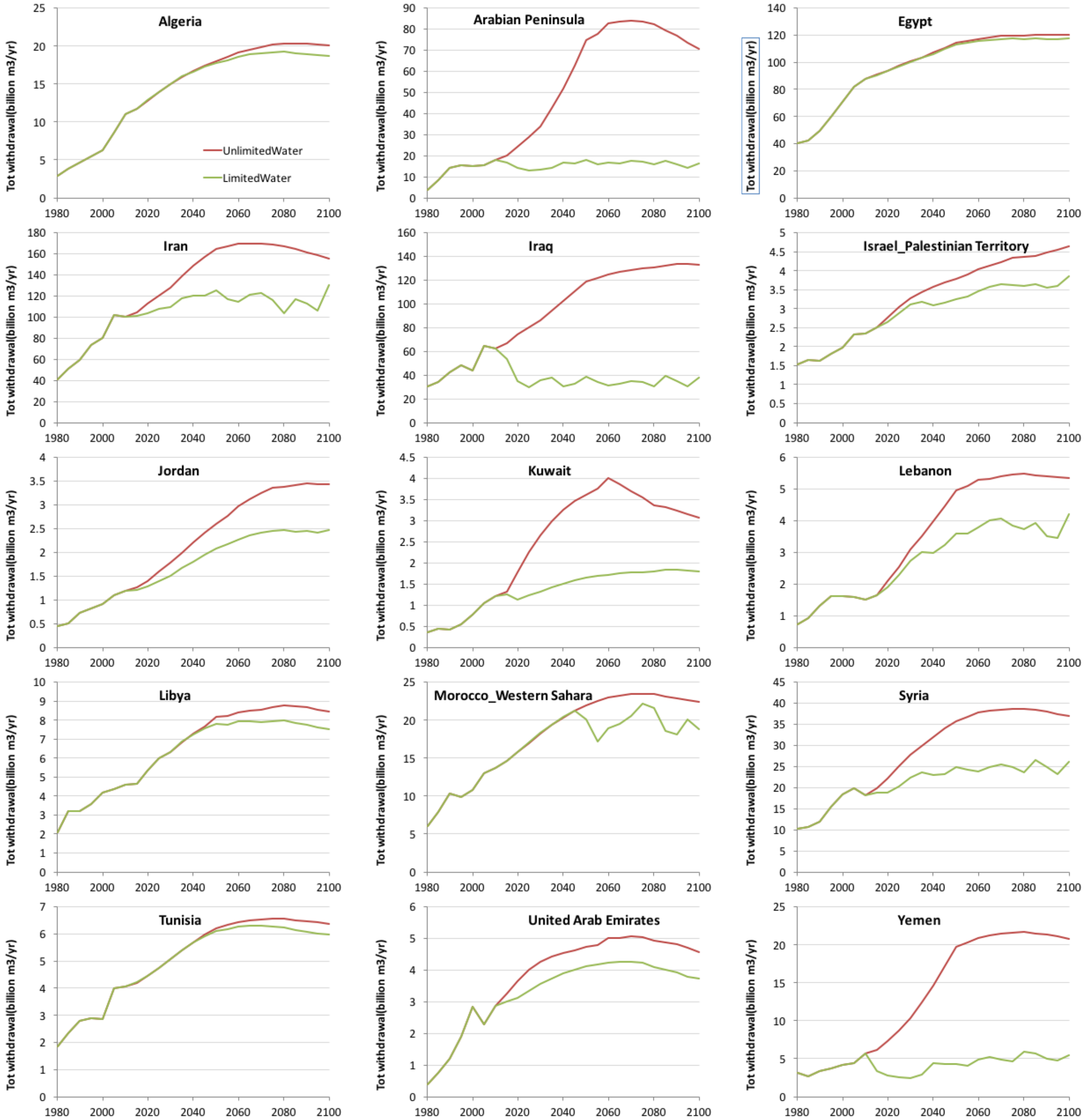


Figure 22: Total water withdrawal with and without limits on water availability. Demand includes renewable, non-renewable and non-conventional (desalination) sources.

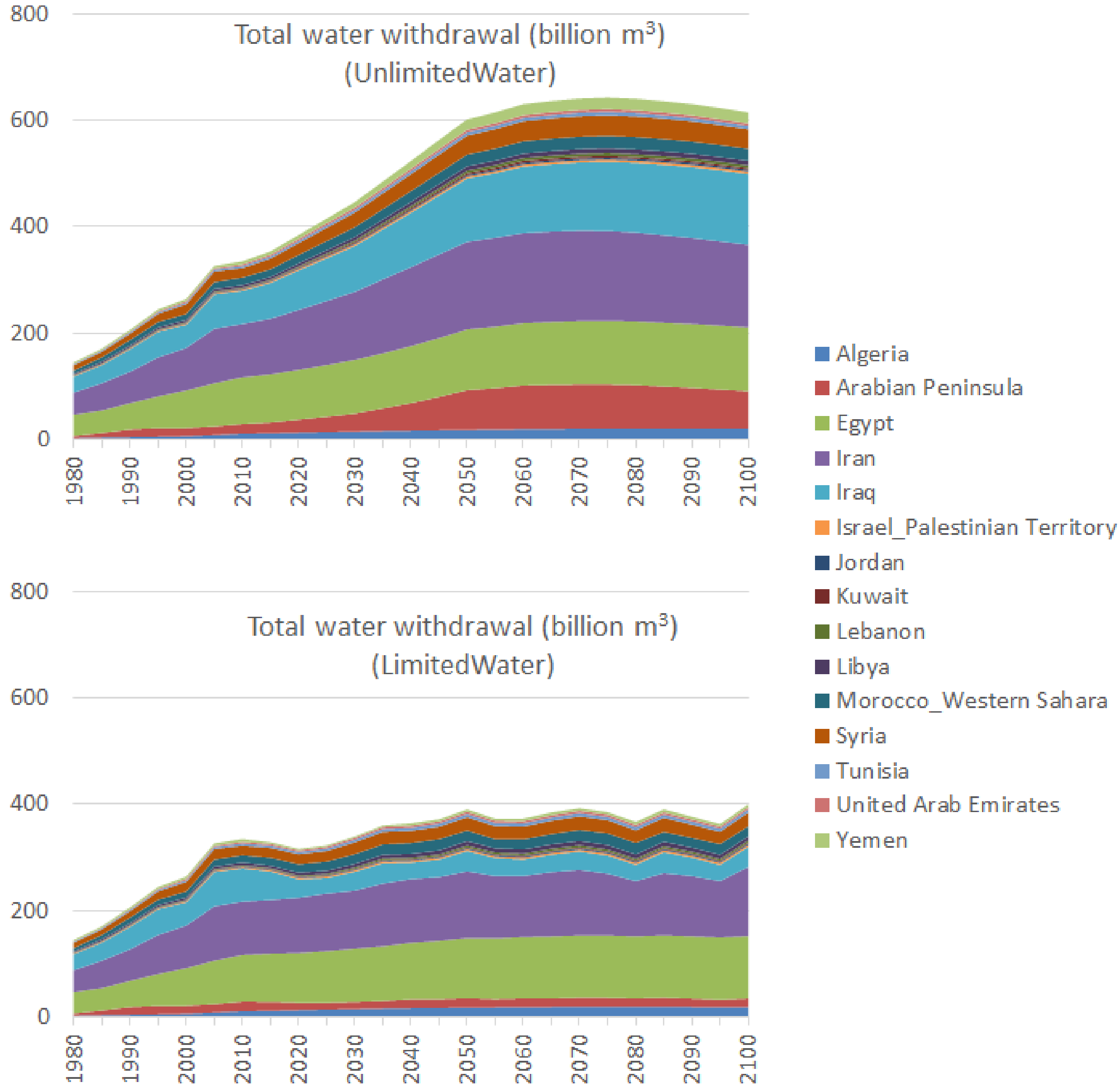


Figure 23: Total water withdrawal by country under the UnlimitedWater and LimitedWater scenarios.

Figure 24 shows the distribution of water demand by source at the country level broken into three primary sources: renewable (surface water and groundwater), depletable (non-renewable) groundwater, and desalination. It is important to note that this distribution is driven by physical factors (availability of each source) as well as economic factors (cost of each source). For instance, with the exception of Jordan, continued depletion of groundwater either represents a very small fraction of demand, or is halted completely in most countries in the region. Desalination gains prominence in several countries (e.g., Yemen, Jordan, UAE, Saudi Arabia, Kuwait) who use it to sustain a growing demand that is constrained to in-basin water availability (LimitedWater). Other countries like Tunisia, Egypt, Algeria, Iran, Libya and Morocco are able to sustain demand with renewable water sources.

Also worth noting in these results is the interannual variability of the renewable water demand in some countries. These interannual changes are due to combination of different factors. Some countries have no rivers and very limited surface water resources, with most of the renewable water resource is in the form of renewable groundwater (e.g., UAE, Kuwait, Algeria); these countries show little to no interannual variability in renewable water demand. In the rest of the region, the demand fluctuation can be attributed to the fluctuation in the renewable water term which is driven by the climate variability; when water supply is low, water demand also drops due to higher costs attributed to reliance on non-traditional sources. Countries with larger proportion of renewable water are showing larger variability. Also, climate variability in some of these countries (in term of precipitation patterns) is milder than other neighboring countries; in countries with almost no precipitation year round, the variability is more attributed to evaporation, while in the other regions we observe more fluctuation due to the variability in precipitation as well.

Future research efforts should focus on compiling country-specific data on the fractions of the various sources of water (i.e., renewable water, non-renewable water, and desalinated water) used to meet historical water demand to improve GCAM-MENA's ability to account for existing projects of utilizing non-traditional water resources, e.g., the Great Man-Made River in Libya, which is not shown in the results displayed in Figure 26.

A primary response to water scarcity in regions with serious water limitations is the use of desalination. Desalination exceeds 10 percent of total water demand for the region under the LimitedWater scenario, i.e., compare **Figure 25** to Figure 25. Of course, these results vary by country; desalination is highest in those countries with the greatest WSI. Without desalination, it would be necessary to reduce water withdrawals, which includes the Arabian Peninsula, Jordan, Kuwait, and the UAE. The diminishing slope over time (plateaus in the second half of century) is mainly explained by the shape of the water demand projections (see Figure 21) which exhibit a similar trend. Also, the fluctuations and the drop toward the end of the century are driven by the inherent variability in the renewable water resource in the region; i.e., the period towards 2100 is a relatively wet period in the reference climate scenario used to generate these results. Thus, a smaller amount of desalinated water is produced. Note that different climate scenarios would lead to different results.

While desalination serves to some degree as a backup water supply, it does not come without a cost. The cumulative investment in the LimitedWater scenario exceeds \$20 billion by 2050 and reaches almost \$70 billion by 2100 (**Figure 26**). It is important to note that the demand for desalination and the associated investment needs would vary noticeably among the SSPs (SSP2 is used in LimitedWater), based on the demands for water in the different scenarios. Also, the projected increase in desalinations using current technologies would have serious implications on marine ecosystems due to brine disposal, and mitigating such negative environmental concerns would incur additional costs to the MENA region.

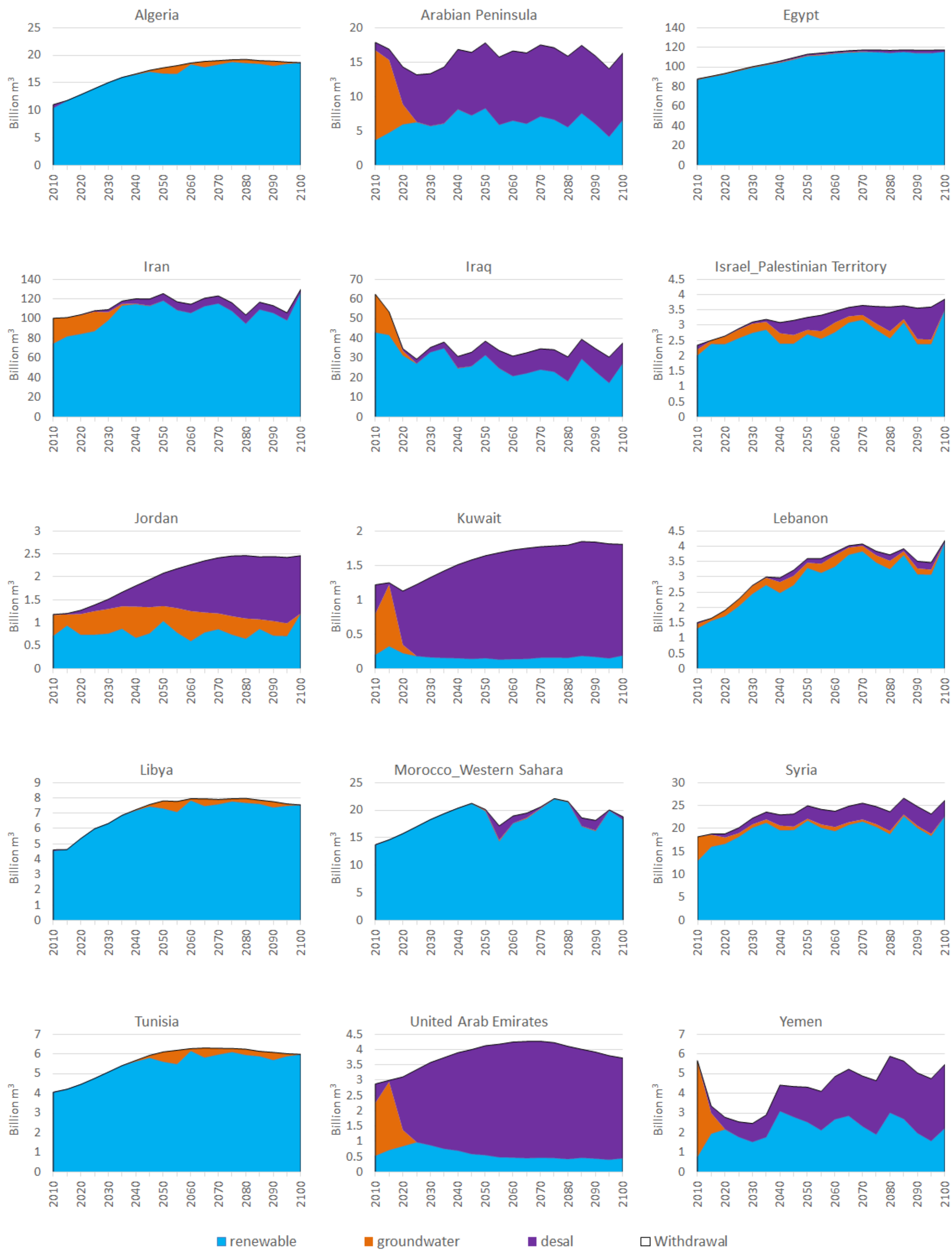


Figure 24*: Projections of total water demand by country; withdrawals are broken by the three sources of water (renewable, groundwater, and desalinated water); the black line is the total water withdrawal; results are based on the LimitedWater scenario.*

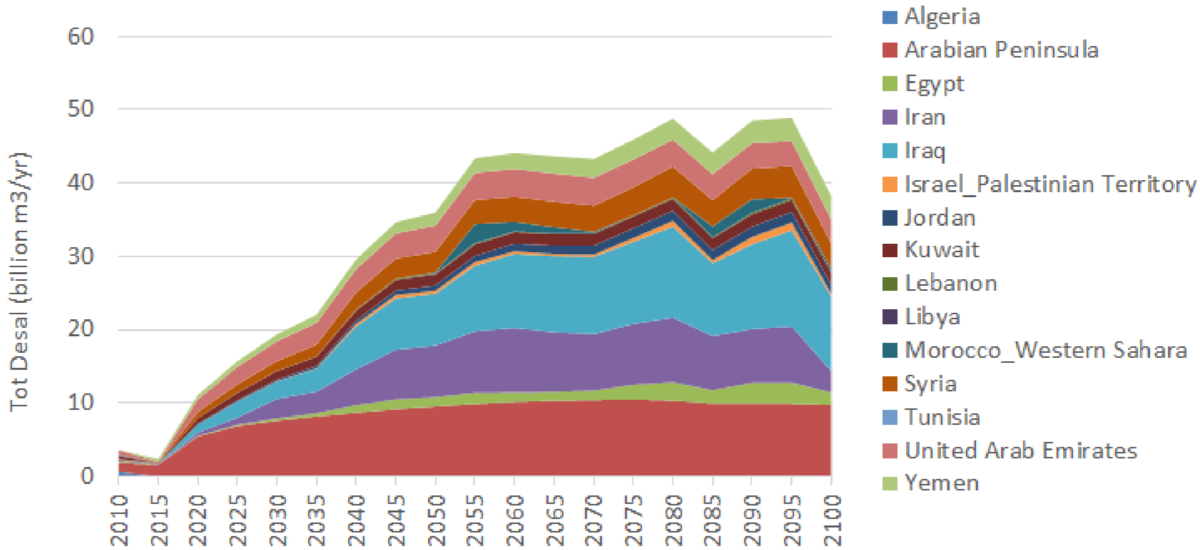


Figure 25: Total amount of desalinated water that is produced under the LimitedWater scenario.

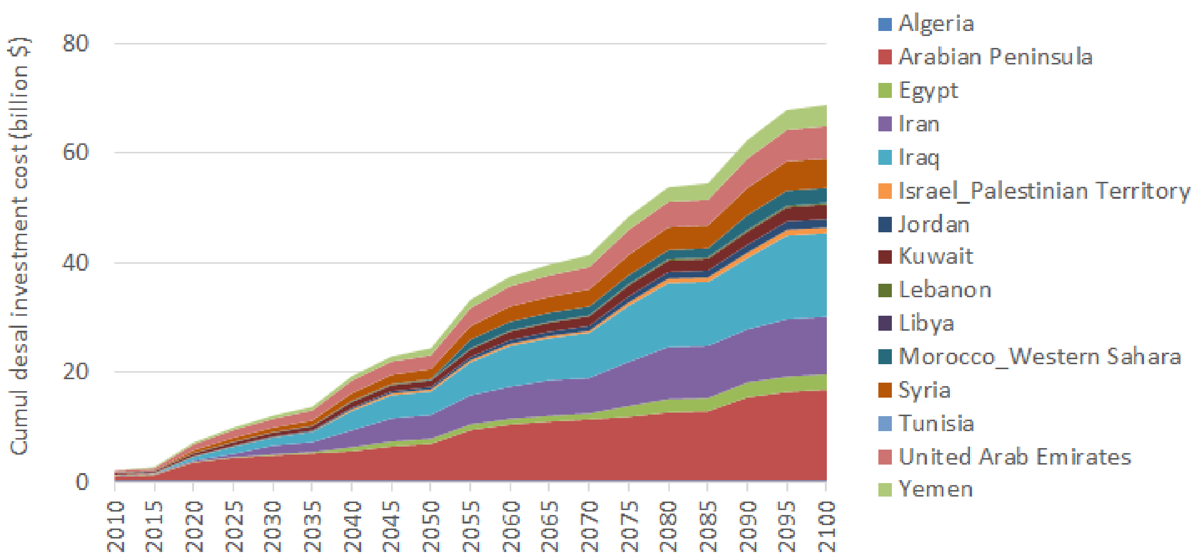


Figure 26: Cumulative investment cost that is required to meet the projected desalinated water demand in MENA countries, LimitedWater scenario.

Limits on water availability will have important impacts across economic sectors. Given the necessity for water in agriculture, the impacts on that sector are particularly important. Limiting water leads to large reductions in regions that have their water demands exceed renewable water supplies under the UnlimitedWater scenario, and their water demands dropped substantially under the LimitedWater scenario (as shown above in Figure 24 and Figure 25). Notable among these are the Arabian Peninsula and Yemen, somewhat reduced in Kuwait, as depicted in **Figure 29**. Production decreases almost three-fold in Saudi Arabia and approximately 60 percent in Yemen.

At the same time, the reduction in production of agricultural commodities that arises as a result of constraining water in the MENA region can have a significant impact on the demand for such products within the region itself (**Figure 28)**. This reflects the international character of agricultural trade. If supplies of agricultural commodities drop in one region, other regions will make up for that loss, and demands can still be met. In other words, when water is constrained in the MENA region, we observe a drop in agricultural production due to lack of water, and the result is that these regions are forced to import their agricultural needs from other regions where water and land resources are not binding. So demand decrease is negligible in the region, confirming the relative inelastic character of food demand. At the country level, the signal is relatively more pronounced for countries such as Iran, Saudi Arabia and Yemen (**Figure 29**). As these countries face higher costs and depleting water resources, they become even more reliant on importing agricultural commodities; hence, they experience a large decline in their net agricultural exports. The result of these changes in terms of trade is a change in agricultural revenues (**Figure 30).** Saudi Arabia experiences a cumulative loss of over \$1.2 trillion, followed by Iran (over \$400 billion), Yemen (over \$200 billion) and other countries in the region.

It is important to note that these results derive from several assumptions in the scenario, notably a robust market for international trade in agricultural products and a willingness of countries to increase their dependence on imported agricultural goods. Were either of these assumptions not to hold in reality – for example, for reasons of food security and self-sufficiency – this might imply smaller changes in domestic production, the use of lower-water crops, greater use of highly-efficient irrigation technologies, and lower domestic consumption. All of these implications would be valuable to explore in future analyses.

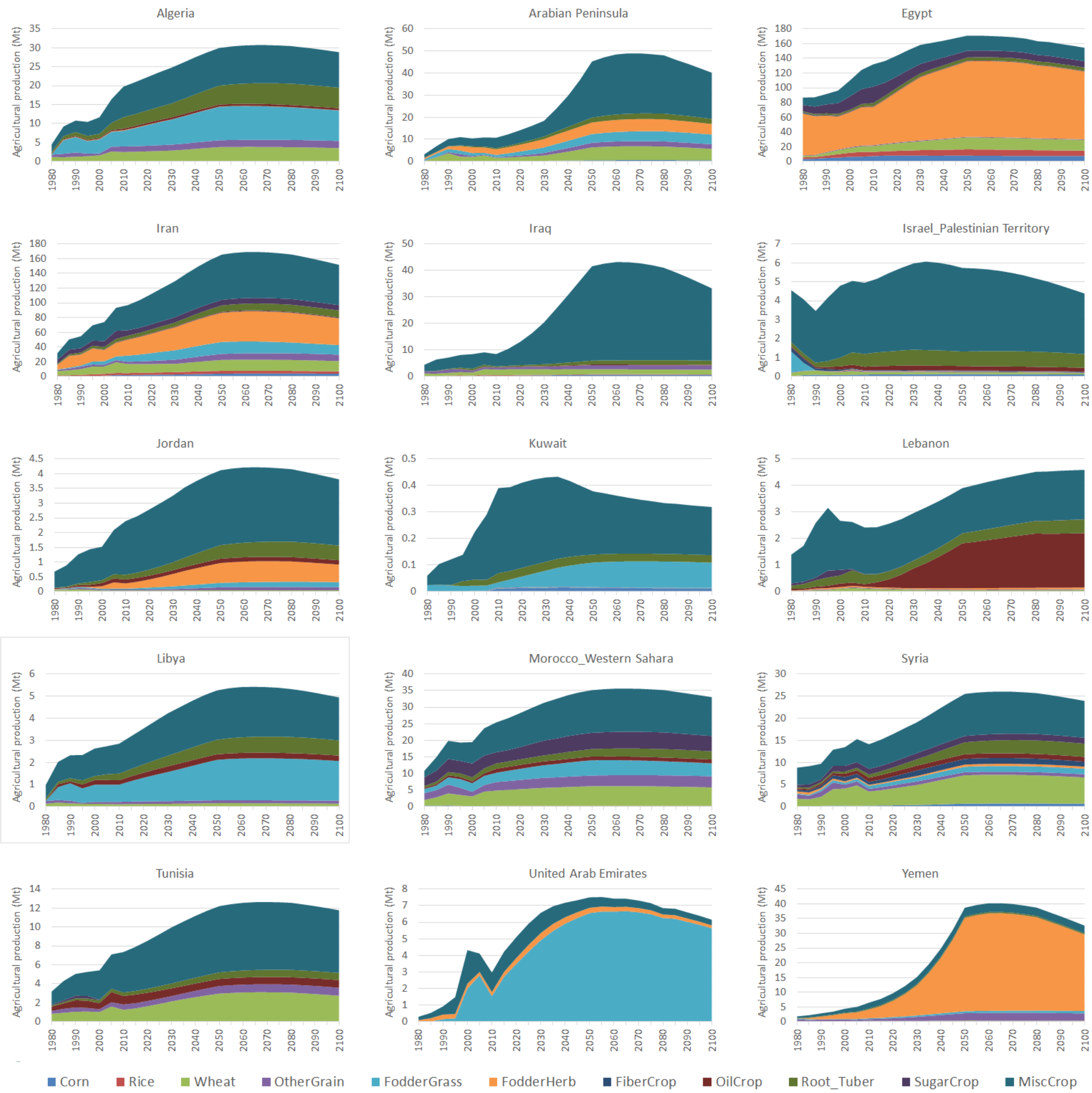


Figure 27a: Total agricultural production per crop type in the MENA region (in Mt), UnlimitedWater scenario.

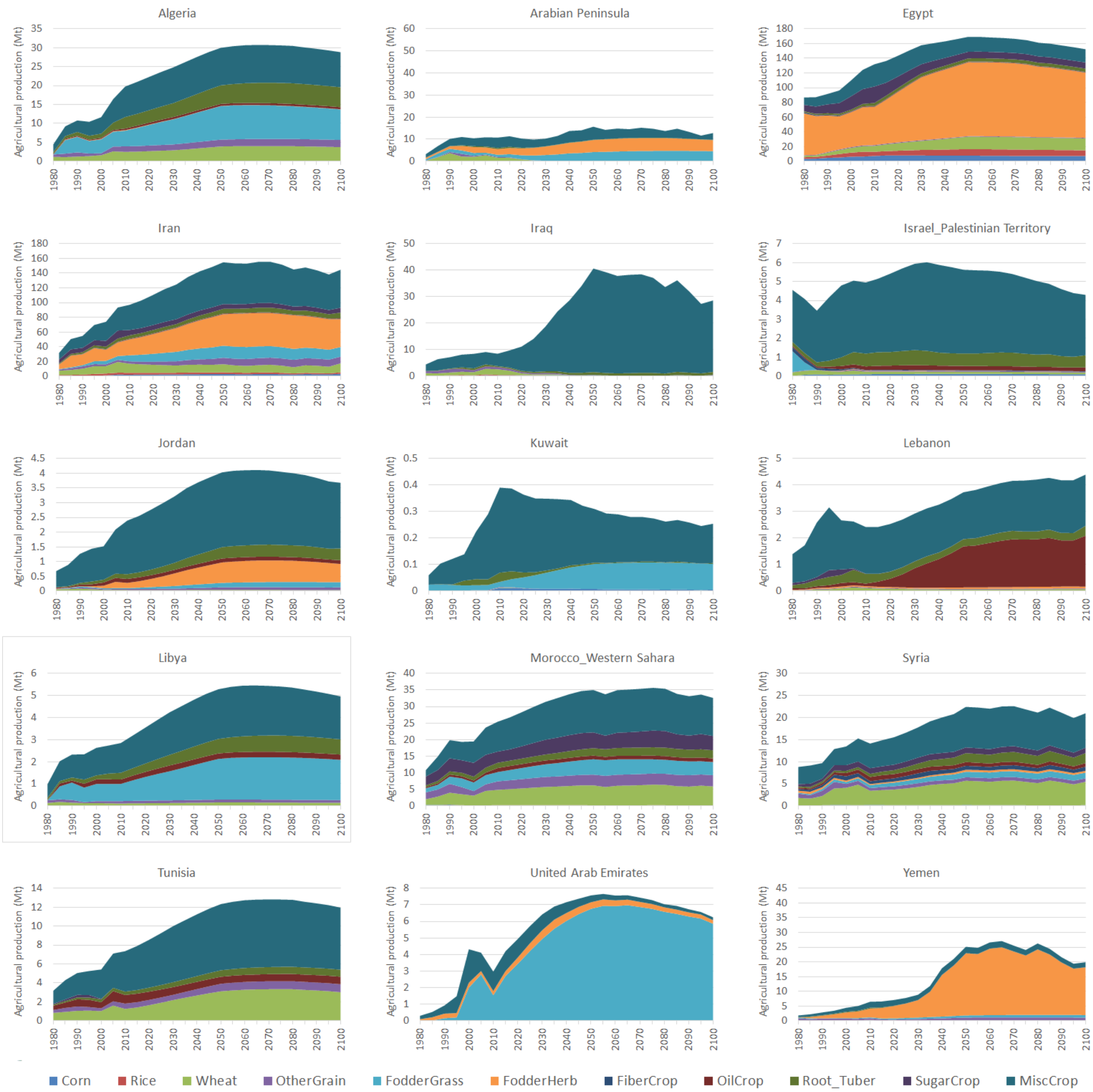


Figure 27b: Total agricultural production per crop type in the MENA region (in Mt), LimitedWater scenario.

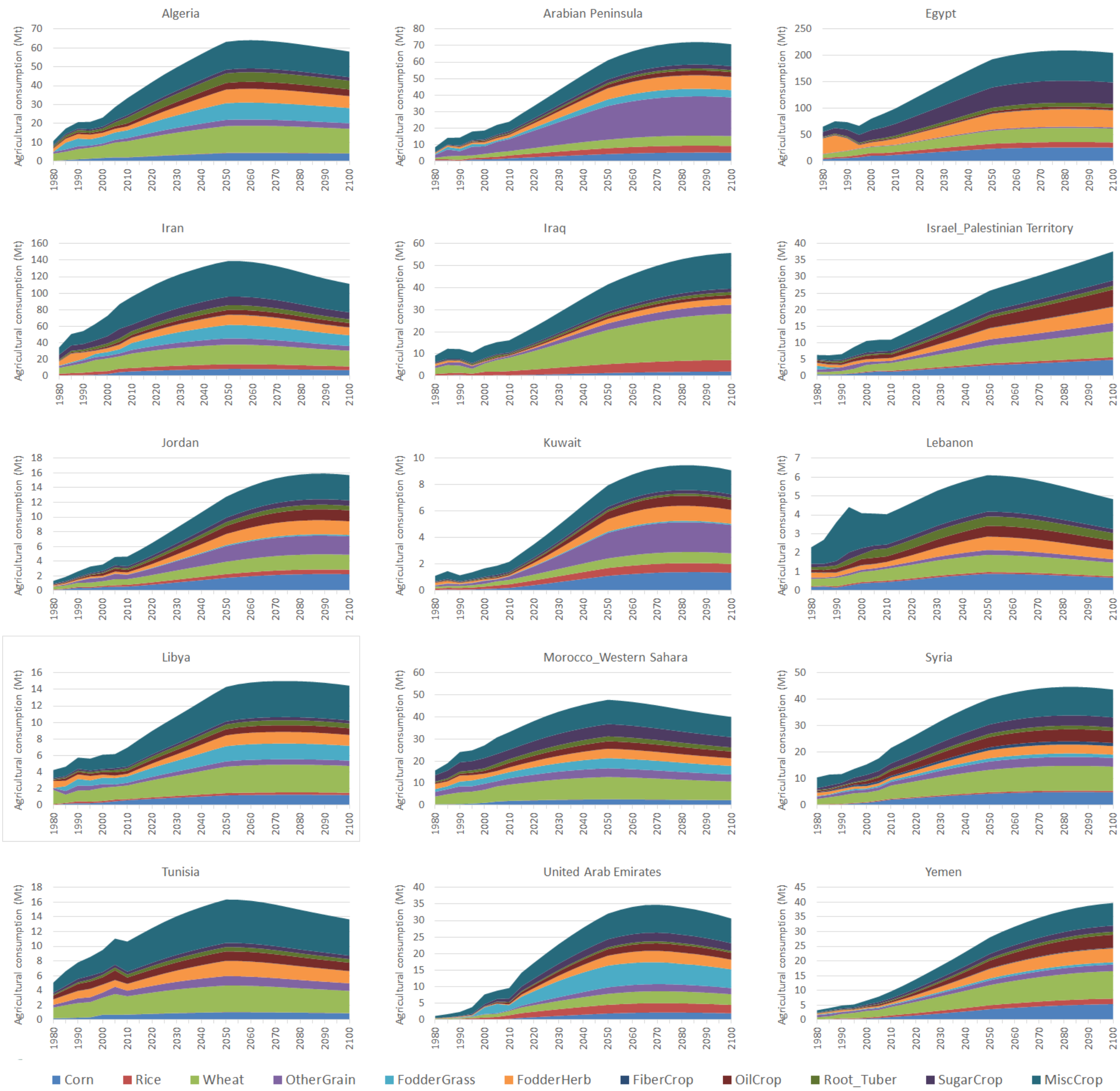


Figure 28a: Total demand for agricultural products in the MENA region (in Mt) under the UnlimitedWater scenario.

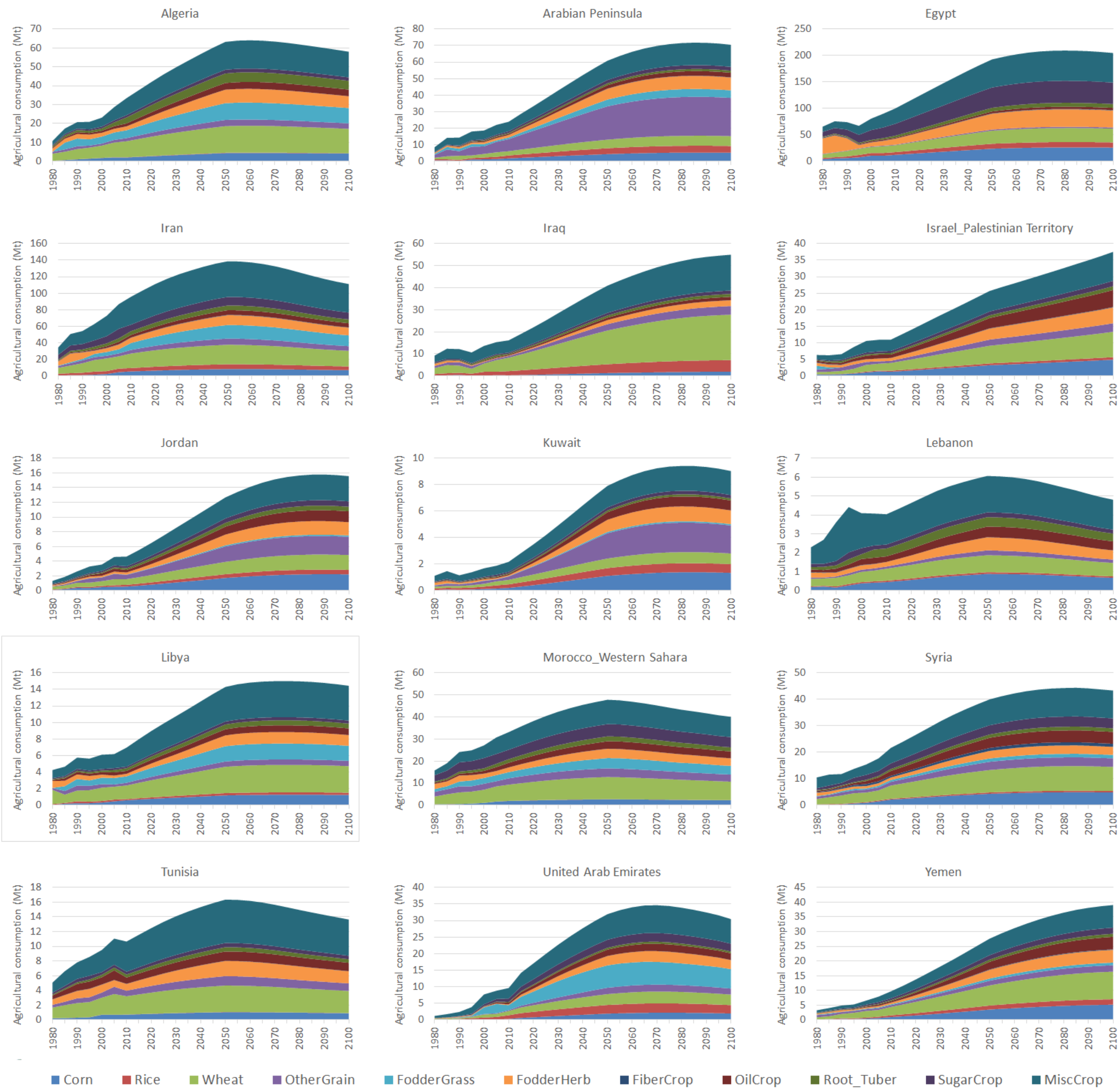


Figure 28b: Total demand for agricultural products in the MENA region (in Mt) under the LimitedWater scenario.

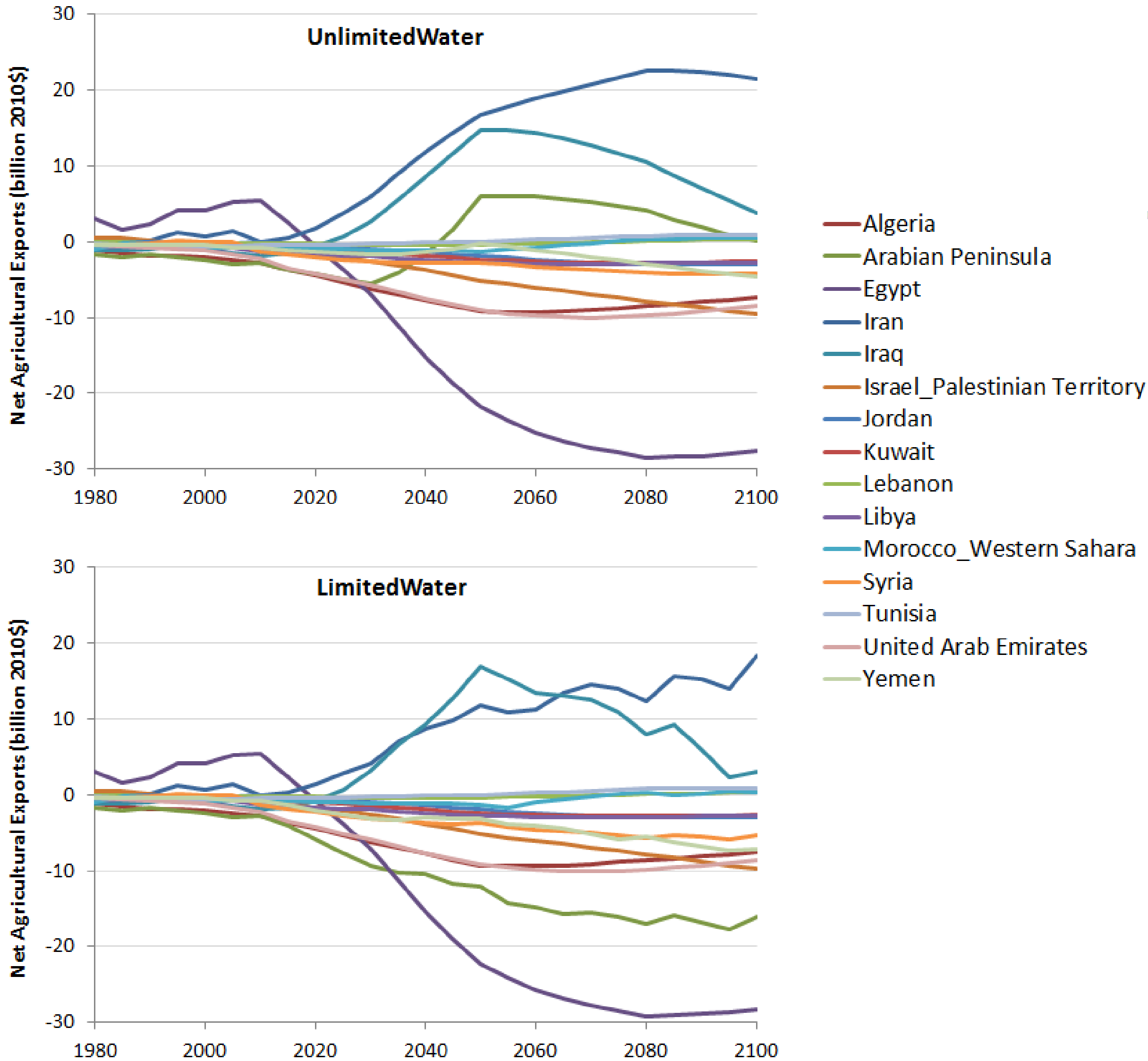


Figure 29: Total net exports (billion $) in the agricultural sector under the UnlimitedWater and LimitedWater scenarios.

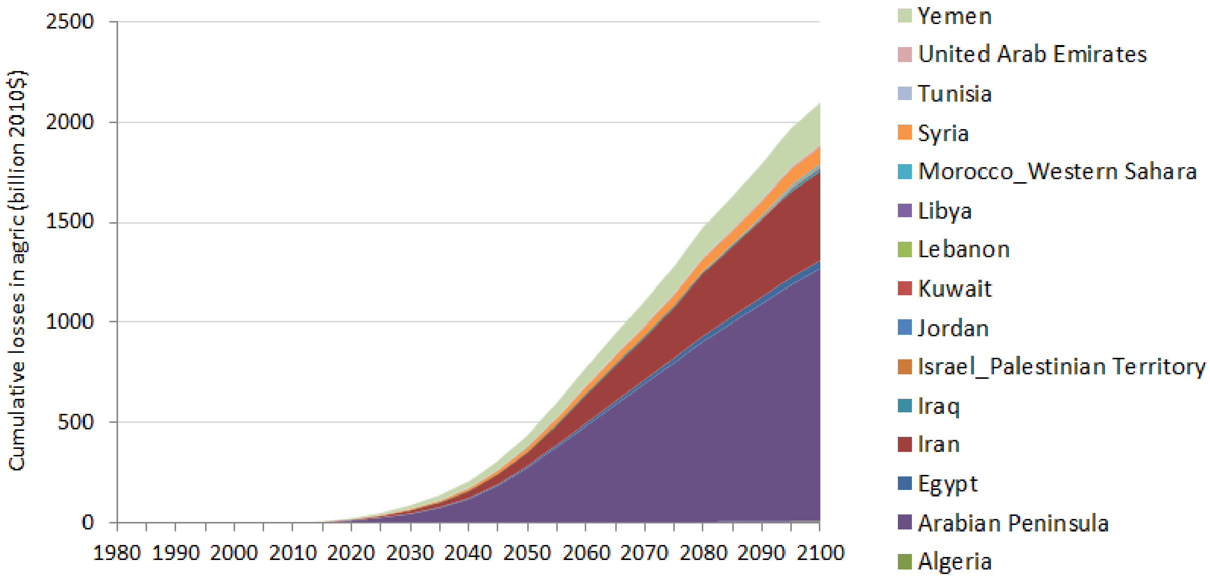


Figure 30: Cumulative change (losses) in net exports (billion $) in the agricultural sector in MENA countries (LimitedWater vs UnlimitedWater scenarios).

Agriculture is not the only sector influenced by limits on water availability. Because electricity uses water for cooling, it is also subject to the effects of water availability. Overall, the results of this work suggest that the effect on electricity production is negligible (on the order of 0.1 EJ, or 0.5 percent difference between the two scenarios) shown in **Figure 31**. The reason for this is the inherent flexibility of the electricity sector to reduce its wataer footprint through shifting fuels and water cooling technologies (**Figure 32**). In addition, the MENA region already relies extensively on cooling technologies with limited withdrawals of renewable water, such as the use of seawater, recirculating cooling, and dry cooling. This means that only modest adjustments are necessary to address water limitations. Indeed, the modest percentage of once-through cooling used in the region shown in Figure 34 for the LimitedWater scenario is dramatically decreased in the presence of water limits. The water withdrawal-intensity of the once-through cooling technology is roughly an order of magnitude higher than the recirculating cooling technology, so even a small change in fraction in once-through may still yield large reductions in water withdrawals. Nonetheless, water limits do alter the electricity investment profile. Countries that are faced with the most stringent water stress conditions (e.g., Iraq, Saudi Arabia, Yemen) are likely to incur the highest cost due to additional investments in more expensive power technologies and more expensive cooling options (**Figure 33**). While most countries experience only a modest increase in investment, the cumulative total through the end of the century exceeds $100 billion for the difference between the LimitedWater and UnlimitedWater scenarios considered here. In part, this is due to increases of needed investments in more expensive, but lower water technologies such as solar and wind power (**Figure 34**). It is interesting to note that these investments would be incurred in scenarios focused on reducing greenhouse gas emissions. Multiple studies (e.g., Kyle et al. 2013; Liu et al. 2014; Strzepek et al. 2014; Wallis et al. 2014) have demonstrated how efforts to decrease greenhouse gas emissions are synergistic with efforts to reduce water consumption for electricity.

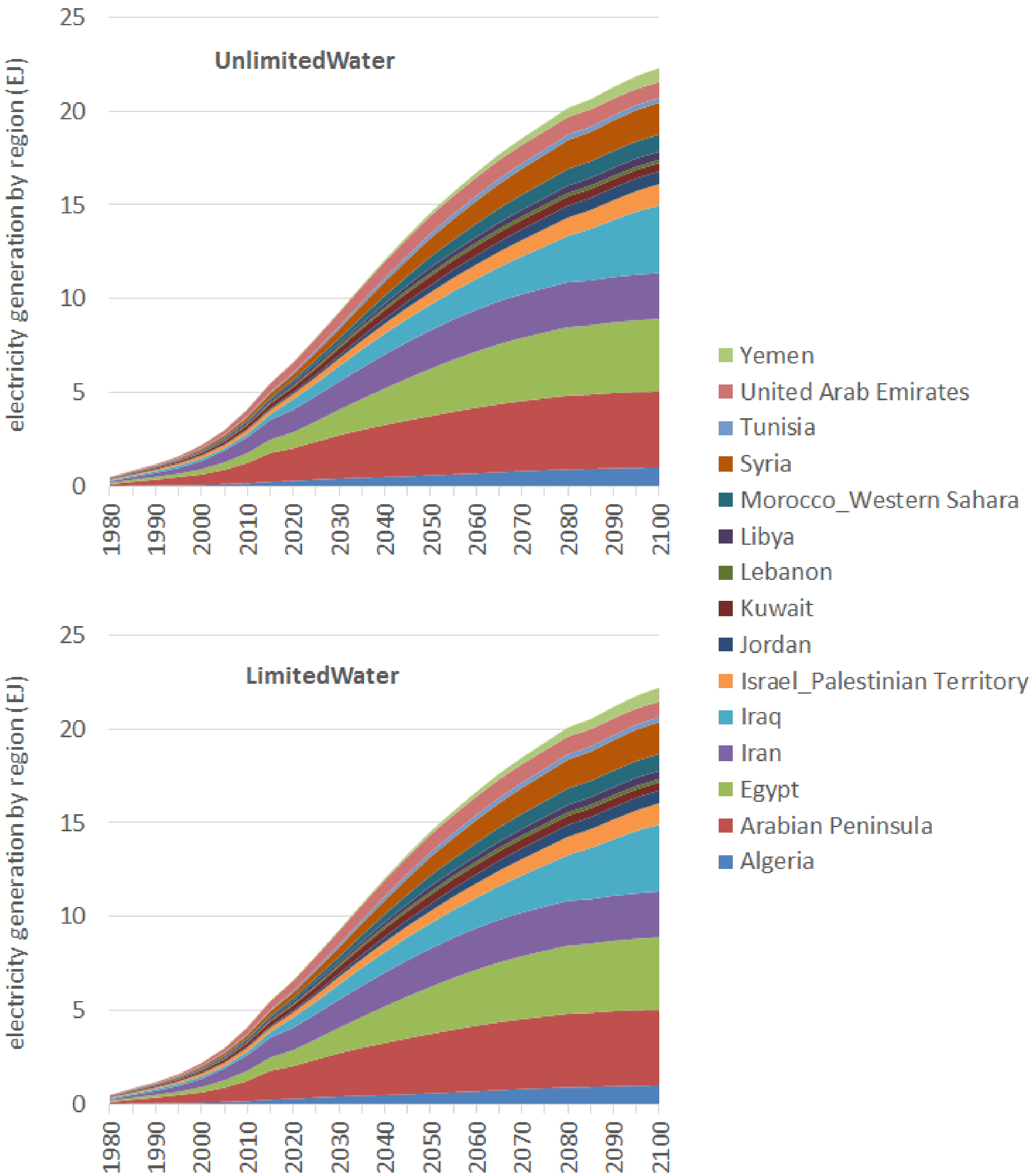


Figure 31: Total electricity generation by MENA region under the UnlimitedWater and LimitedWater scenarios.

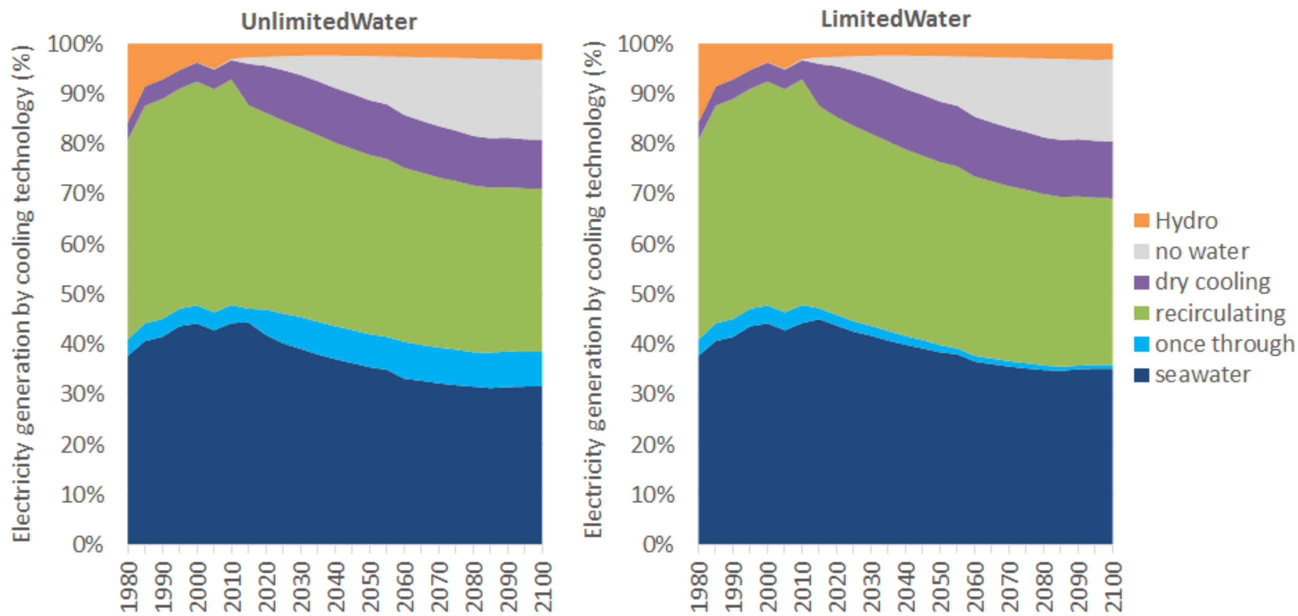


Figure 32: Distribution of electricity generation in the MENA region by cooling technologies for the UnlimitedWater and LimitedWater scenarios.

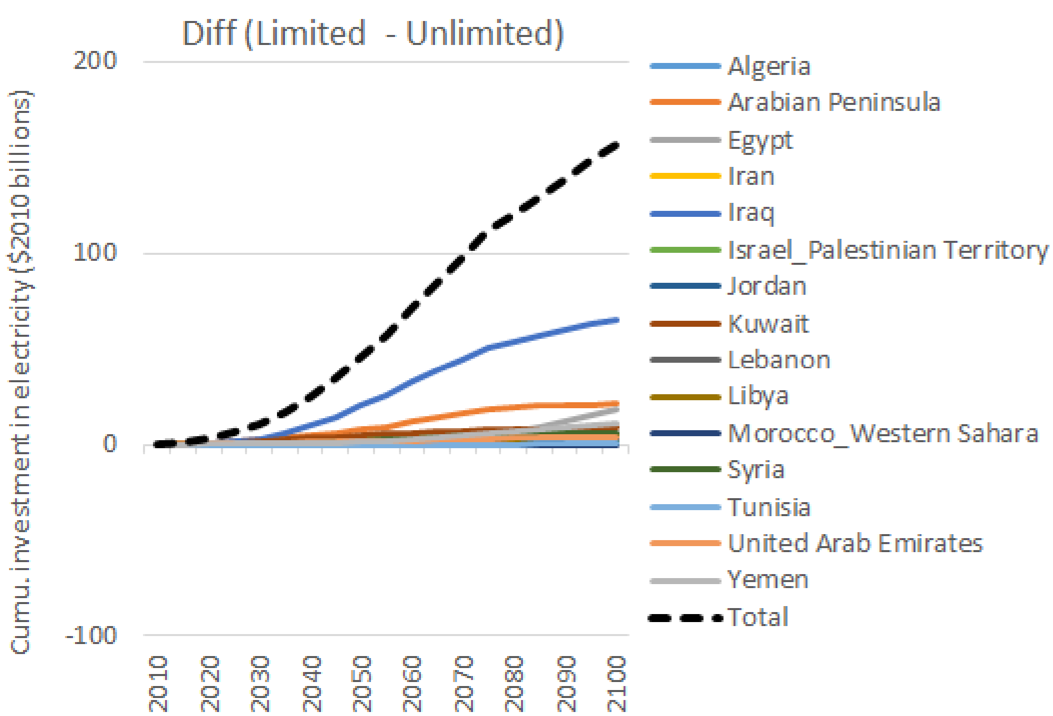


Figure 33: *The difference in cumulative total investment in the electricity sector between the LimitedWater and UnlimitedWater scenarios. The dashed-black line is the total sum across all 15 GCAM-MENA regions.*

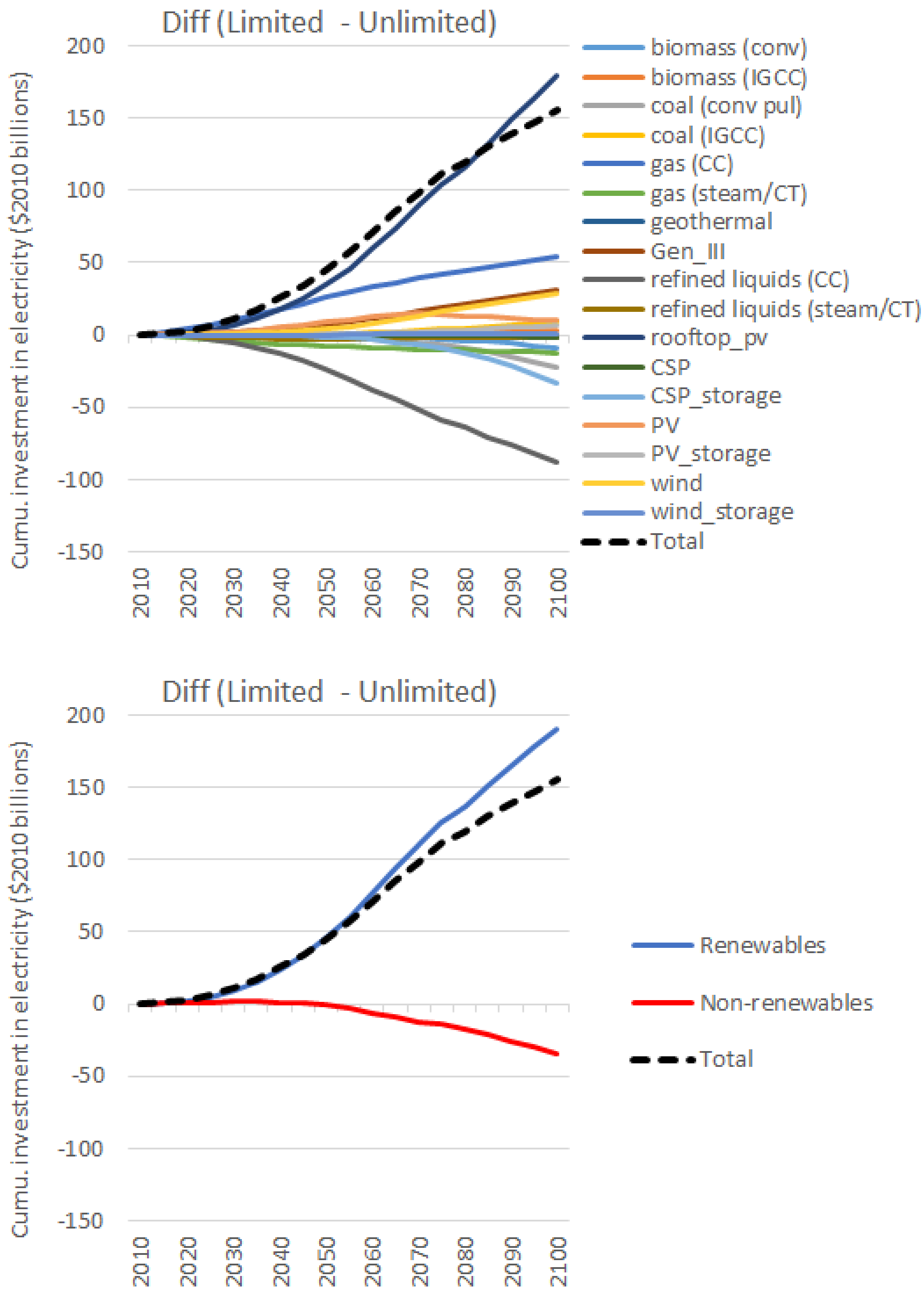


Figure 34: The difference in cumulative total investment in the electricity sector between the LimitedWater and UnlimitedWater scenarios, and by electricity technology. The dashed-black line is the total sum across all 17 technologies (as well as for the entire MENA region).

G. CONCLUDING REMARKS

In the MENA region, the nexus between water, energy and food is relevant for the region's sustainability, security, stability and continued growth. Countries in this region are arid to semiarid, with many areas already facing water stress and a highly variable precipitation rate due to their geographic and climatic conditions. Although to date governments in the region have been in general successful in satisfying the needs of the population through ambitious dam building, groundwater, reduction in leakages, conservation, desalination, reuse and water transfers, per capita supply is declining due to growing population, increased urbanization, extended irrigated agriculture and highly water intensive crops together with the development of the industrial and the tourism sectors. This decline in per capita supply has increasingly pushed the region to think of ambitious desalination plans to supply water to coastal cities and agricultural areas, and to explore the possibility of large transfers of water to the region. These options (desalination, reuse and water transfers) require relatively larger large amounts of energy, mainly electricity.

Through this project, an analytical framework to analyze the water-energy-food nexus in the MENA region has been developed and illustrated so that it can be used by the World Bank in its dialog with countries in the region to help formulate integrated (nexus) approaches for water, energy and food activities. This analytical framework is based on an integrated assessment model for the MENA region (GCAM-MENA), which implements an integrated resource (nexus) modeling approach. This report places focus on: (i) using GCAM-MENA to analyze the current status of water resources in the region; (ii) a scenario analysis focused on water scarcity and potential impacts on other sectors in the region (e.g., agriculture); and (iii) recommendations for further analysis that can inform policy making at the national level, and contribute to ongoing efforts towards integrated planning at the regional level, such as those discussions taking place in the Gulf Cooperation Council (GCC) countries.

The analysis of current and projected water scarcity results obtained from the GCAM-MENA model show a general trend upwards in the majority of countries of the MENA region, under a variety of climate (RCP) and socioeconomic development (SSP) scenarios. This is reasonable to expect given increased pressure in water resources (increased demand) as a result of population growth, development and other factors. The water scarcity index results are found to be fairly consistent among three climate models used (dry, average and wet), suggesting that water scarcity is dominated by water demands rather than by the climate-influenced water availability (surface and groundwater). It appears that severe and moderate water scarcity around the region advance significantly within the next few decades (i.e., through 2050) throughout the region. Therefore, it is important for MENA countries to be proactive on both the supply side (expand sources, e.g., desalination, water reuse) and demand side (e.g., agricultural efficiency) moving forward.

Two water resources management scenarios (UnlimitedWater and LimitedWater) were comparatively analyzed to understand the effects of constraining water use at the basin level in an effort to curb water demand for multiple uses. Constraining water is found to translate into impacts on water use for agricultural production across a number of crops. Countries can optimize their return on water by choosing different crop mixes, which will lead to different returns on the agricultural water used. Relatively large reductions in agricultural production occur in Saudi Arabia (almost 3-fold reduction when limiting water) and Yemen (approx. 60 percent overall reduction) as a result of constraining water demand. This reduction in production of agricultural commodities that arises as a result of constraining water in the MENA region does not necessarily imply a reduction in consumption of agricultural goods, assuming robust international trade and a willingness to increase reliance on agricultural imports. Even in this circumstance, however, the reduction in production does have an important impact on the magnitude of agricultural exports from the region; these impacts were found to be more pronounced for countries such as Iran, Saudi Arabia and Yemen. The result of these changes in terms of trade is a reduction in agricultural revenues through 2100; Saudi Arabia experiences a cumulative loss of over $1.2 trillion, followed by Iran (over $400 billion), Yemen (over $200 billion) and other countries in the region.

It is important to note that these results derive from several assumptions in the scenarios analyzed, notably a robust market for international trade in agricultural products and a willingness of countries to increase their dependence on imported agricultural goods. Were either of these assumptions not to hold in reality – for example, for reasons of food security and self-sufficiency – this might imply smaller changes in domestic production, the use of lower-water crops, greater use of highly-efficient irrigation technologies, and lower domestic consumption. All of these implications would be valuable to explore in future analyses.

With respect to energy security, countries that are faced with the most stringent water stress conditions (e.g., Iraq, Saudi Arabia, Yemen) are likely to incur the highest cost due to additional investments in more expensive power technologies and more expensive cooling options. While most countries experience only a modest increase in investment, the cumulative total through the end of the century exceeds $100 billion for the difference between the LimitedWater and UnlimitedWater scenarios considered here. In part, this is due to increases of needed investments in more expensive, but lower water technologies such as solar and wind power. It is worth noting that these investments would also be incurred in scenarios focused on reducing greenhouse gas emissions; there are synergies to be realized in efforts to decrease greenhouse gas emissions are synergistic and efforts to reduce water consumption for electricity.

While desalination serves the region as an important additional water supply, cost considerations need to be highlighted. The cumulative investment in the LimitedWater scenario exceeds $20 billion by 2050 and reaches almost $70 billion by 2100. It is important to note that the demand for desalination and the associated investment needs would vary noticeably based on the demands for water in the different scenarios. Also, the projected increase in desalination using current technologies would have serious implications on marine ecosystems due to brine disposal, and mitigating such negative environmental concerns would incur additional costs to the MENA region. This is an issue that merits further investigation.

In addition to this, sensitivity of the investment cost results to changes in interest rate is an issue that should be explored further. The capital recovery factor formulation used in this work is sensitive to changes in interest rates. Interest rates differ from one country to another as well, so this implies the need for more detailed financial analyses of different nexus configurations among countries in the region.

By providing an economic quantitative framework for integrated analysis of water supply and demand, multiple demand sectors, climate inputs, and other forcing factors such as land use change, policy interventions and technological developments, integrated assessment models such as GCAM-MENA provide a viable tool to explore additional issues related to the water-energy-food nexus. Further research along these lines can be focused on such issues as the implications of water reuse (particularly wastewater recycling) as a future water supply and its effect on urban services, food and energy security; the effects of sudden extreme events or shocks of physical or socioeconomic natures; the repercussions of removing existing distortions (i.e., subsidies) in water availability and distribution in the future; the economic costs (of inaction) of non-cooperation across basins/countries/regions and the potential benefits of cooperation; quantify tradeoffs in water availability and its impact on major economic sectors; define effective adaptation strategies/investments that are necessary to mitigate the impact of climate change on water scarcity and stress; identify and plan key investments at regional and country levels to address economic water scarcity.

The analysis performed through this project can contribute to identify synergies to meet sectoral needs in a manner consistent with regional goals of environmental sustainability, water-energy-food security and socioeconomic development. The results of this analysis can be used to incorporate nexus approaches in the formulation of planning practices and design investments in the region. This work can contribute to building integrated planning capabilities in MENA countries and help flag any potential constraints and opportunities that may arise from an integrated long-term view at water, energy and food needs in the region**.** Climate change impacts are also incorporated in this exercise in order to facilitate robust and resilient WEF sector development planning.

Managing the water-energy-food nexus in the region and satisfying the future water needs of all sectors is a strategic challenge for the MENA region for the coming years. In some parts of the region, the combined effects of population growth, increasing hydrological variability and climate change may result in increased reliance on relatively energy-intensive water supply options. At the same time, agriculture is expected to continue to pose major pressures on the region’s diminishing water supplies. The nexus poses not only challenges for sustainability in the MENA region, but also for the region’s food, energy and water security, and improving its social, economic and political stability.

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