Middle-East and Northern Africa Water Outlook

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Preface

This study is conducted as part of the World Bank initiative to update the regional water outlook for the MENA region and to contribute to the writing of a climate change flagship report. This specific consultancy is defined as the "Middle East and North Africa (MENA) Regional Water Outlook—With Special focus on Water Resources availability and Water Demand Analysis".

This report describes a study undertaken by FutureWater under a World Bank contract as signed on 13-Aug-2010, under number 7156425, and covering a 90 person-days input .

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The study has undergone a rigorous review process at various stages. First of all the broad group of authors provided feedback and comments on their colleagues work during an internal review. Subsequently, various comments were received from World Bank staff, followed by a more formal review process. Finally, the results of the study were presented and discussed during a workshop with various World Bank and MENA country representatives in Oman (22 and 23 February 2011).

The consultants wish to acknowledge the support, fruitful discussions and useful comments from World Bank staff, various anonymous reviewers and stakeholders in the countries. In particular Dr. Bekele Debele Negewo is acknowledged for starting this initiative and his support and advice on the study.

Executive Summary

Water scarcity is a major problem in many parts of the world affecting quality of life, the environment, industry, and the economies of developing nations. The Middle East and North Africa (MENA) region can be considered as the most water-scarce region of the world. Large-scale water management problems are already apparent in the region. Aquifers are over-pumped, water quality is deteriorating, and water supply and irrigation services are often rationed—with consequences for human health, agricultural productivity, and the environment.

As the MENA region's population continues to grow, and is projected to double over the next 40 years, per capita water availability is said to fall by more than 50 percent by 2050. Moreover, climate change will affect weather and precipitation patterns with the consequence that the MENA region may see more frequent and severe droughts.

Earlier studies on water availability in the MENA region provided insight in the severity of the problem and some first assessments how to overcome the projected water shortage have been presented. However, a solid, comprehensive and uniform assessment of the current and future water resources in the MENA region is lacking so far. The World Bank has therefore taken the initiative to generate an improved understanding of water issues in the region and overview of available options under different scenarios of water supply and demand management with special focus on desalination. As part of this initiative, FutureWater undertook a study on the assessment of water issues in the MENA region, including associated marginal cost of water supply to meet the growing water need. In summary, the focus and objective of the current study are to (i) perform a detailed water assessment analysis for all countries in MENA, including water availability and demand analysis including climate change impacts; and (ii) identification of various options to meet the water supply need, and associated marginal cost of water supply.

The current study applied state-of-the-art and scientifically accepted approaches to assess the current and future water demand, supply and shortage in the 21 MENA countries and to explore options, and associated costs, to overcome water shortage. The costs of adaptation are presented at country level, but the full demand and supply analysis were undertaken at smaller scales of 10 km^2. Similar, results are presented for three periods (2000-2010, 2020-2030, 2040-2050), but all analysis were done on a daily base for a period of 50 years (2000-2050). Finally, the study results are summarized for an average, a dry and a wet climate scenario, but the analysis were all based on results of nine global climate change models (GCM).

The results of the study show that water shortage will be about 200 km^3 per year in 2040-2050 based on the average climate change projection (Figure 53). Uncertainty in the climate change projections was considered and the 10% and 90% range in water shortage is between 90 and 280 km^3 per year. Unmet demand for the entire MENA region, expressed as percentage of total demand, will increase from 16% currently to 37% in 2020-2030 and 51% in 2040-2050. Water shortage for the individual countries will vary substantially (Table 10).

To overcome current and future water shortage countries have a range of options at their disposal to respond and adapt. These options can be summarized into three broad categories: (i) increasing the productivity, (ii) expanding supply, and (iii) reducing demand. For each of these three categories typical options were explored in the study resulting in the following framework:

- Increasing the productivity:
  - A: Improved agricultural practice (including crop varieties)
  - B: Increased reuse of water from domestic and industry
  - C: Increased reuse of irrigated agriculture
- Expanding supply:
  - D: Expanding reservoir capacity (small scale)
  - E: Expanding reservoir capacity (large scale)
  - F: Desalinisation by means of using solar energy
  - G: Desalination by means of fossil fuel
- Reducing demand:
  - H: Reduce irrigated areas
  - I: Reduce domestic and industrial demand

Obviously, each of these options is associated with certain marginal unit costs, ranging from US$ 0.02 per m^3 for improving agricultural practices to US$ 2.00 per m^3 in case of reducing supply to domestic and industrial demand. It is clear that in general the cheapest options will be introduced first, but at the same time might not be sufficient to overcome water shortage completely and more expensive options are required to bridge the water gap. By ranking the adaptation options by their unit costs country specific water marginal costs curves are constructed. The water availability cost curve's use is limited to comparing measures' financial costs to close the gap. It is important to note that these might be different from the economic costs for society as a whole. The cost curve should be therefore considered as a guide for comparing the financial costs of measures for decision-making.

The results of the current study indicate that for the entire MENA region annual costs[1] to overcome water shortage in 2050 are about US$ 100 billion per year (Figure 56 and Figure 59). Depending on the climate change projection considered these costs are between US$ 27 billion (wet projection) and US$ 212 billion per year (dry projection) and costs vary substantially between individual countries (Table 17). These total costs per country can also be expressed per capita. For the entire MENA region the average cost is US$ 150 per year per capita in 2050, with large differences between countries up to over US$ 500 per year per capita in 2050. When expressed as a fraction of the GDP the total cost to bridge the water gap seems relatively low for the entire MENA region. However, this is strongly influenced by the source of the GDP projections for 2050 and a substantial variation between the individual countries exists.

The study concludes that water shortage in the MENA region will be enormous in the next decades and that about 20% can be attributed to climate change and 80% to a steep increase in demand owing to strong population growth and fast economic development. The study clearly indicates that a mix of approaches is required and that these are country specific. Further country-specific studies are required to explore these approaches more in-depth in close collaboration with policy makers and planners to develop concrete actions. The study concludes that most countries might be able to bear the burden of adaptation measures in 2050, however, policies should be put in place now to act timely.

[1] All costs are annualized and converted to 2010 US$ prices

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1 Introduction

The Middle East and North Africa (MENA) region is considered the most water-scarce region of the world. Large-scale water management problems are already apparent in the region. Aquifers are over-pumped, water quality is deteriorating, and water supply and irrigation services are often rationed—with consequences for human health, agricultural productivity, and the environment. Disputes over water lead to tension within communities, and unreliable water services are prompting people to migrate in search of better opportunities. Water investments absorb large amounts of public funds, which could often be used more efficiently elsewhere. And the challenge appears likely to escalate. As the region's population continues to grow, per capita water availability is said to fall by 50 percent by 2050, and, if climate change affects weather and precipitation patterns as predicted, the MENA region may see more frequent and severe droughts and floods.

One of the major challenges in the MENA is to increase agricultural production to sustain the fast growing population besides other options such as increasing import and investing in other regions. The "agriculture towards 2030/2050" study of FAO (FAO, 2006) shows that on a global scale the demand for agricultural products will slow, because the population growth rates stabilize and fairly high levels of per capita food consumption have been reached in many countries. On a global scale FAO expects that agricultural production can grow in line with agricultural demand, however in the MENA region the situation differs as high population growth rates are expected and water is a crucial constraint. The study estimates that 58% of the renewable water resources in the MENA will be used by 2030 and far-fetching efficiency measures are required.

The 4th Assessment Report of the IPCC projects strong changes in climate across the MENA region. Temperature increases combined with substantial decreasing precipitation are projected. The elevate temperature results in a higher evapotranspiration demand and will, in combination with a decrease in precipitation, severely stress the water resources in the region.

The need for alternative and improved water management options is therefore urgently needed, but a clear overview on what the main focus should be is lacking. A broad range of options exists which can be grouped by different approaches such as reducing the demand, increasing the supply, transfer between different sectors, transfer within different sectors, increase storage and an important aspect for the MENA region includes desalination.

The World Bank study "Making the Most of Scarcity: Accountability for Better Water Management Results in the Middle East and North Africa" (2007) asks the question whether countries in MENA can adapt to meet these combined challenges. The study argues that they have to do, because if they do not, the social, economic, and budgetary consequences will be enormous. Drinking water services will become more erratic than they are already, cities will come to rely more and more on expensive desalination and will have to rely more frequently on emergency supplies brought by tanker or barge. Service outages will put stress on expensive network and distribution infrastructure. In irrigated agriculture, unreliable water services will depress farmers' incomes. The economic and physical dislocation associated with the depletion of aquifers or unreliability of supplies will increase. All of this will have short and long-term effects on economic growth and poverty and will put increasing pressure on public budgets. The study concludes that the MENA countries have made considerable advances in dealing with the water problems, but that efforts have focused on reducing physical water scarcity and improving organizational capacity. To overcome the water problems further basic economic reforms need to be implemented and its effects assessed. The question remains how these reforms and interventions can be best assessed.

The study by the 2030 Water Resources Group “Charting Our Water Future” shows that the challenge in identifying the optimal mix of technical measures to close a given supply-demand gap lies in finding a way to compare different measures. To address this need, the 2030 Water Resources Group developed a “water-marginal cost curve” as a tool to support decision-making (Figure 1). The cost curve’s horizontal axis measures the amount of water made available by each measure to close the supply-demand gap. In applying the cost curve in the case study countries, the net impact of each measure on water availability is estimated. The vertical axis of the cost curve measures the cost per unit of water released by each measure in the year of the cost curve. This is the annualized capital cost, plus the net operating cost compared to business as usual. These are costs as measured from an integrated view—in other words the actual financial savings, rather than redistribution effects such as subsidies. In this study we will adopt this concept in assessing the potential to overcome the supply-demand gap in the MENA region.

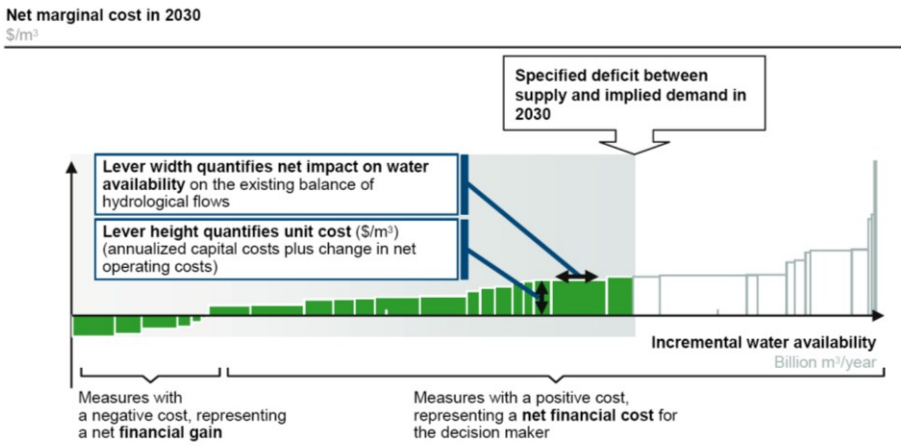

Figure 1. Example of the water availability cost curve (source: Water resources group 2030).

There is no question that the demand-supply gap has to be closed and as a last resort large scale seawater desalination may be used to close the gap. A comprehensive study by the DLR on concentrating solar power (CSP) for seawater desalination in the MENA (DLR, 2007), further referred to as the AQUA-CSP study, suggests that CSP desalination may be a viable means to close the demand-supply gap in the MENA from 2030 onwards. They estimate the gap between demand and supply for the entire MENA based on FAO statistics and assumptions on growth rates. They project an increase in total water demand from 270 km^3 in 2000 to 460 km^3 in 2050 and that the demand-supply gap will increase from 50 km^3 in 2000 to 150 km^3 in 2050. They conclude that there is a huge market for CSP desalination and that the cost price may drop from around 1 US$/$m^3$ to 0.40 US$/$m^3$, which is still too high for extensive use in irrigated agriculture and the solution for the water crisis in the MENA should really be sought in a set of measures following the cost curve approach.

Although all these studies provide insight in the severity of the problem and some first assessment how to overcome the projected water shortage, a solid and comprehensive assessment of the current and future water resources in the MENA is lacking. Previous studies have based their analysis on annual countries statistics and generalized assumptions on future developments. In reality the hydrological system is more complex and there are strong intra-annual mismatches between supply and demand, which can be partly compensated for by reservoirs or other water management structures and an assessment of this interaction between hydrological processes and human interventions in the system at a monthly time-scale is required to assess the true scale of the problem. In addition, previous studies have not taken into account potential impacts of climate change on water resources availability and this may have a very strong impact on the results of such an analysis.

To explore different options the World Bank has therefore started an initiative to generate an improved understanding of water issues in the region and overview of available options under different scenarios of water supply and demand management with special focus on desalination, taking into account the energy nexus and environmental concerns. As part of this initiative an assessment of water stress in the MENA region, including associated marginal cost of water supply to meet the water supply need, was undertaken.

In summary, the focus and objective of the current study are to (i) perform a detailed water assessment analysis for all countries in MENA, including water availability and demand analysis including climate change impacts; and (ii) identification of various options to meet the water supply need, and associated marginal cost of water supply. This project is twinned to another project commissioned by the Bank and executed by another consultant. Their objective is to assess the potential to implement desalination technology using renewable energy to close the water gap in the MENA.

This report describes the methodology and results to fulfill these objectives. First we describe how climate change scenarios are generated for the MENA region. These data are used to assess the future water availability which is discussed in the next chapter. Then the water demand side is analyzed across the irrigation, industrial and domestic sectors. Using a water allocation model we then analyze water stress by confronting water availability with water demands. Finally we derive water availability costs curves which show how much investment is required to close the water gap in each of the MENA countries.

2.1 Modeling approach

A two tire modeling approach is used in this study. First we use an advanced distributed hydrological model to determine the renewable water resources including external renewable water resources for the current and future climate. In combination with sectorial water demands the results of the water availability analysis feed into a water allocation model that is used to assess water demand on a monthly basis. The water allocation model includes groundwater, surface water and reservoirs as sources of water which are used to sustain the sectorial water demands. The allocation model links supply and demand for each country, sector and supply source. The hydrological model provides monthly time series of surface water and natural groundwater recharge to the water allocation model. The water allocation model is subsequently used to assess the effects of different supply and demand options.

The project methodology is organized according to Figure 2. First climate change scenarios are generated for the MENA region. These data are used to assess the future water availability based on the PCR-GLOBWB model. Then the water demand side is analyzed across the irrigation, industrial and domestic sectors. Using a water allocation model (WEAP) water stress is assessed by confronting water availability with water demands. Finally water availability costs curves are derived using the same modeling framework indicating how much investments are required to close the water gap in each of the MENA countries.

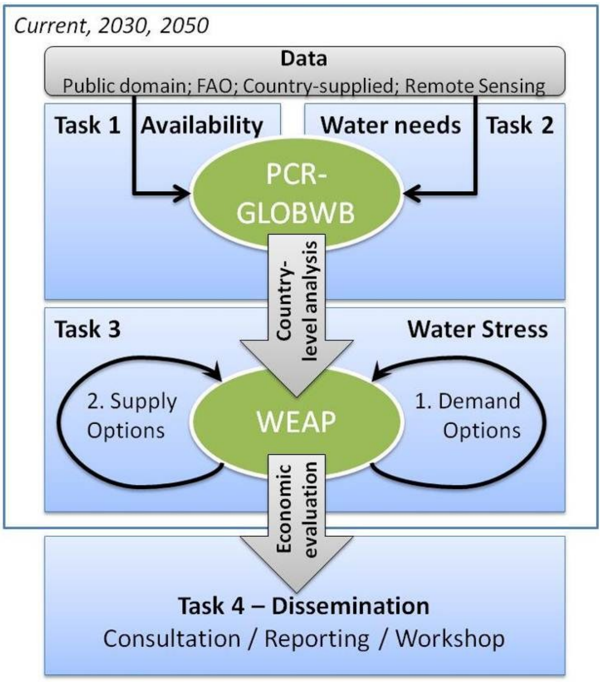

Figure 2. Study setup for Water Outlook MENA region.

It is of paramount importance in these kinds of studies to have a well-defined set of definitions. Many studies are hampered by a loose use of terminology, making interpretation of results difficult. More importantly, policy decisions might be less appropriate due to misconceptions in terminology. A classic example is “efficiency”, where the real question should be “what happens with the non-efficient water?". Following the definitions of FAO (2003) in this study a distinction is made between:

Internal renewable water resources account for the average surface flow of rivers and the recharge of groundwater generated from endogenous precipitation. Internal renewable water resources also account for *green water*, which is captured in the root zone and evaporated by plants without becoming part of the surface water system.

External renewable water resources refer to surface water and to renewable groundwater that come from other countries plus part of shared lakes and border rivers as applicable, taking into account the net consumption of the country in question. Dependency on incoming water from external sources is quantified by the dependency ratio.

Total renewable resources are the total of internal and external surface and groundwater resources. Special care is taken to avoid double counting of surface water and groundwater.

Non-renewable groundwater resources are naturally replenished only over a very long timeframe. Generally, they have a negligible rate of recharge on the human scale (<1 percent) and thus can be considered non-renewable. In practice, non-renewable groundwater refers to aquifers with large stocking capacity in relation to the average annual volume discharged.

In the MENA region fossil groundwater reserves are extensively mined to satisfy the water demands by the different sectors. These fossil groundwater reserves are non-renewable as the pumping exceeds the natural recharge. Moreover the total storage of these fossil groundwater reserves is unknown and therefore focus should be on reducing the dependence on these aquifers.

2.2 Monthly approach

Using a monthly approach in assessing water stress is a crucial component of this assessment. Many studies assess water stress on an annual scale which underestimates actual water stress because water demand and supply are not in phase. This is illustrated in Table 1 which shows the available renewable water resources, the irrigation water requirements and the water stress on a monthly basis for a hypothetical irrigation scheme. On annual basis the water stress would be equal to 20 mm (260-240), while in reality the difference between available and required water should be determined on a monthly basis and then aggregated. This approach would results in an annual water stress of 120 mm. This example assumes that renewable water from the previous month is somehow lost, not accumulated in the ground or a reservoir that could be used for irrigation in the following month. This obviously is a simplification of reality, but the annual approach followed frequently assumes an unlimited storage, which is often not reality. Reservoirs are of course used to attenuate this mismatch in time between demand and supply. However, the use of reservoirs leads to undesirable loss of water due to open water evaporation. The impact of reservoirs is taken into account using the water allocation model. In summary, the often followed annual approach is unrealistic and in our analysis a daily and monthly approach is used where groundwater and reservoir storage is included.

Table 1. Hypothetical example of the importance of using a monthly approach in assessing water stress, assuming no storage in groundwater or reservoirs.

Month	Renewable (mm)	Irrigation requirement (mm)	Water stress (mm)
January	30	10	0
February	20	10	0
March	10	30	20
April	10	30	20
May	10	40	30
June	10	40	30
July	10	20	10
August	10	20	10
September	20	20	0
October	30	20	0
November	40	10	0
December	40	10	0
TOTAL	**240**	**260**	**120**

2.3 Water availability cost curves

Based on the analysis with the water allocation model the amount of water that is required to sustainably close the gap between supply and demand is known. The gaps will most likely increase tremendously as availability is decreasing and demand is projected to increase. A number of supply and demand measures (e.g. desalination, increasing reservoir capacity, improving water productivity) will be analyzed using the water allocation model and water availability cost curves will be derived.

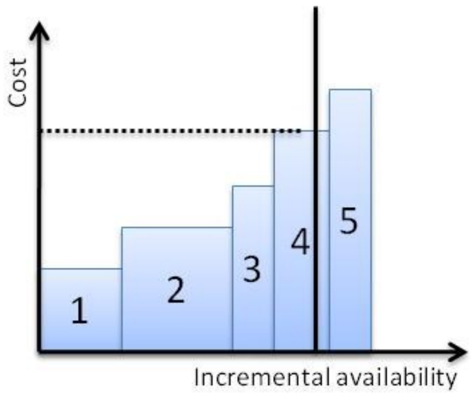

Figure 3. Illustration of prioritization of different options.

The cost-effectiveness of various measures to close the supply-demand gap will be compared in this study by means of the “water-marginal cost curve”, as presented by the 2030 Water Resources Group (2009). This cost curve shows the cost and potential of a range of different measures- spanning both productivity improvements and supply expansion – to close the gap. Such a water-marginal cost curve is estimated for each MENA country to assess the total costs to close the supply-demand gap projected in the base case (2010) and under various climate change scenarios in 2030 and 2050. A hypothetical graph of such a curve is shown in Figure 3. On the vertical axis the marginal costs in US$/m^3 of each measure is shown, while on the x-axis the total amount of water (m^3) is shown that can be conserved (or supplied) using the approach. The vertical line crossing box 4 shows the water gap in for example 2030. The first block is the cheapest measure. The surface under the water availability cost curve up to the line showing the water gap equals the investment required to close the water gap.

3 Downscaling Climate Change Scenarios

3.1 Why downscaling?

In this study we will use precipitation and temperature outputs of nine General Circulation Models (GCMs). These outputs cannot be used directly in impact studies for two different reasons. First, the resolution of GCMs is the order of several hundreds of kilometers which is too coarse for detailed hydrological assessments. Second, time series for the past climate, which are generated by GCMs, show a statistically different pattern than observed climate records. There are two methods which are commonly used in downscaling. Statistical downscaling uses observed climate records to adjust GCM output such that the statistic behavior during a historical period is similar. Dynamic downscaling nests a regional climate model (RCM) at a higher resolution in the domain of the GCM. The GCM provides the boundary conditions and the RCM generated output at a higher resolution. In this study we use an ensemble of nine different GCMs and deploy a statistical downscaling approach.

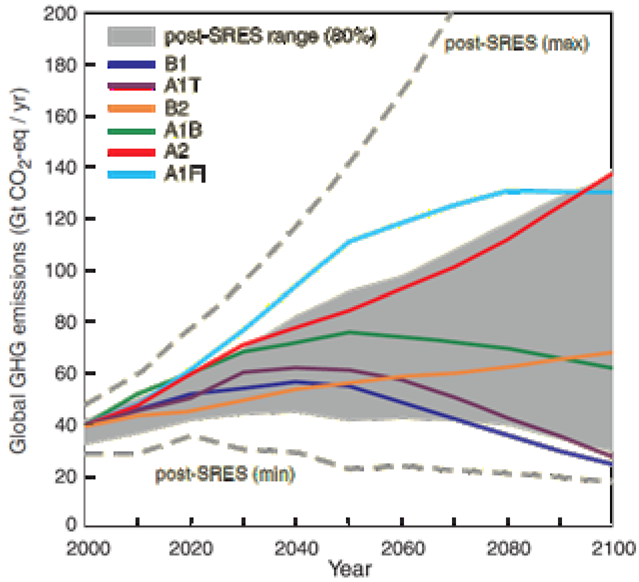

Figure 4. Global GHG emissions in the absence of additional climate policies (http://www.ipcc.ch).

3.2 Projected climate change in the MENA

According to the IPCC (Intergovernmental Panel on Climate Change), there is high agreement and evidence that with current climate change mitigation policies and related sustainable development practices, global Green House Gas (GHG) emissions will continue to grow over the next decades. The IPCC uses four scenario families (A1, A2, B1 and B2), which are described in the IPCC Special Report on Emissions Scenarios (SRES, 2000). The scenario families explore alternative development pathways, covering a wide range of demographic, economic and technological driving forces and resulting GHG emissions. The A1 scenario family is divided into a number of groups that describe alternative directions of technological change. The SRES GHG emissions of these families and groups are shown in Figure 4.

This study uses the A1B GHG emission scenario. This scenario is chosen because it is widely used and recommended by the IPCC. According to the IPCC, the A1B scenario is the most likely scenario, because it assumes a world of rapid economic growth, a global population that peaks in mid-century and rapid introduction of new and more efficient technologies. The A1B group assumes a balance across all sources. A balance across all sources is defined as not relying too heavily on one particular energy source, where the energy sources are defined as fossil-intensive and non-fossil. It is assumed that similar improvement rates apply to all energy supply and end use technologies. A1B can be seen as an intermediate between the B1 (with the smallest GHG emissions) and A2 (with the largest GHG emissions) scenario. GHG emissions of the A1B scenario show a rapid increase during 2000-2050 and a decrease for 2050-2100 (Figure 4).

According to the IPCC it is very likely that hot extremes, heat waves, and heavy precipitation events will become more frequent during the 21st century. Global changes in surface temperature are shown in Figure 5 for some SRES scenarios, including A1B used in the current study. For the A1B scenario we can expect a global rise in surface temperature of 1.3 °C around 2050 relative to 2000, and a rise of 2.6 °C at the end of the 21st century.

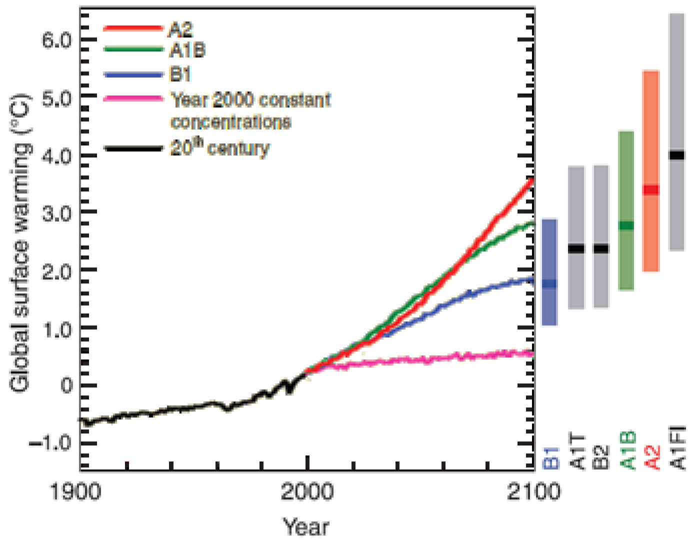

Figure 5. Multi-model global averages of surface warming (relative to 1980-1999) for the SRES scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. The pink line is for the experiment where concentrations were held constant at year 2000 values. The bars on the right of the figure indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios at 2090-2099 relative to 1980-1999 (source: IPCC 2007).

Regional projections in Africa can be summarized as (Christensen et al., 2007):

- All of Africa is likely to warm during the 21st century.
- Warming is very likely to be larger than the global, annual mean warming throughout the continent and in all seasons, with drier subtropical regions warming more than the moister tropics.
- Annual rainfall is likely to decrease in much of Mediterranean Africa and northern Sahara.

- There is likely to be an increase in annual rainfall in East Africa.

The geographical structure of the projected warming for the A1B scenario is shown in Figure 6 . It can be seen that smaller values of projected warming, near 3 °C, are found in equatorial and coastal areas and larger values, above 3 °C, in the Western Sahara. The largest temperature responses in North Africa are projected to occur in June-July-August (JJA).

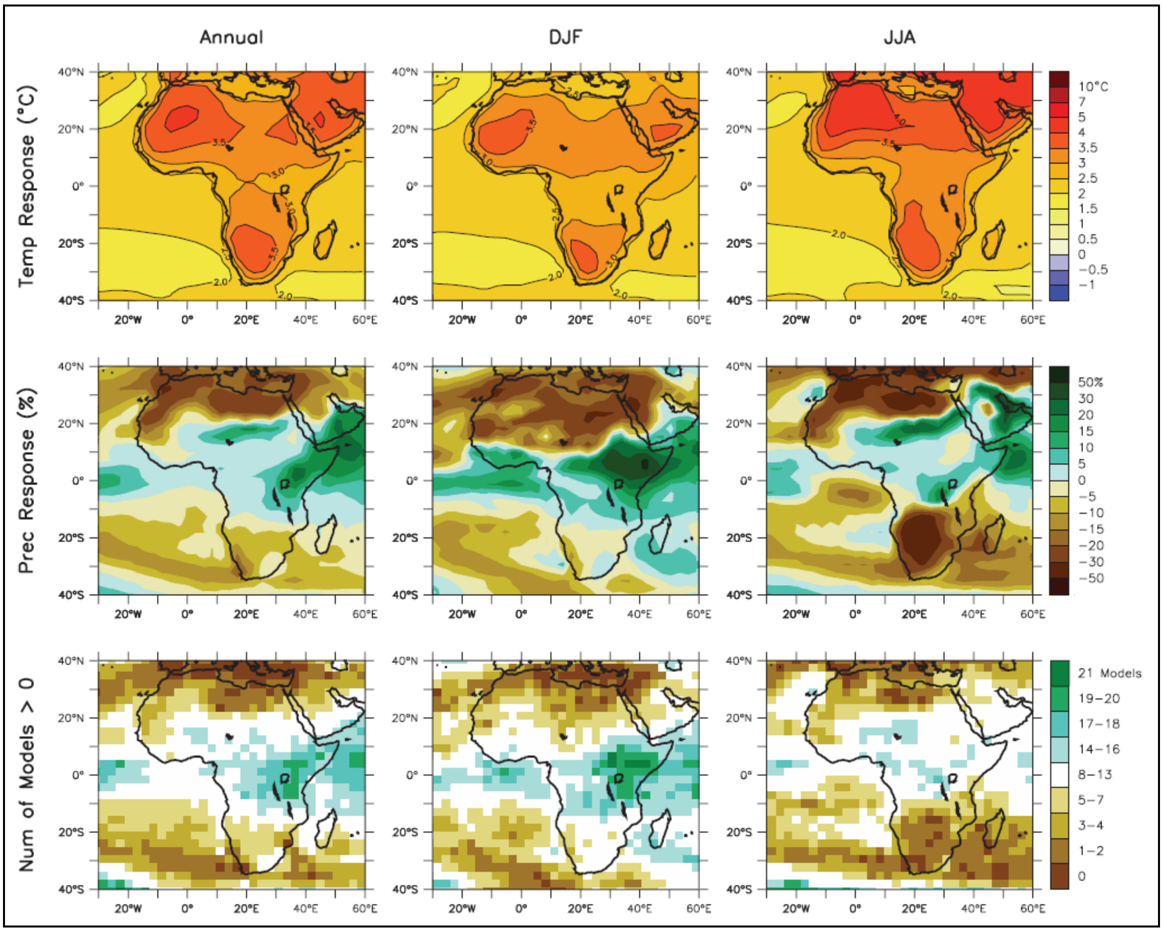

Figure 6. Temperature and precipitation changes over Africa from the MMD-A1B simulations. Top: Annual mean, DJF and JJA temperature change between 1980 to 1999 and 2080 to 2099, averaged over 21 models. Middle: same as top, but for fractional change in precipitation. Bottom: number of models out of 21 that project increases in precipitation (Christensen et al., 2007).

Projected precipitation responses of the MMD (Multi Model Database) A1B scenario are also shown in Figure 6. The large-scale picture is one of drying in much of the sub-tropics and a limited increase in precipitation in the tropics. A 10 to 20% drying in the annual mean is typical along the African Mediterranean coast in A1B towards the end of the 21st century compared with 1980 -1999 climate. This drying pattern is seen throughout the entire year and is generated in nearly every MMD model. This drying signal extends into the northern Sahara, and down the west coast as far as 15 °N. In hyper-arid areas that receive less than 50 mm / year some care should be taken when interpreting these relative changes as a small absolute decrease in rainfall results in a very high relative change. This is particularly true for Egypt and for large parts of the Sahara. In East-Africa an increase in precipitation can be noticed. This increase extends into the Horn of Africa, and is robust across the ensemble of models, with 18 of 21 models projecting an increase in the core of this region, east of the Great Lakes (Lake Victoria).

Because of the large variation between different climate models results of nine Global Circulation Models (GCMs) will be used in this project to study the impact of climate change in the MENA region. The selection of these GCMs is described in following section.

3.3 Selection of GCMs

Probable changes in climate in Africa have been addressed by Shongwe et al. (2009, 2010). They evaluated the performance of all IPCC GCMs in different regions of Africa by comparing their outputs from 1960-1990 with the CRU TS2.1 dataset (New at al., 2000). The CRU dataset provides gridded values of observed climate data. The results for North-East Africa are shown in Table 2 and are based on the mean of monthly correlation and mean squared difference between 20th century GCM experiments and the CRU TS2.1 analysis. The best nine performing models were selected to be used in this study.

Table 2. Overview of GCM performance in North-East Africa. The first nine GCMs are included in the current study. The table shows the mean of monthly correlation and mean squared difference of 20th century GCM experiments with the CRU TS 2.1 analysis (http://www.knmi.nl/africa_scenarios/technical.shtml).

Model	r (-)	MSE (mm /day)	Included
BCCR CM2.0	0.81	1.12	1
CCCMA CGCM 3.1 T47	0.79	1.12	1
CNRM CM3	0.79	1.23	1
CSIRO Mk3.0	0.75	0.97	1
GFDL CM2.0	0.82	1.00	1
IPSL CM4	0.78	0.84	1
MPI ECHAM5	0.88	0.59	1
HadCM3	0.76	0.90	1
HadGEM1	0.81	0.78	1
CCCMA CGCM 3.2 T63	0.84	1.22	0
GFDL CM2.1	0.68	1.03	0
GISS AOM	0.59	1.60	0
GISS EH	0.65	1.19	0
GISS ER	0.71	1.18	0
IAP FGOALS 1.0g	0.60	1.19	0
INM CM3.0	0.58	1.07	0
MIROC 3.2 (hires)	0.83	1.59	0
MIROC 3.2 (medres)	0.76	1.17	0
MIUB ECHO-G	0.61	1.56	0
MRI CGCM 2.3.2a	0.81	1.78	0
NCAR CCSM 3	0.54	1.79	0
NCAR PCM1	0.55	2.11	0

It is well known that GCM are stronger in their ability to simulate temperatures compared to precipitation. This is also reflected in the Mean Square Error (MSE) as presented in Table 2. In order to overcome this deviation, all nine GCMs were downscaled using observations for precipitation and temperature, as will be discussed in the next sections.

3.4 Approach to downscaling

3.4.1 Data

Forcing data of the reference climate and nine GCMs are distributed at different resolutions. These resolutions need to be uniform for comparison reasons, and to force the PCRGLOB-WB model, which runs at a spatial resolution of 10 km. Therefore both the reference climate data and GCMs climate data need to be downscaled to a resolution of 10 km. The spline interpolation (Mitasova and Mitas, 1993) function in ArcMap was used to perform the spatial interpolation. This method was chosen because it uses a mathematical function that minimizes overall surface curvature, resulting in a smooth surface that passes exactly through the input points.

For the reference precipitation dataset TRMM[2] (Tropical Rainfall Measuring Mission) data were used. TRMM is the only satellite with an active precipitation radar onboard and has the following characteristics:

- The data is available at a high spatial resolution of 0.25 degrees (approx. 25 km).
- Daily datasets are available for the entire MENA region.
- The data cover the entire timespan from January 2000 through December 2009.

These data were made available by the Goddard Earth Sciences Data and Information Services Centre of NASA[3] (National Aeronautics and Space Administration).

For temperature and evapotranspiration data the NCEP/NCAR[4] Reanalysis 1 surface fluxes were taken. These data are used because:

- Data was available at a spatial resolution of 1.9 degrees. This was the smallest resolution available for average-, maximum- and minimum temperature for the desired period of time and region of interest.
- The temporal resolution is daily.
- It covers the entire current climate from January 2000 through December 2009.

These data were made available by the Earth System Research Laboratory (ESRL) of the National Oceanic and Atmospheric Administration[5] (NOAA). Reference evapotranspiration was calculated with the daily average, daily maximum and daily minimum temperature, using the method of Hargreaves (Hargreaves and Samani, 1985). This is a well-known method for the calculation of reference evapotranspiration, if only average temperature, maximum temperature and minimum temperature are available.

To address the impact of climate change, we used monthly climate data of nine GCMs, available for 2000-2050. The current study uses the IPCC A1B scenario, which has been used as input in these nine GCMs. These data were provided by the WCRP CMIP3 multi-model

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[2] http://mirador.gsfc.nasa.gov/cgi-bin/mirador/presentNavigation.pl?tree=project&&dataGroup=Gridded&project=TRMM&dataset=TRMM_3B42_daily.006&version=006&CGISESSID=0b5c99f25a40a58f0f7c5bb16841cfba

[3] http://www.nasa.gov/

[4] http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis.surfaceflux.html

[5] http://www.noaa.gov/

database[6], with a different spatial resolution for each GCM. This database was only used to retrieve the monthly GCM temperature data. For precipitation we used the monthly anomalies between 1961-1990 and 2046-2065, which were made available by the IPCC Data Distribution Centre[7]. These anomalies were based on the reference period 1961-1990, and were also made available by the IPCC Data Distribution Centre. The data which are used for the current and future climate are summarized in Table 3 and Table 4.

Table 3. Information about the forcing variables used for the current climate.

Forcing variable	Data source	Spatial resolution	Temporal resolution
Precipitation	TRMM	0.25 degrees	Daily
Average temperature	NCEP/NCAR Reanalysis 1: surface fluxes	1.9 degrees	Daily
Minimum temperature	NCEP/NCAR Reanalysis 1: surface fluxes	1.9 degrees	Daily
Maximum temperature	NCEP/NCAR Reanalysis 1: surface fluxes	1.9 degrees	Daily

Table 4. Information about the forcing variables used for the future climate.

Forcing variable	Data source	Spatial resolution	Temporal resolution
Precipitation	a) Anomalies between 2046-2065 and 1961-1990. IPCC Data Distribution Centre	Different, depending on the GCM	Monthly
	b) Reference period 1961-1990. IPCC Data Distribution Centre	Different, depending on the GCM	Monthly
Temperature	WCRP CMIP3 multi-model database	Different, depending on the GCM	Monthly

3.4.2 Preparing the reference data set

The water availability in the MENA region is evaluated with the use of a hydrological model as described in chapter 5. The model will be set-up to run at a spatial resolution of 10 km, with an Africa Albers Equal-Area projection (geographic coordinate system), and at a daily time-step. To make the forcing data for the reference period suitable as input for the hydrological model several steps need to be taken. The TRMM and NCEP/NCAR data are in a different geographic projection, and in different spatial and temporal resolution than what the model requires. Figure 7 shows schematically the steps taken to process the reference climate dataset. The final

[6] https://esg.llnl.gov:8443/index.jsp

[7] http://www.ipcc-data.org/ar4/scenario-SRA1B-change.html

results of this procedure are a daily time series from 2000 to 2009 for precipitation, air temperature and reference evapotranspiration.

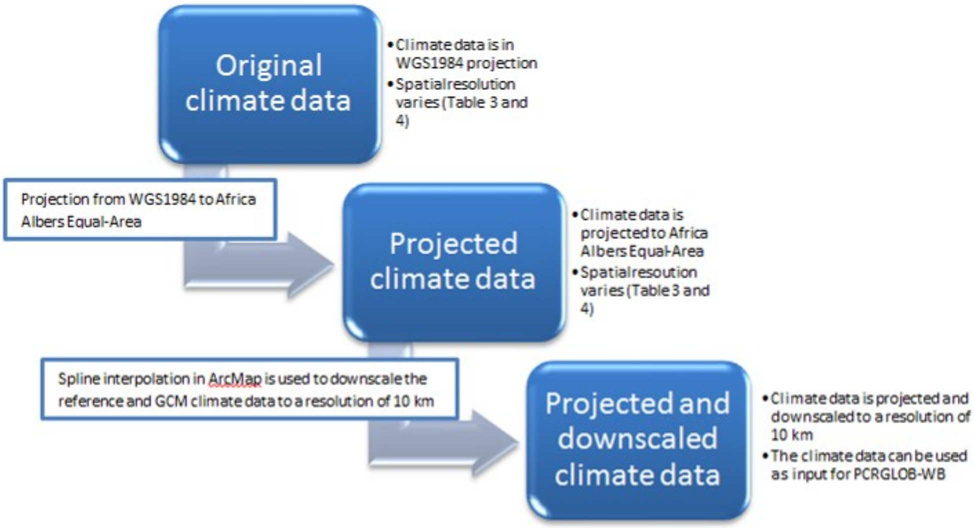

Figure 7. Processing steps to project and downscale the current climate forcing data.

3.4.3 Processing of future climate

The future climate from 2010 to 2050 for the A1B scenario for the nine different GCMs needs to be available at the same resolution (10 km) and time step (daily) as the reference period. In addition the data need to be statistically downscaled. The approach used is slightly different for temperature, reference evapotranspiration and precipitation.

To process the temperature date the following steps have been taken

1. For each GCM, a time-series with random years was created, based on the period 2000-2009. This means that for each year in the period 2010-2050, we have selected a random year from the period 2000-2009.
2. The average GCM temperature per month for the reference period 2000-2009 was calculated.
3. For each month in 2010-2050, we calculated the absolute difference in temperature with respect to the average value (step 2).
4. The temperature differences from step 3 were projected and downscaled (Figure 7).
5. For each day in 2010-2050, we calculated the new temperature value using.

$$TF_i = TR_i + \Delta T_{y,m}$$

Where: TF_i = Future temperature [°C] on day *i* [1-365];
TR_i = Temperature [°C] in random year on day *i* [1-365];
$\Delta T_{y,m}$ = Temperature difference [°C] for year *y* [2010-2050] during month *m* [1-12];

For the generation of the reference evapotranspiration the following steps have been taken:

1. For each GCM, a time-series with random years was created, based on the period 2000-2009. This means that for each year in the period 2010-2050, we have selected a random year from the period 2000-2009;

2. For each day in 2010-2050, we used the downscaled temperature and the minimum and maximum temperature from the specific day of the random year, to calculate the reference evapotranspiration (Hargreaves and Simani, 1985):

$$ETref_i = 0.0023 * 0.408 * RA * (TF_i + 17.8) * (TR\max_i - TR\min_i)^{0.5}$$

Where: $ETref_i$ = Future reference evapotranspiration [mm] on day i [1-365];
RA = Extraterrestrial Radiation;
TF_i = Future temperature [°C] on day *i* [1-365];
$TRmax_i$ = Maximum temperature [°C] in random year on day i [1-365];
$TRmin_i$ = Minimum temperature [°C] in random year on day i [1-365];

For precipitation a different procedure was chosen, because for precipitation a change factor is required instead of an absolute difference in precipitation. In the MENA there are extensive areas where monthly precipitation is close to zero. If we would calculate the anomaly (factor) between the monthly precipitation and the average precipitation for that month during 2000-2009, then it may happen that we divide by a very small (almost zero) value, resulting in erroneous large precipitation factors. If this would be interpolated to a resolution of 10 km, then large areas could be affected by these large factors. This means that in areas where precipitation should decrease in the future, it could instead increase due to the interpolation of these large factors.
Therefore we applied the following steps for the generation of daily GCM precipitation:

1. A time series with random years similar to temperature and reference evapotranspiration was generated.
2. The monthly anomalies of 2046-2065 were projected and interpolated to a resolution of 10 km.
3. The monthly reference precipitation of 1961-1990 were projected and interpolated to a resolution of 10 km.
4. For each month [1-12], the factor for that month was calculated by dividing the anomalies (result of step 2) by the reference precipitation (result step 3) for that month. The result is the precipitation factor.
5. This factor is applicable for the difference between 2046-2065 and 1961-1990, which is a period of approximately 80 years in length. Therefore we divided the factor of step 4 by 80, to retrieve the average in- or decrease in precipitation per year.
6. Finally, the new precipitation value is calculated using.

$$PF_i = PR_i + (PR_i * (y - 2009) * Pfac_m)$$

Where: PF_i = Future precipitation [mm] on day i [1-365];
PR_i = Precipitation in random year on day i [1-365];
y = Future year [2010-2050];
$Pfac_m$ = Precipitation factor in month *m* [1-12];

Selecting random years is necessary to produce a natural transient daily time-series of future climate data. We have selected a random year from the reference climate period 2000-2009 and we added the projected monthly anomalies for precipitation and temperature to this random climate year. If we would repeat the reference climate over the entire period, the time-series would show an unrealistic recurrence interval of 10 years (Figure 8). The selected random years were similar for the precipitation, reference evapotranspiration and the temperature.

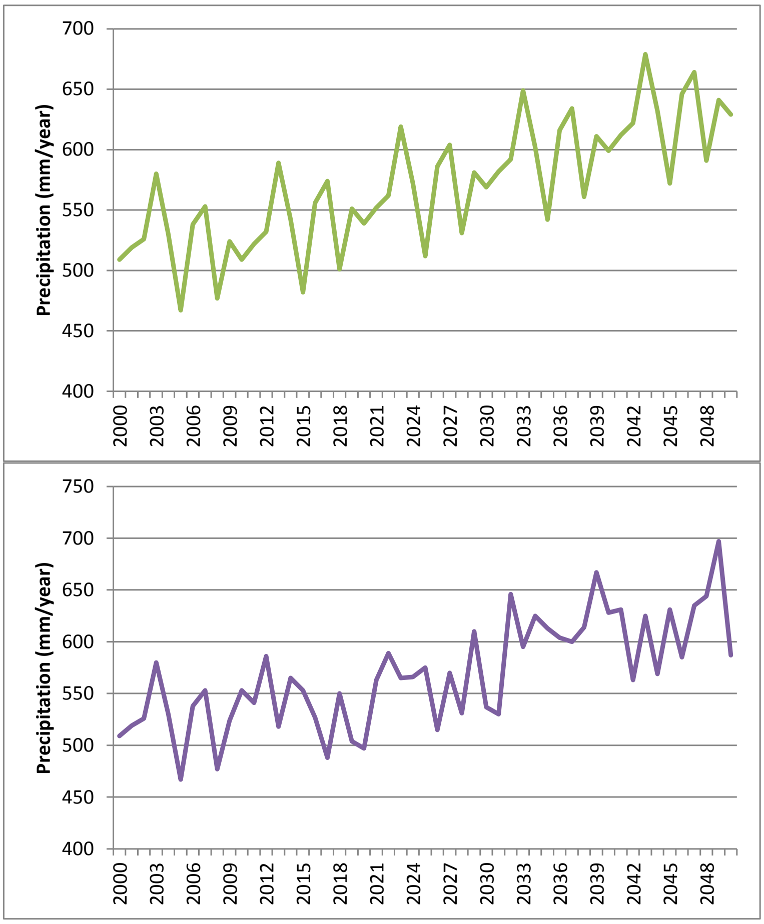

Figure 8. Example of downscaling climate change scenarios using a non-random approach (top) and a random approach (bottom).

3.5 Projected climate change in the MENA

3.5.1 Country averages and GCM variation

To quantify the change in precipitation for each country, we have calculated the average yearly precipitation sum for each country for the current climate (2000-2009), and for each GCM for 2020-2030 (P1), and 2040-2050 (P2). The results of this analysis are shown in Figure 9 for P1 and in Figure 10 for P2. These figures show for each country the variation in precipitation anomalies (P1 or P2, with respect to 2000-2009) between the 9 GCMs. The horizontal line represents the median of GCMs, while the low and high end of the box marks the 25-percentile and 75-percentile, respectively. The open circles represent a GCM which can be classified as an outlier.

According to Figure 9 it is clear that the majority of GCMs show a decrease in precipitation for most countries during 2020-2030. Decreases of 5-10% are quite common. In some countries, like e.g. Djibouti, Kuwait, Omar, and Yemen, also an increase in precipitation is shown among the GCMs. This is in good agreement with the results from all AR4 GCMS (Figure 6).

The variation among GCMs is larger during 2040-2050 (Figure 10). Again most countries are exposed to a decrease in precipitation, while for a few countries the GCMs show both a decrease and increase in precipitation. Decreases in P2 are larger than in P1, with the largest decrease calculated for Morocco. The uncertainty in precipitation change is largest for the United Arab Emirates.

For the reference evapotranspiration, the variations in anomalies are shown in Figure 11 and Figure 12 for P1 and P2 respectively. Most countries show an increase in reference evapotranspiration during P1, with the largest increase calculated for the Gaza Strip. A few countries show a decrease in reference evapotranspiration. These decreases, however, are very small (1-2%). It should be mentioned that this is related to the range between maximum and minimum temperature. The reference evapotranspiration becomes smaller if the range between the maximum and minimum temperature becomes smaller. As mentioned in Section 3.4.3, we use the maximum and minimum temperature of a random year, because the GCMs do not generate a daily maximum and minimum temperature. It seems that during the period 2020-2030, there are some random years where the range between the maximum and minimum temperature is small. This causes a small decrease in reference evapotranspiration for Egypt, Iraq, Jordan, Libya, Malta and Syria.

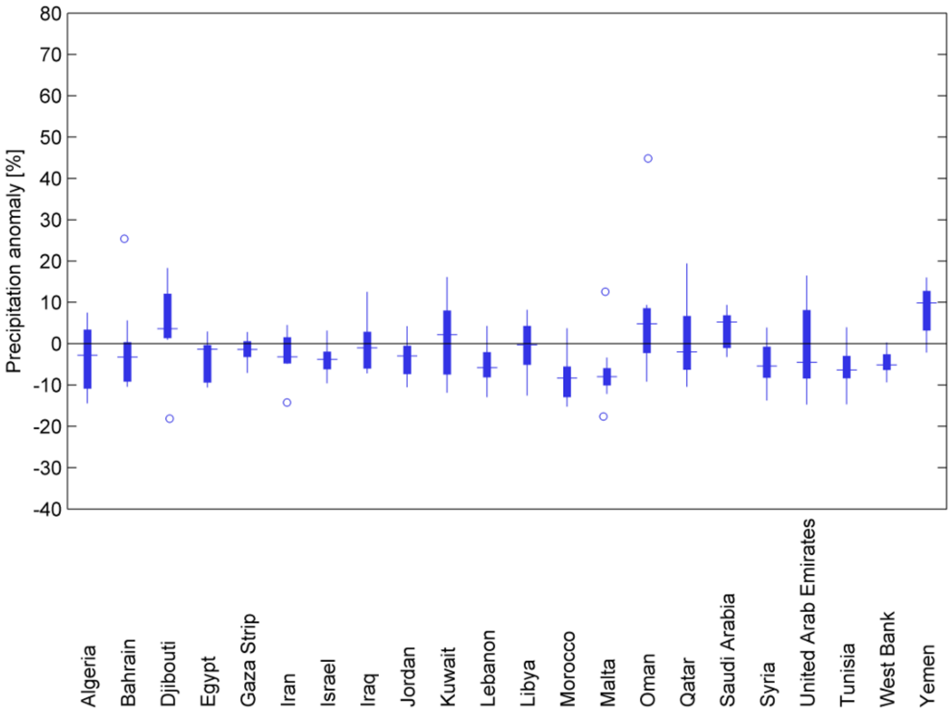

Figure 9. Precipitation anomalies [%] of 2020-2030 with respect to 2000-2009. Each box shows the variation between the nine GCMs, based on the average yearly precipitation sum.

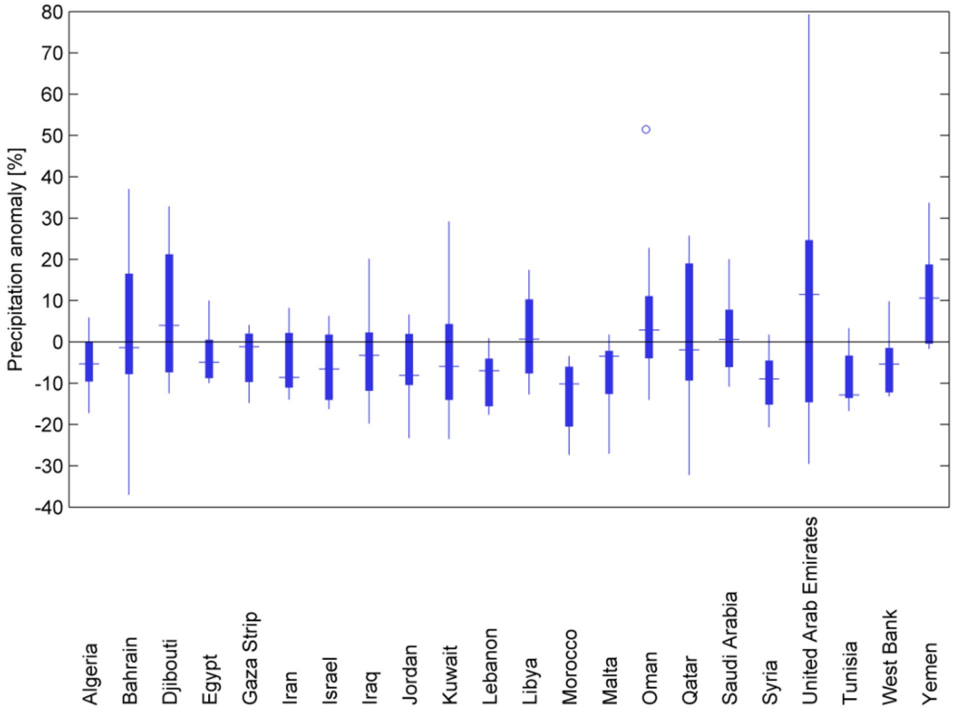

Figure 10. Precipitation anomalies [%] of 2040-2050 with respect to 2000-2009. Each box shows the variation between the nine GCMs, based on the average yearly precipitation sum.

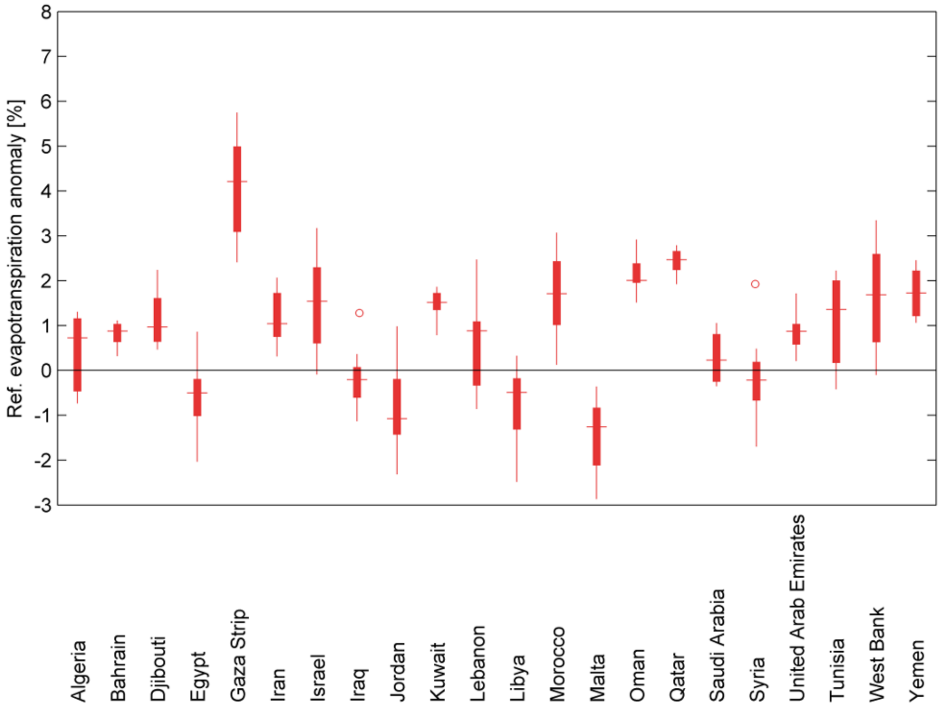

Figure 11. Reference evapotranspiration anomalies [%] of 2020-2030 with respect to 2000-2009. Each box shows the variation between the nine GCMs, based on the average yearly reference evapotranspiration sum.

The reference evapotranspiration is increasing for all countries during 2040-2050. The increase is larger than for the first period. Again the largest increase in reference evapotranspiration (6-7%) can be seen in the Gaza Strip. For the other countries the increase is in the range of 1-4%.

3.5.2 Time-series per country

The previous section discussed the range in anomalies between the nine GCMs for 2020-2030 and 2040-2050. It is also interesting to plot time-series of precipitation, temperature and reference evaporation for some selected countries. Typical examples of the analysis will be demonstrated for five countries: Algeria, Egypt, Israel, Morocco, and the United Arab Emirates. For each of these countries we have plotted a time-series of precipitation, temperature, and reference evapotranspiration for the period 2010-2050. These time-series are shown in Figure 13, Figure 14, Figure 15, Figure 16 and Figure 17 for the countries mentioned. The bold line in each graph represents the average of the 9 GCMs, while the low and high grey lines represent the 2nd lowest, and 2nd highest GCM, respectively. For each year the value is calculated as an moving average over five years.

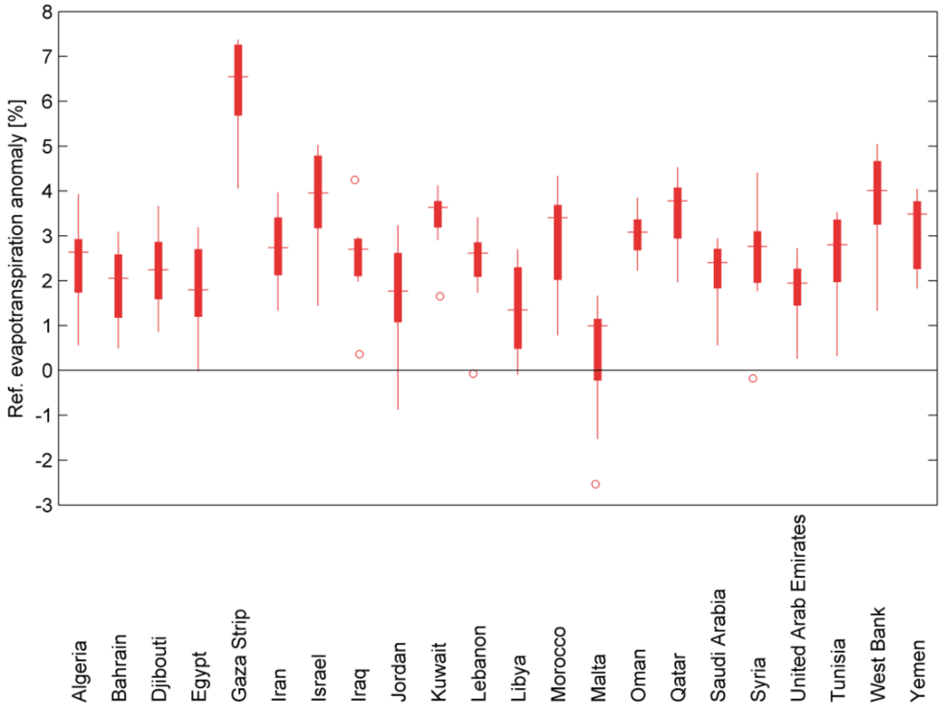

Figure 12. Reference evapotranspiration anomalies [%] of 2040-2050 with respect to 2000-2009. Each box shows the variation between the nine GCMs, based on the average yearly reference evapotranspiration sum.

For Algeria a small decrease in precipitation can be seen. This decrease is strongest during 2015-2025 and almost insignificant during 2025-2050. The climate signal for temperature and reference evapotranspiration is much stronger. Both temperature and the reference evapotranspiration show an increase from 2010 through 2050. The increase in average yearly temperature is approximately 1.5 °C. Reference evapotranspiration increases in the order of 100 mm.

Egypt is known to be a country with very small precipitation amounts. Due to climate change these precipitation amounts will become even smaller. The precipitation for Egypt shows a small decreasing trend for 2010-2020. For 2020-2050, the yearly precipitation sum is more or less constant, and fluctuates around 16 mm. If we consider the 2nd lowest GCM, then the decrease in precipitation is more obvious. Temperature and reference evapotranspiration again show an increase from 2010 through 2050, with the strongest increase during 2027-2050. Over the entire period, an increase of nearly 1.5 °C can be seen for temperature, and an increase of roughly 100 mm is noticed for the reference evapotranspiration.

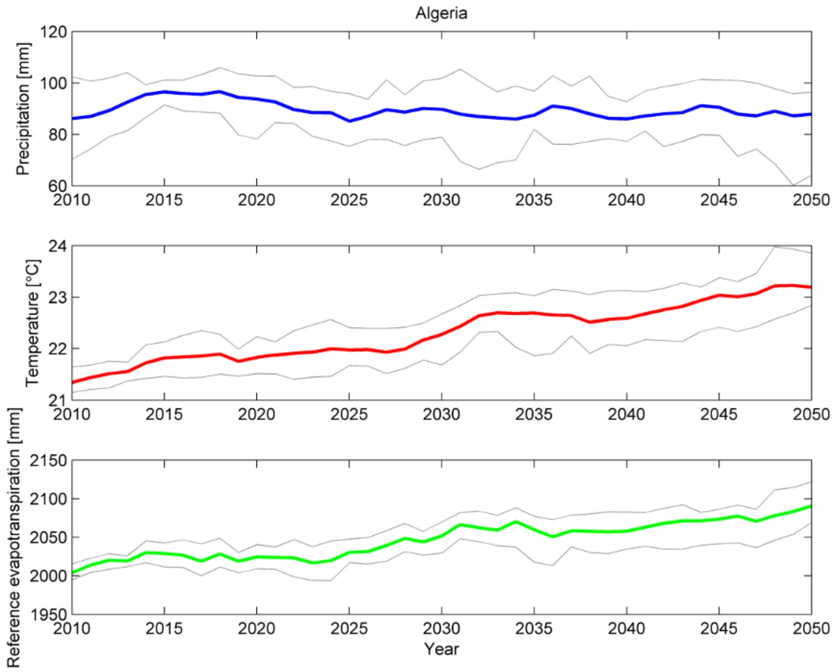

Figure 13. Moving average of yearly precipitation sum (top), average yearly temperature (middle), and yearly reference evapotranspiration sum (bottom) in Algeria. The bold line represents the average of 9 GCMs. The grey lines represent the 2nd lowest GCM and 2nd highest GCM.

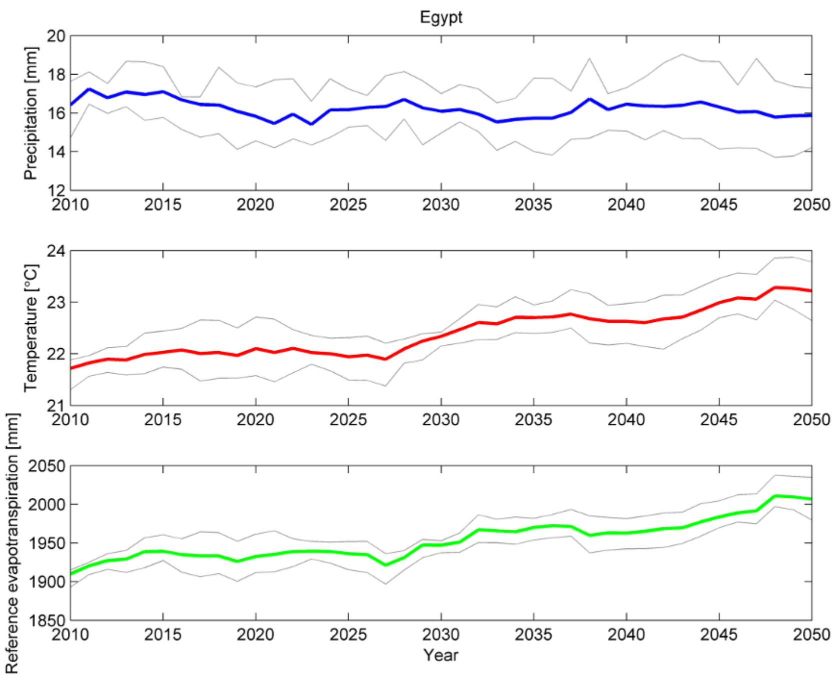

Figure 14. Moving average of yearly precipitation sum (top), average yearly temperature (middle), and yearly reference evapotranspiration sum (bottom) in Egypt. The bold line represents the average of nine GCMs. The grey lines represent the 2nd lowest GCM and 2nd highest GCM.

Israel shows a clear decrease in precipitation over the entire period. The yearly precipitation sum decreases approximately from 180 to 160 mm. The trends in temperature and reference evapotranspiration are comparable with those found in Algeria and Egypt: an increase of approximately 1.5 °C for temperature and nearly 100 mm for reference evapotranspiration.

In Morocco, precipitation increases slightly during 2010-2015. For the remainder of the period we notice a decrease in precipitation. If we consider the 2nd lowest GCM, however, then the decrease in precipitation is more obvious. It is clear that the range in precipitation between the GCMs is quite large. This is the case for all countries. The range between the GCMs is much smaller for temperature and reference evapotranspiration. It is known that the spatial variability of precipitation is much higher than for temperature and reference evapotranspiration, and therefore the uncertainty range for precipitation is larger among the GCMs. The temperature in Morocco increases roughly 2 °C, which is slightly higher than in Algeria and Egypt. Despite the higher increase in temperature, the reference evapotranspiration increases roughly with 75 mm, which is less than in Algeria and in Egypt.

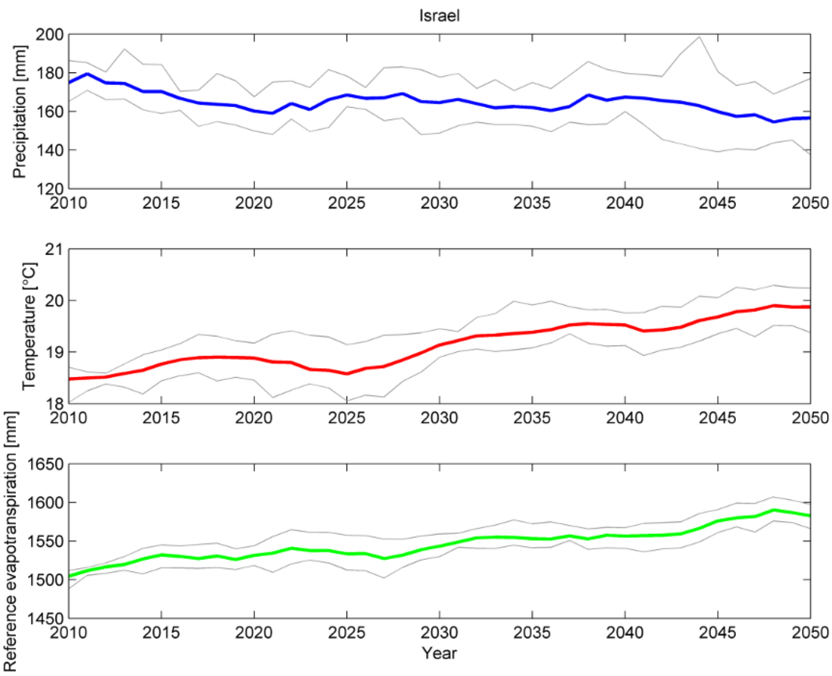

Figure 15. Moving average of yearly precipitation sum (top), average yearly temperature (middle), and yearly reference evapotranspiration sum (bottom) in Israel. The bold line represents the average of nine GCMs. The grey lines represent the 2nd lowest GCM and 2nd highest GCM.

In the United Arab Emirates the yearly precipitation sum is more or less the same during the entire period. Again the range between the 9 GCMs is large. For temperature there is almost a linear increase throughout the period 2010-2050. Temperature rises with approximately 1.5 °C. Also the reference evapotranspiration shows an increase during the entire period 2010-2050. The increase is more or less 100 mm, which is comparable to the increase in Algeria, Egypt, and Israel.

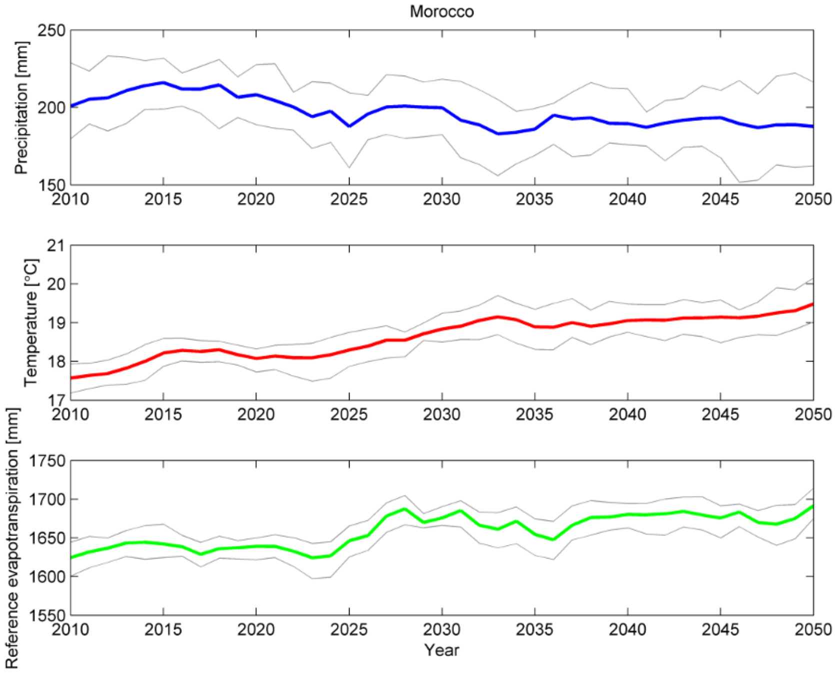

Figure 16. Moving average of yearly precipitation sum (top), average yearly temperature (middle), and yearly reference evapotranspiration sum (bottom) in Morocco. The bold line represents the average of nine GCMs. The grey lines represent the 2nd lowest GCM and 2nd highest GCM.

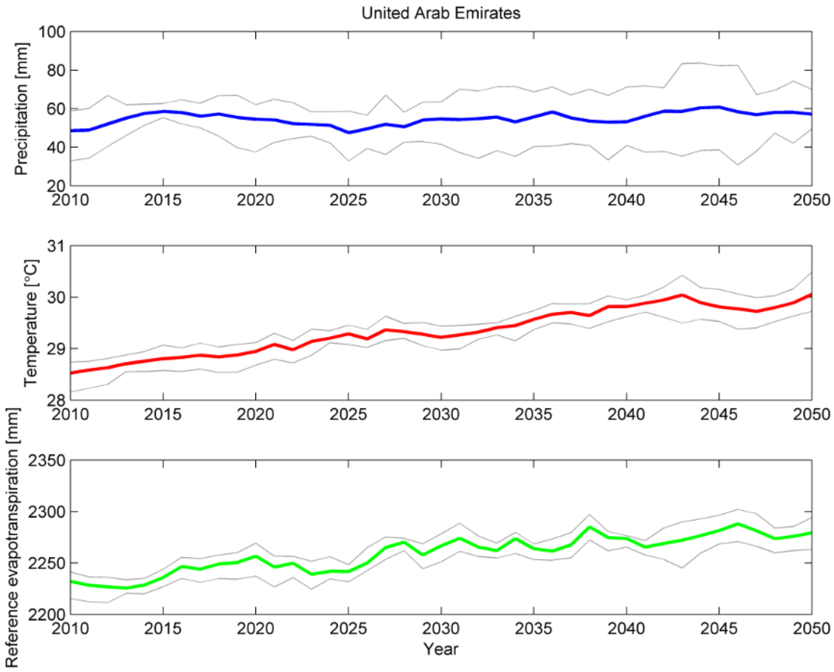

Figure 17. Moving average of yearly precipitation sum (top), average yearly temperature (middle), and yearly reference evapotranspiration sum (bottom) in the United Arab Emirates. The bold line represents the average of nine GCMs. The grey lines represent the 2nd lowest GCM and 2nd highest GCM.

3.5.3 Spatial climate projections

The previous two sections covered the climate change projections averaged per country. Within a country, however, it is likely that the climate projections are spatially not the same. For example, that temperature changes in coastal areas are likely to be smaller than temperature changes in the Sahara regions. To analyze the spatial climate projections within a country, we have calculated for the current climate per grid cell the average yearly precipitation sum, the average yearly temperature, and the average yearly reference evapotranspiration sum. The same is done for 2020-2030, and for 2040-2050. For the latter two, the anomalies with respect to the current climate have been calculated, to see whether there is an increase or decrease in the variable of interest. The results of this analysis are shown in Figure 18 for precipitation, in Figure 19 for temperature, and in Figure 20 for reference evapotranspiration.

It is obvious that in the majority of countries the annual precipitation sum for the current climate is low. Especially in Egypt and Libya the annual precipitation sum is very small (< 25 mm). The wetter areas are the coastal areas of Morocco, Algeria, Tunisia, Lebanon, Syria, Iran and Yemen. If we consider the period 2020-2030, then we see decreases in precipitation in nearly every country, with the largest decreases found in southern Egypt, Morocco, the central and coastal areas of Algeria, Tunisia, central Libya, Syria, and in the central and eastern part of Iran. Decreases are in the range of 5-15% for most countries, with a decrease of more than 20% in southern Egypt. In several regions, also increases in precipitation are noticed. Increases are in the range of 0-20%. It should be mentioned that the annual precipitation sum in these regions is very low, meaning that an increase of for example 20% in southeast Libya, means an annual increase of roughly 5 mm.

For 2040 through 2050 we see a larger decrease in precipitation for the majority of countries than for 2020 through 2030. Especially in Morocco, the central and northern part of Algeria, Tunisia, Syria, the southern and central part of Saudi Arabia, the northern part of Iraq, and in Iran, precipitation has decreased with respect to the current climate and 2020-2030.

If we consider the temperature projections (Figure 19), then it is clear that the MENA region is characterized by high average annual temperatures. Very high temperatures are found in the southwestern part of Algeria, the western and eastern part of Saudi Arabia, in Yemen, in Oman, and in the southern part of Iran. Temperature projections for 2020-2030 indicate a rise in temperature throughout all countries. The smallest increases in temperature (<0.15 °C) are found in North Libya, North Egypt, Israel, Lebanon, Jordan, and West Syria. The largest temperature increases (>0.65 °C) are found in the northern part of Morocco and Algeria, South Algeria, the southern part of Saudi Arabia and Iran, and in the central and northern part of Yemen and Oman.

Temperature projections for 2040-2050 indicate an even larger increase in temperature throughout the MENA region. An increase of more than 1.7 °C is not an exception. These findings are higher than the global average (Figure 5). The smaller temperature increases are found in the same regions as in the period 2020-2030. Large temperature increases (>1.5 °C) are found in the northern part of Morocco and Algeria, central and South Algeria, the central and southern part of Saudi Arabia, and in the northern part of Iraq, Iran and Yemen.

The last climate variable of interest is the reference evapotranspiration (Figure 20). A clear pattern of annual reference evapotranspiration is observable for the current climate. The coastal areas have the smallest annual reference evapotranspiration, while moving inland the reference evapotranspiration becomes higher. The largest annual reference evapotranspiration values

(>2200 mm) are found in South-West Algeria, South Egypt, Djibouti, the southeastern part of Saudi Arabia, the southern part of Iraq and Iran, North-East Yemen, and West Oman.

If we consider the anomalies for 2020-2030, then we notice a slight increase in annual reference evapotranspiration. This increase is in the range 0-1% for the largest part of the countries. Despite the lowest values of annual reference evapotranspiration found in the coastal areas, these areas are exposed to the largest (up to more than 9%) increase in annual reference evapotranspiration. In some countries, like for example in Algeria, Libya, Egypt and Jordan, we see a small decrease in annual reference evapotranspiration. This is caused by the range between the maximum and minimum temperature for the selected random year, as was already explained in Section 3.4.3. For 2040-2050 there is an increase in annual reference evapotranspiration in all countries, except for some small regions in Morocco, Libya, and Egypt. Again these decreases are very small. The highest increases are again found in the coastal regions, with increases of more than 9%.

3.6 Conclusions

Data from different GCMs were statistically downscaled for all MENA countries at 10 km resolution at a daily time step required for the water availability assessments. There is a vivid scientific debate on downscaling approaches of GCM output. Both dynamical and statistical methods are used and both have their advantages and disadvantages (Wilby, 1998). A recent study that deploys dynamic downscaling of GCM output in Morocco also reveals large uncertainties of the generated output (Soroshian, 2011). In addition dynamic downscaling using an ensemble of GCMs is impossible in this case, given the large area that would require enormous computation time. We have used robust and simple statistical downscaling procedures based on high resolution reference datasets and an ensemble of 9 different GCM which allows us to take into account inter-model variation and comply with the data requirements for the hydrological modeling. The GCMs were preselected based on past performance and our approach resulted for each GCM in a daily time series from 2010 to 2050 for the A1B emission scenario for precipitation, temperature and reference evapotranspiration.

The overall conclusion is that considerable changes in precipitation, temperature and reference evapotranspiration are projected for the MENA region. The findings are in line with the AR4 findings based on the 21 model analysis. For precipitation both increases and decreases are projected but the negative trend dominates in the countries with most rainfall (Morocco, Algeria, Syria, Iran).Yemen is an exception and an increase in precipitation is projected as the country is more under influence of the Eastern Africa climate system. However, the overall trend is a decrease in precipitation.

Both temperature and reference evapotranspiration show a consistent increase throughout the region. The strongest increases in reference evapotranspiration are identified along the Mediterranean coast and in Yemen and Oman.

In general it can be stated that climate change will affect the water resources in the MENA region from two sides. An overall decrease in precipitation in combination with a higher evaporative demand will reduce the water availability considerably.

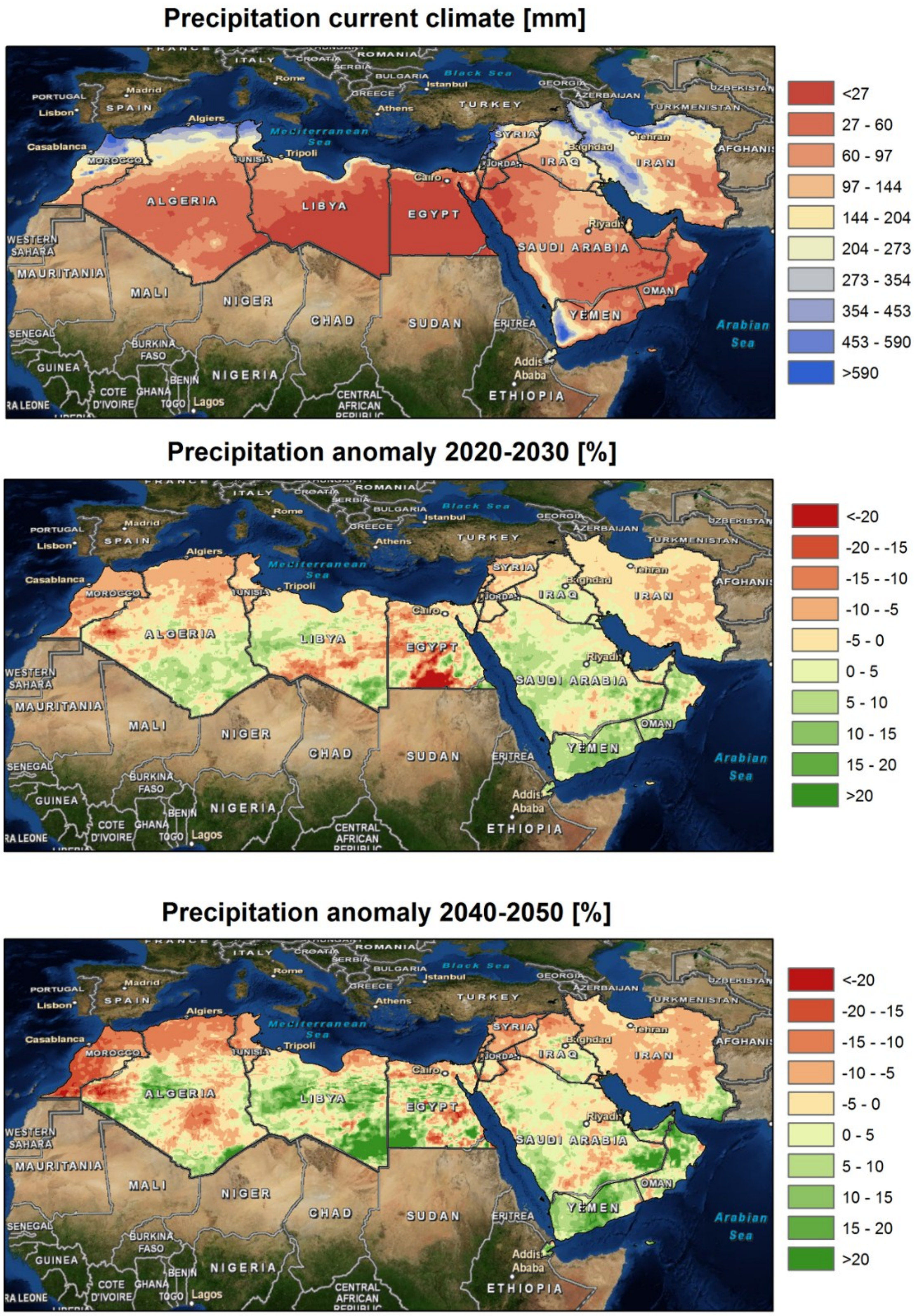

Figure 18. Spatial patterns of precipitation projections. Top: Average yearly precipitation sum of the current climate. Middle: Precipitation anomalies of 2020-2030 with respect to the current climate. Bottom: Precipitation anomalies of 2040-2050 with respect to the current climate.

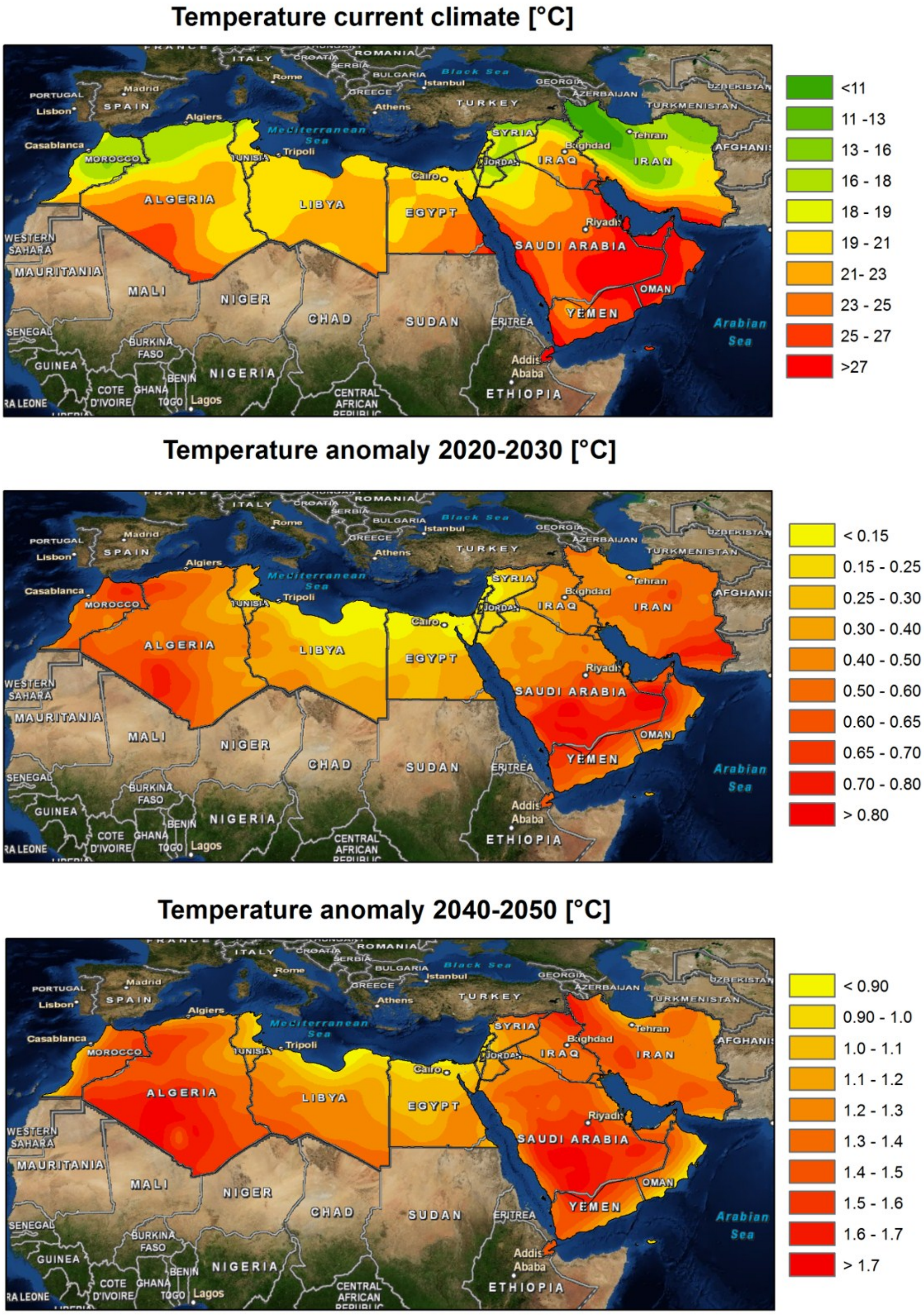

Figure 19. Spatial patterns of temperature projections. Top: Average yearly temperature of the current climate. Middle: Temperature anomalies of 2020-2030 with respect to the current climate. Bottom: Temperature anomalies of 2040-2050 with respect to the current climate.

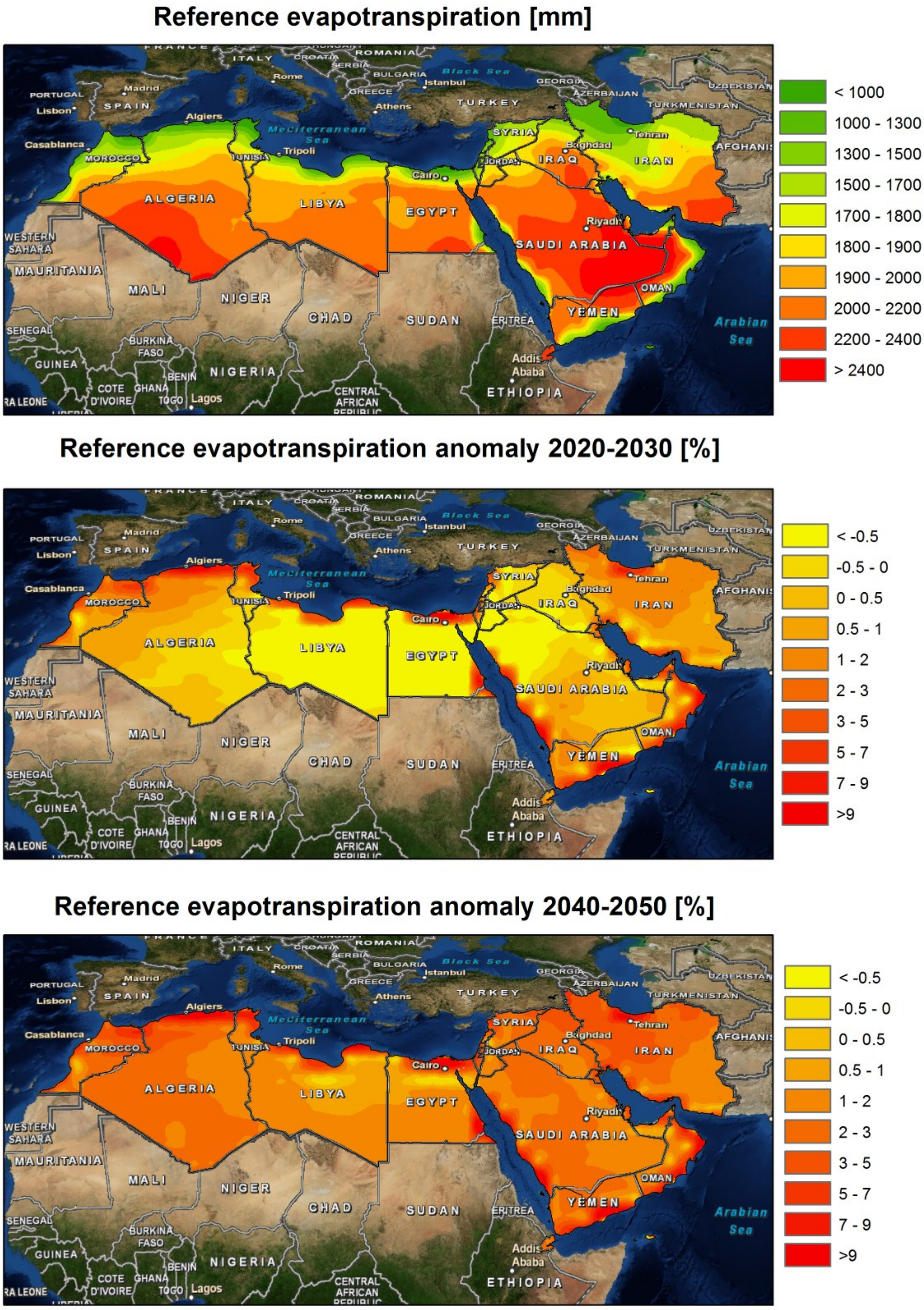

Figure 20. Spatial patterns of reference evapotranspiration projections. Top: Average yearly reference evapotranspiration sum of the current climate. Middle: Reference evapotranspiration anomalies of 2020-2030 with respect to the current climate. Bottom: Reference evapotranspiration anomalies of 2040-2050 with respect to the current climate.

4 Current and Future Water Demands

4.1 Irrigation water demand

4.1.1 Irrigation water requirements

The evapotranspiration of a crop under irrigation is obtained by multiplying the reference evapotranspiration (ETo) with a crop-specific coefficient (Kc). This coefficient has been derived for four different growing stages: the initial phase (just after sowing), the development phase, the mid-phase and the late phase (when the crop is ripening to be harvested). In general, these coefficients are low during the initial phase, after which they increase during the development phase to high values in the mid-phase again lower in the late phase. It is assumed that the initial phase, the development phase and the late phase each take one month for each crop, while the duration of the mid-phase varies according to the type of crop. For example, the growing season for winter wheat in Morocco starts in October and ends in April, as follows: initial phase: October (Kc = 0.4), development phase: November (Kc = 0.8), mid-phase: December - March (Kc = 1.15), and late phase: April (Kc = 0.3).

Evapotranspiration requirements of crops in irrigated agriculture are calculated by converting data of irrigated area by crop (at the national level) into a cropping calendar with monthly occupation rates of the land equipped for irrigation. Cropping calendars have been developed for each of the countries or country groups of the study. Table 5 presents as an example the irrigation cropping calendar for Morocco for the base year 2005/07.

Table 5 Cropping calendar in irrigation for Morocco for the base year 2005 / 2007

Crop under irrigation	Irrigated area (1000 ha)	Crop area as share (%) of the total area equipped for irrigation by month											
		J	F	M	A	M	J	J	A	S	O	N	D
Wheat	768	61	61	61	61						61	61	61
Maize	219			17	17	17	17	17					
Potatoes	61					5	5	5	5	5			
Beet	36				3	3	3	3	3	3			
Cane	14	1	1	1	1	1	1	1	1	1	1	1	1
Vegetables	145					12	12	12	12	12			
Citrus	80	6	6	6	6	6	6	6	6	6	6	6	6
Fruits	141	11	11	11	11	11	11	11	11	11	11	11	11
Fodder	120	10	10							10	10	10	10
Sum over all crops	1305	89	89	96	99	55	55	55	38	48	89	89	89
Equipped for irrigation	1258												
Total cropping intensity	127 %												

The rate of evapotranspiration coming from the irrigated area per month and per grid cell is calculated by multiplying the area equipped for irrigation with cropping intensity and crop evapotranspiration for each crop:

$$ETc(t) = IA * \Sigma c(CIc * Kc * ETo(t))$$

where:

ETc(t)	=	actual evapotranspiration of an irrigated grid cell in mm
IA	=	irrigated area in percentage of cell area for the given grid cell
c	=	crop under irrigation
Σc	=	sum over the different crops
CIc	=	cropping intensity for crop c
Kc	=	crop coefficient, varying for each crop and each growth stage

The difference between the calculated evapotranspiration of the irrigated area ETc and actual evapotranspiration under non-irrigated conditions ETa is equal to the consumptive use of water in irrigated agriculture in the grid cell, i.e. the net irrigation water requirement.

4.1.2 Irrigation water withdrawal

Assessing the impact of irrigation on water resources requires an estimate of the water effectively withdrawal for irrigation, i.e. the volume of water extracted from rivers, lakes and aquifers for irrigation purposes. Irrigation water withdrawal normally exceeds the consumptive use of irrigation because of water lost in its distribution from its source to the crops. The ratio between the estimated irrigation water requirements and the actual irrigation water withdrawal is usually referred to as "irrigation efficiency". Data on irrigation efficiencies are generally not easily available at field, irrigation scheme or river basin levels and only very scattered and unreliable information is available at country level. The use of the word "irrigation efficiency" is subject of debate. The word "efficiency" implies that all the water that exceeds the irrigation water requirements is wasted. In reality, however, this water can recharge aquifers or it can flow back to the river basin from where it can be re-used. It is for this reason that we use the term "water requirement ratio" (WRR) will be used to indicate the ratio between irrigation water requirements and the amount of water withdrawn for irrigation. The WRR is calculated as follows:

$$WRR = IWR / AWW$$

where:

WRR	=	water requirement ratio
IWR	=	irrigation water requirement, calculated
AWW	=	total agricultural water withdrawal, obtained from country surveys.

4.1.3 Future projections for irrigation

The basis for projection for irrigation is the map with areas equipped for irrigation (Siebert 2005). Projections for future areas under irrigation are based on data collected in two major FAO-databases: FAOSTAT and AQUASTAT. FAOSTAT is the main FAO statistics database that brings data together as collected from countries' statistical offices. AQUASTAT is FAO's information system on water and agriculture. In AQUASTAT, the value of irrigation potential is systematically compiled from national surveys. Irrigation potential, in combination with past trends, is an important indicator to help assessing future irrigation development. It is expressed in units of area and indicates how close the countries are from maximum extension of irrigated land. It refers to the extent of land suitable for irrigation and for which sufficient water is available. Methods to compute irrigation potential vary, however, from one country to another, and it is difficult to obtain a homogeneous assessment of this indicator across countries. In particular, in countries with abundant water resources, the concept of irrigation potential also includes some consideration of economic feasibility of irrigated land, therefore reducing the total amount of land with irrigation potential. In arid lands, however, the AQUASTAT country surveys have shown that countries had a fair and relatively detailed estimate of their irrigation potential. The irrigation potential was taken into account in projecting irrigation and the projections to 2050 assume that agricultural water demand will not exceed available water resources. However, the concept of irrigation potential is not static. It varies over time, in relation to the country's economic situation or as a result of increased competition for water for domestic and industrial use. In addition, estimates of irrigation potential also are based on renewable water resources, i.e. the resources replenished annually through the hydrological cycle. In those arid countries where mining of fossil groundwater represents an important part of water withdrawal, or where groundwater resources are over-exploited through depletion of the aquifers, the area under irrigation can be larger than the irrigation potential.

Assessment of area under irrigation in 2050 was done on a country basis, through an iterative process, on the basis of the "Agriculture towards 2050, AT2050" (FAO, 2006) estimates of aggregated agricultural demand. The AQUASTAT information base provided estimates of base year (2005/2007) values of land under irrigation, cropping patterns and cropping intensities in irrigation, and national projections for irrigation development in the forthcoming years. The AT2050 study provided estimates of aggregated agricultural demand in 2030 and 2050. On the basis of these estimates, in combination with information from the Global Agro-Ecological Zones database, areas under agricultural production and crop yields for irrigated were deducted, for the base year, 2030 and 2050. This information was used to derived a set of future crop factors and cropping intensities that were input in the model. The results for future irrigation water demand are shown in chapter 6.

4.2 Industrial water demand

For estimating both industrial and domestic water withdrawals use is made of AQUASTAT, and population and GDP projections. Population and GDP projections from the Center of for International Earth Science Network (CIESIN) of Colombia University are used (CIESIN, 2002). Population and GDP projections from the Center of for International Earth Science Network (CIESIN) of Colombia University are used (CIESIN, 2002). Figure 21 shows that the entire MENA population is projected to grow enormously from 316 million in 2000 to 697 million in 2050. Egypt and Yemen show the largest increase in population.

Future industrial water withdrawals (IWW) is a function of the gross domestic product (GDP) and GDP per capita (GDPP) according to the following equation (AQUASTAT, 2010):

$$IWWy = IWWy\text{-}1 * GDPy / GDPy\text{-}1 * GDPPy\text{-}1 / GDPPy$$

where IWW is the industrial water withdrawal. The rationale for this equation is that if a country produces more GDP, but it doesn't get richer per person (constant GDPP), industrial water demands will change equally to GDP. If the country also gets richer per person it is more inclined to safe water. Data on industrial water withdrawals during the reference period are taken from FAO's AQUASTAT database. It is assumed that 20% of the industrial water withdrawals are consumed and the remainders are return flows.

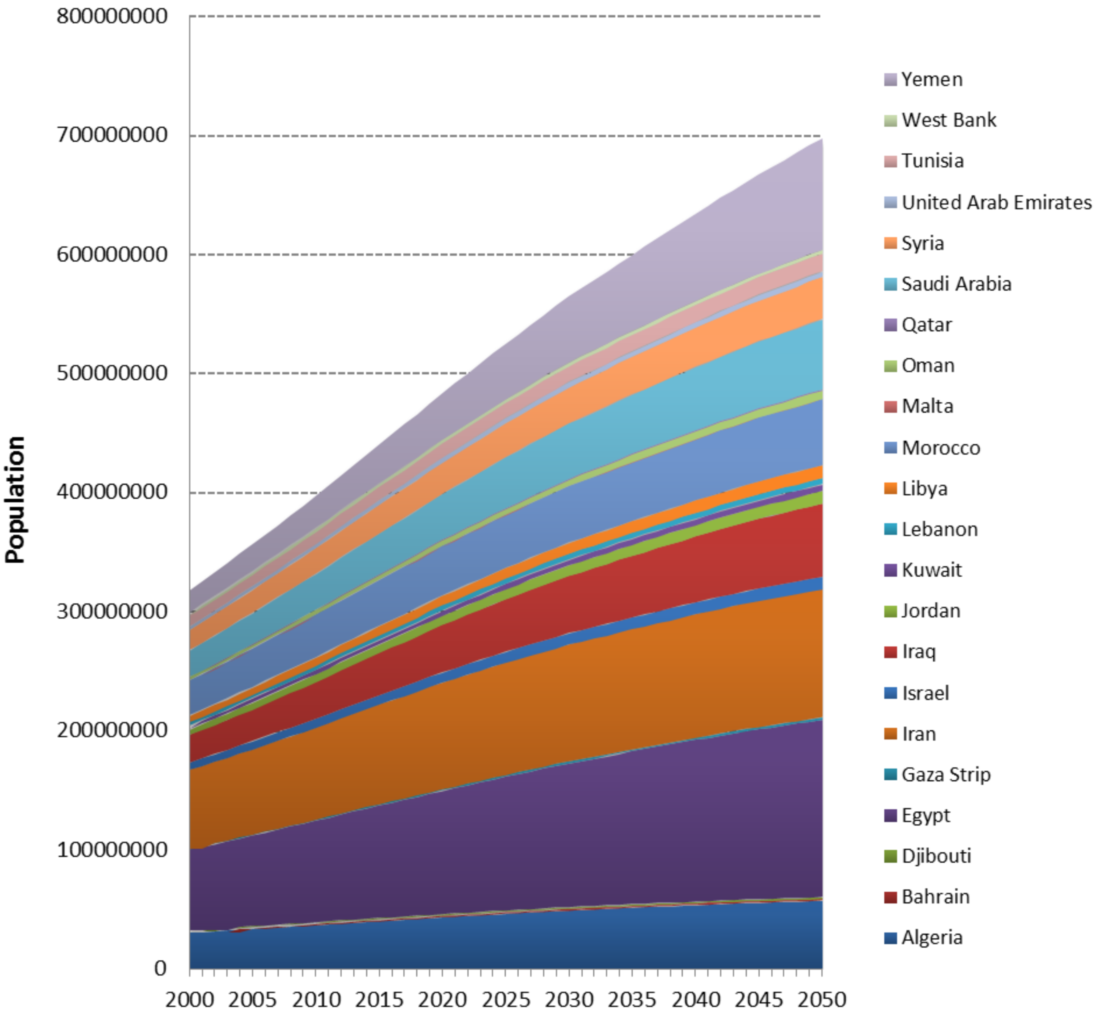

Figure 21 Projected population growth in the MENA region.

4.3 Domestic water demand

The domestic water demand is a function of the population and the GDPP. First a relation is identified between per capita domestic water withdrawal and the GDPP per country (Figure 22). The rationale behind this is that with increasing prosperity the domestic water withdrawals per capita will also increase (washing machines, bathrooms, watering gardens, swimming pools, etc.). The increase in water withdrawals is not linear but the growth rate reduces with increasing GDPP. Once the GDPP reaches 70.000 US$ it is assumed that the per capita water consumption remains constant. Theoretically it is possible that once people get very rich there will also be substantial investments in water saving technologies and per capita domestic water withdrawals would decrease. To date this has hardly observed in even rich and technologically advanced countries in the world and therefore we assume this not to be the case in the MENA region up to 2050.

For the USA the per capita domestic water use decreases only marginally, due to water saving washing machines, toilets etc. But the decrease is very slow and there is also a counter effect that people use more water for showering, washing cars, swimming pools and watering gardens. There is however no single proof that this will happen also in the MENA countries. The advances in technologies do not outweigh the increase for more domestic water requirements, especially for countries at relatively low GDP.

The approach followed here is exactly similar as the one applied by FAO to develop their domestic water demands as presented in AQUASTAT (FAO, 2010).

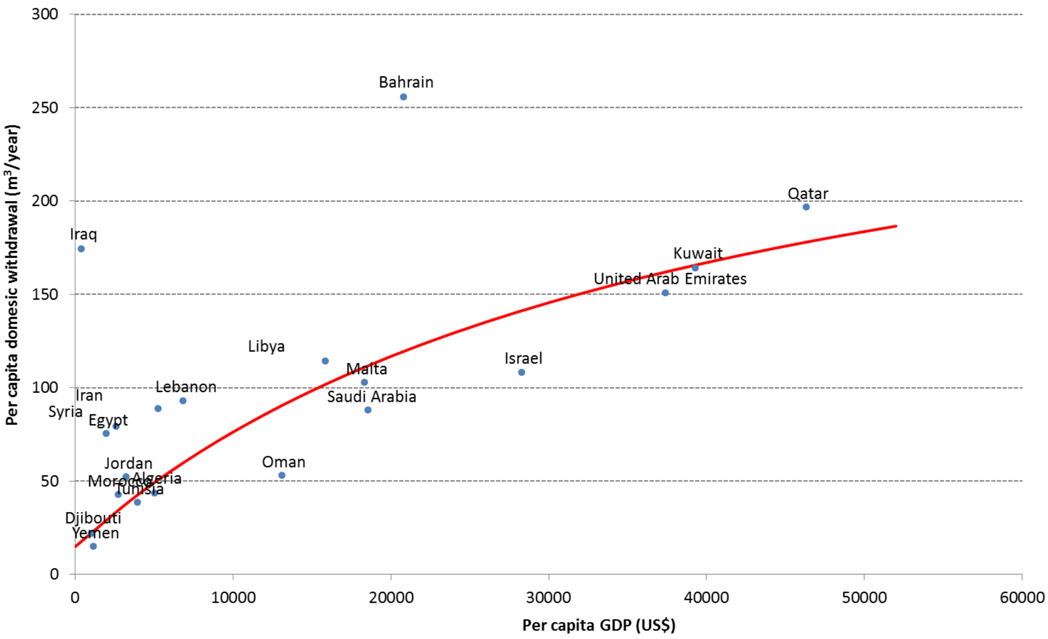

Figure 22. Relation between per capita domestic water withdrawals and GDPP (FAO, 2010).

Figure 22 shows that there is generally a clear relation and this relation is used in combination with population projections to estimate future domestic water withdrawals. Two countries do not match the curve. Both Iraq and Bahrain have a much higher per capita domestic water withdrawal than what can be expected on the basis of the GDPP. The GDPP in Iraq has suffered enormously from the war while domestic water withdrawals have remained constant as the infrastructure has been in place. Bahrain is a very small country and is a popular tourist destination in the GCC region. Tourism consumes a lot of water and this water is attributed to the small population of Bahrain, hence the high number. The reference data for domestic water withdrawals have been taken from the AQUASTAT database. It is assumed that 20% of the domestic water withdrawals are consumed and the remainders are return flows.

5 Current and Future Water Availability

5.1 Hydrological model description

5.1.1 PCR-GLOBWB

The current and future water availability is assessed using the PCR-GLOBWB hydrological model. The name PCR-GLOBWB stands for PCRaster Global Water Balance. The model is developed at the department of physical geography of Utrecht University in the Netherlands with the explicit aim to simulate terrestrial hydrology at macro-scales, under various land use and climate conditions with a temporal resolution of one to several days (Van Beek, 2009). This requires that the main terrestrial hydrological processes are described in a physically consistent way so that changes in storages and fluxes can be assessed adequately over time and space. Yet, the scarce and limited nature of the available data asks for a parsimonious model that preserves the physical basis of its parameterization. Therefore, a conceptual, dynamic and distributed model was preferred. The basic version of the PCR-GLOBWB model is written in the meta-language of the PCRaster GIS package (Wesseling et al., 1996). Its origins were based on the HBV-model (Bergström, 1995), with the basic difference that PCR-GLOBWB is fully distributed and implemented on a regular grid. The present model replaces much of its original process-descriptions with newer versions, which in turn were partly based on existing macro-scale hydrological models and common practice. Thus, the PCR-GLOBWB model forms part of a long-standing tradition whilst aiming to improve some recognized weaknesses in the description and parameterization of terrestrial hydrological processes at the macro-scale. The model was recently applied at a higher resolution in Asia with the aim to assess future water availability in large Asian river basins in relation to food security (Immerzeel, 2010).

5.1.1.1 Discretization

The model is implemented on a regular grid. The original global model is setup at a spatial resolution of 0.5°, however the model can be easily setup for specific domains at higher resolution. For the MENA region we set the model up at a spatial resolution of 10km. This is the optimum tradeoff between required detail for hydrological processes, data availability and calculation times. The cell values still represent averages over relatively large areas, but sub-grid variability is taken into account. The most fundamental subdivision is that of each cell into the open water surface and the land surface. The hydrological processes on the land surface (or soil compartment) are confined to a single cell. Within each cell, the parameterization is further subdivided on the basis of vegetation. A distinction is made between short and tall vegetation since tall vegetation more effectively draws water from deeper in the soil and generally incurs higher interception losses. Where a distinction is made between land cover types at the sub-grid level, state variables are stored as the cell average.

5.1.1.2 Processes

PCR-GLOBWB simulates the most direct pathways of water that reaches the Earth surface back to the ocean or atmosphere (Figure 23); within each cell precipitation in the form of rain or snow either falls on soil or in open water surface.

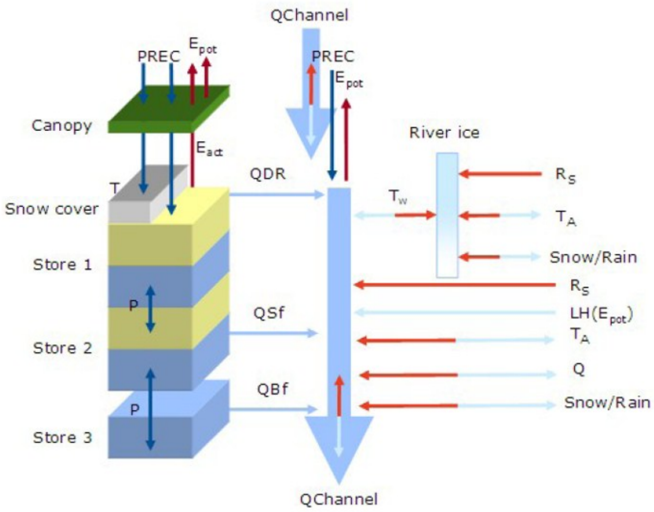

Figure 23. Model concept of PCR-GLOBWB.

Figure 23 shows the model concept of PCR-GLOBWB. The left side shows the soil compartment, which is divided in the two upper soil stores and the third groundwater store, and their corresponding drainage components: direct runoff (QDR), interflow (QSf) and base flow (QBf). In the center of the figure, the resulting discharge along the channel (QChannel) with lateral in- and outflow and local gains and losses are depicted. On the right, the energy balance for the open water surface and the possible formation of ice are shown. Any precipitation that falls on the soil surface can be intercepted by vegetation and in part or in whole evaporated. Snow is accumulated when the temperature is sufficiently low, otherwise it melts and adds to the liquid precipitation that reaches the soil as rain or through-fall. A part of the liquid precipitation is transformed in direct or surface runoff, whereas the remainder infiltrates into the soil. The resulting soil moisture is subject to soil evaporation when the surface is bare and to transpiration when vegetated; the remainder contributes in the long-term to river discharge by means of slow drainage which is subdivided into subsurface storm flow from the soil and base flow from the groundwater reservoir.

5.1.2 Model domain

The MENA (Middle East and North Africa) region includes 21 countries according to the World Bank definition and will be used for this study. Given the different nature of West Bank and Gaza they have been separately analyzed in this study, resulting in the following 21 regions (countries)[8]:

- Algeria
- Bahrain
- Djibouti
- Egypt
- Gaza Strip
- Iran
- Iraq
- Israel
- Jordan
- Kuwait

[8] For clarity these 22 regions will be referred to as “countries” in this report.

- Lebanon
- Libya
- Malta
- Morocco
- Oman
- Qatar
- Saudi Arabia
- Syria
- Tunisia
- United Arab Emirates
- West Bank
- Yemen

To assess the availability of water resources in the MENA region it is necessary to include the upstream river basins of all MENA countries in the model domain. To identify the upstream areas an overlay was made with a map with major drainage basins derived from the Hydro1K database developed at the EROS data center of the U.S. Geological Survey. The proposed model domain for the hydrological assessments is shown in Figure 24. The model domain extends relatively far to the south to include the entire Nile basin boundary. The size of the model domain is 8860 km x 5250 km.

Figure 24. Model domain of the MENA hydrological model (red box). MENA countries are shaded. Red dots show the location of the GRDC station used for calibration.

The optimal model resolution is a tradeoff between the detail of the available input data, the desired output resolution, the physical detail of the model and calculation times. Given these constraints and previous experiences we use a model resolution of 10 km^2 (886 x 525 cells). By using this resolution calculation times are within acceptable limits, errors due to sub-grid variability of hydrological processes are limited and there is reasonable agreement with the level of detail of the available model input.

5.1.3 Data sources

For every grid cell of the model data on the elevation, land use, soils and irrigation practices are required and the model is driven by daily fields of precipitation, air temperature and reference evapotranspiration. These data sets and the major assumptions are summarized hereafter, but a full description on model parameterization may be found in Van Beek (2009).

5.1.3.1 Topography

To determine the distribution of elevation within each 10x10 km grid cell use was made of the HYDRO1K database[9]. HYDRO1k is a geographic database developed to provide comprehensive and consistent global coverage of topographically derived data sets, including streams, drainage basins and ancillary layers derived from the USGS 30 arc-second digital elevation model of the world. HYDRO1k provides a suite of geo-referenced data sets, both raster and vector, which will be of value for all users who need to organize, evaluate, or process hydrologic information on a continental scale. The HYDRO1K dataset provides hydrologically correct DEMs along with ancillary data sets for use in continental and regional scale modeling and analyses.

5.1.3.2 Land use

The model requires information on the fraction of tall and short vegetation for each grid cell, monthly crop factors, monthly fractional vegetation covers and monthly maximum interception storage. This information is derived from the Global Land Cover Characterization (GLCC) database[10]. The U.S. Geological Survey (USGS), the University of Nebraska-Lincoln (UNL), and the European Commission's Joint Research Centre (JRC) have generated this 1-km resolution global land cover characteristics data base for use in a wide range of environmental research and modeling applications. The global land cover characteristics database was developed on a continent-by-continent basis are based on 1-km Advanced Very High Resolution Radiometer (AVHRR) data. The data has been subjected to a formal accuracy assessment.

5.1.3.3 Soil

The model requires different soil physical properties for both soil layers. These properties are derived from the FAO gridded soil map of the world (FAO, 1998). Most prominent features that are required are depth of the soil layers, saturated and residual volumetric moisture contents, saturated hydraulic conductivity and total storage capacities.

5.1.3.4 Irrigated areas

The map with irrigated areas developed by FAO and Kassel University has been used in this project (Siebert et al., 2007). The first version of this map was developed in 1999 but it has been updated continuously. In this study version 4.0.1 was used, which is the most recent

[9] http://eros.usgs.gov/

[10] http://edc2.usgs.gov/glcc/glcc.php

version that was released in 2007. The map (Figure 25) shows the amount of area equipped for irrigation around the turn of the 20th century in percentage of the total area on a raster with a resolution of 5 minutes. The area actually irrigated is smaller, but is varies annually for most countries. How these areas are used in determining water consumption from irrigated agriculture is discussed in 4.1. Figure 25 shows the major irrigation schemes in the MENA clearly: The Nile basin in Egypt, the Euphrates and Tigris basin in Iraq, Central Saudi Arabia, and the Sebou and Oum el Rbia systems in Morocco.

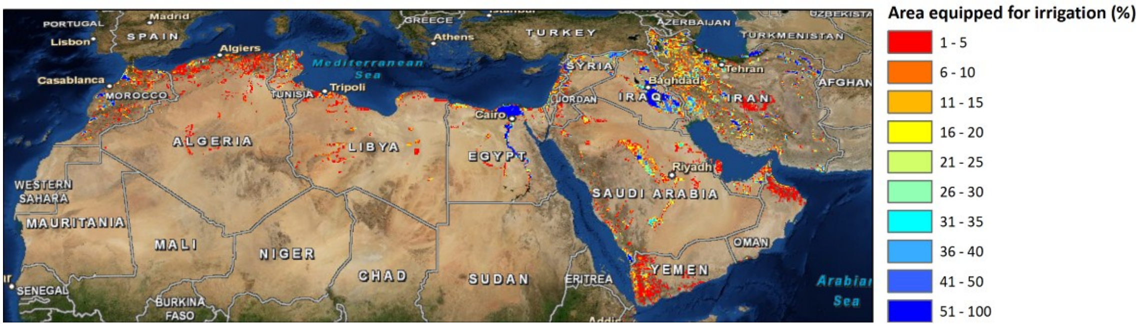

Figure 25. Percentage of pixel equipped for irrigation (source: Siebert et al., 2007).

5.2 Model validation

5.2.1 Observed river flow

The original PCR-GLOB model has been demonstrated to perform well. It was however selected to assess the performance of the fine-scaled model as developed for this study as well. Given the size of the MENA region domain it is not feasible to calibrate the model in detail for each river in the MENA region. For a number of major rivers in the model domain we have calibrated the average annual river discharge. Observed data were downloaded from the Global Runoff Data Centre[11] (GRDC). Due to the absence of recent river flow data the river climatology (e.g. long term average discharge) was used to calibrate the model assuming that if the long term average hydrology is simulated well the model can be trusted to assess future changes in water availability. Moreover, it has been proven that relative model accuracy (= difference between current situation and scenario) is always much higher than relative model accuracy (difference between model output and observations) (Droogers et al., 2008).

Figure 26 shows the results of the calibrated stream flow. There is a very good match between observed and simulated flow and therefore we conclude that model is able to accurately simulate the average hydrological conditions. In the original model there was however one exception for the river Nile in El Ekhsase. The simulated flow in El Ekhsase (2600 m^3/s) was higher than the observed river flow (1250 m^3/s), while the simulated flows in the Blue and White Nile in Khartoum in Sudan agree well with the observed flows. The fact that Blue Nile, White Nile and Atbara tributaries are simulated well is unique as most model studies have severe problems in accurately simulating these rivers (Mohamed et al., 2005). The difference in observed and simulated river flow in the Nile at El Ekhsase can be explained by the following reasons:

[11]http://www.bafg.de

- El Ekhsase is located in the Nile delta and considerable amount of irrigation water are abstracted from the Nile between Khartoum and El Ekhsase (Gezira scheme in Sudan and the Nile delta)
- There is a very significant loss of water in the complex system of the Sudd wetland in Sudan (Mohamed et al., 2006). The Sudd wetland with an approximate area of 35000 km^2 evaporates about half of its inflow.
- There is a significant water loss from Lake Nassar (Aswan dam) in the order of 10 km^3 y^{-1}.

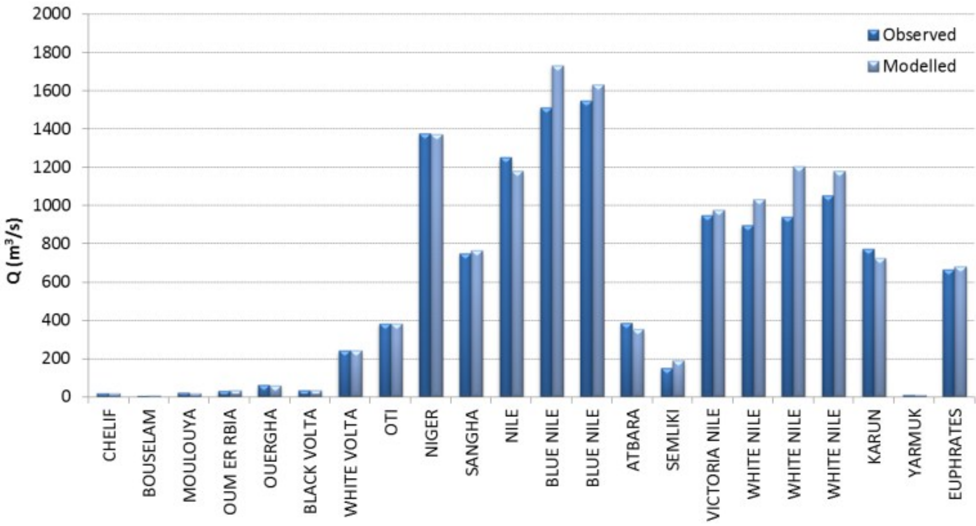

Figure 26. Average annual observed and simulated flow.

To verify this we corrected for irrigation water loss and evaporation from the Sudd and Lake Nassar and compared the corrected Nile flow with water releases from the Aswan dam. Figure 27 shows the water balance of the “natural” river flow at Aswan. It shows that in total 69.7 km^3 is released at Aswan.

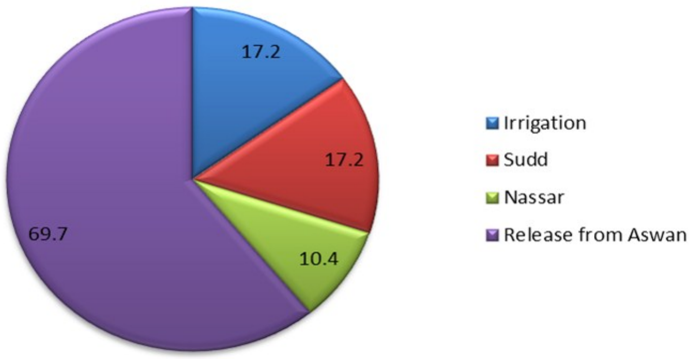

Figure 27. Water balance components of Nile flow at Aswan in km^3.

In Figure 28 the monthly releases from Aswan are shown based on the above described correction. It should be noted that the simulated data series is based on the 2000-2009 PCRGLOB-WB simulation and the observed time series is based on the 1871-1984 time series. It can be concluded that the average monthly flow is well simulated, especially considering the large inter-annual variation in streamflow and the difference in reference period. The average annual simulated release is 69.7 km^3 and the observed release is 87.1 km^3. According to the Nile Water Agreement of 1929 Egypt is entitled to 55.5 km^3 annually.

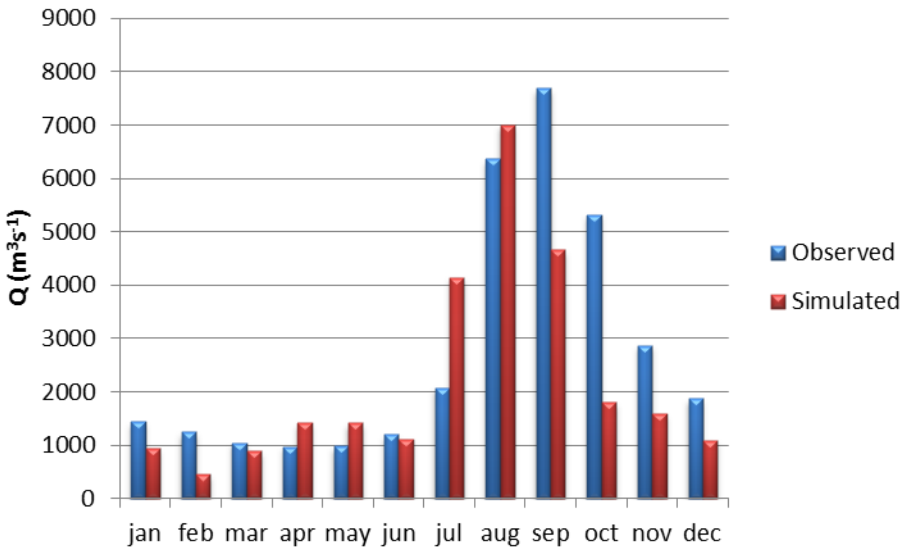

Figure 28. Monthly simulated (2000 to 2009) and observed releases from Aswan (1871-1984).

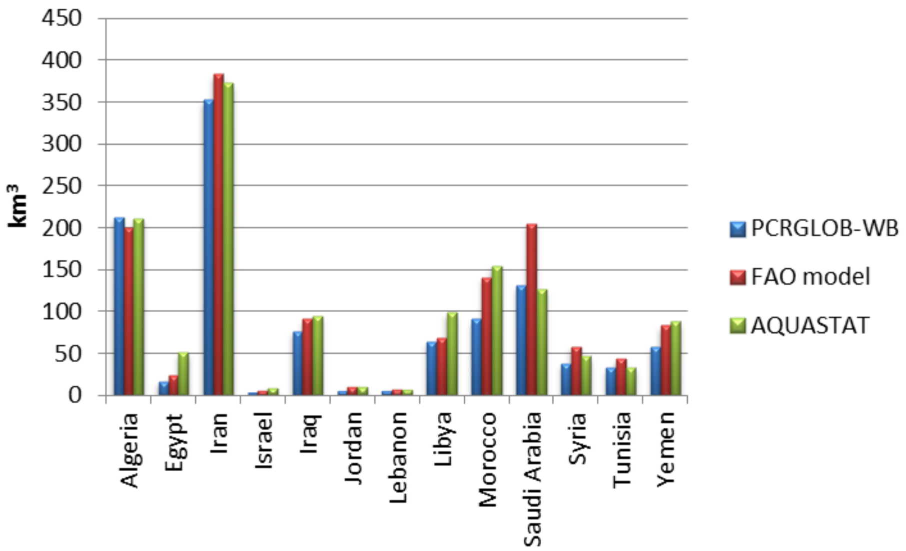

Figure 29. Long term annual precipitation (2000-2009) for some selected countries compared between PCRGLOB-WB, FAO model and AQUASTAT.

In addition, the model outputs from the current study are also compared to AQUASTAT statistics and outputs from a simple water balance model from FAO. These results are shown in Figure 29, Figure 30 and Figure 31. In general there is reasonable agreement between the three data sources. There are some deviations but these can be explained by the different approaches. First of all the PCRGLOB-WB simulations are based on a slightly different period than the other two sources. However, the main reasons are that results of the current study are based on a more rigirous approach than followed in AQUASTAT. For example, the precipitation in Morocco is lowest for PCRGLOB-WB because it is based on TRMM, which provides spatial patterns including the desert areas of Morocco. The other two sources are merely based on average station data, which are not located in the desert and as such the average annual precipitation is higher. Also, the results from the current study refelect a period of 10 years rather than based on an “average” year. Given the highly non-linear processes in hydrology this is of paramount importance. Moreover, the results of the current study are based on daily processe, which is of paramount importance in terms of rainfall-runoff processe. Finally, the PCRGLOB-WB model is far more comprehensive than the simplified model used to generate the AQUASTAT data.

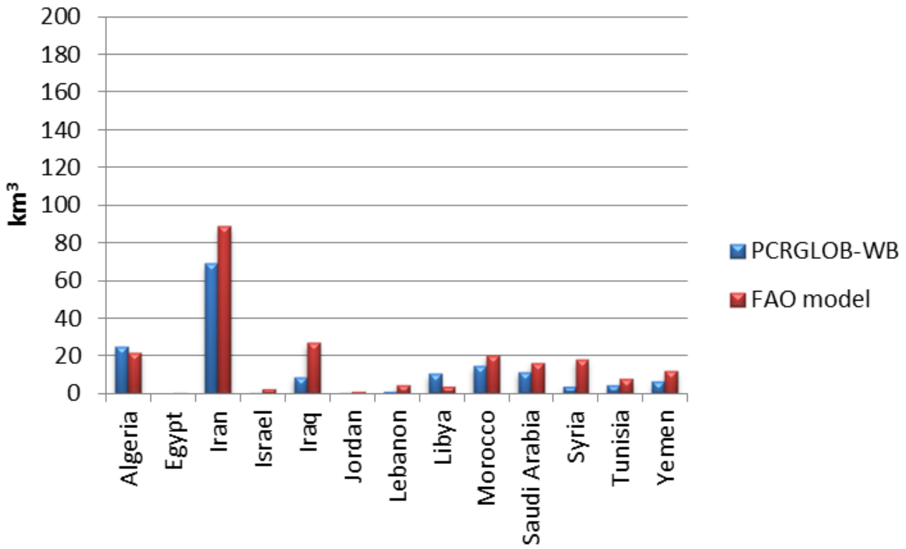

Figure 30. Long term annual average runoff (2000-2009) for some selected countries compared between PCRGLOB-WB, FAO model and AQUASTAT.

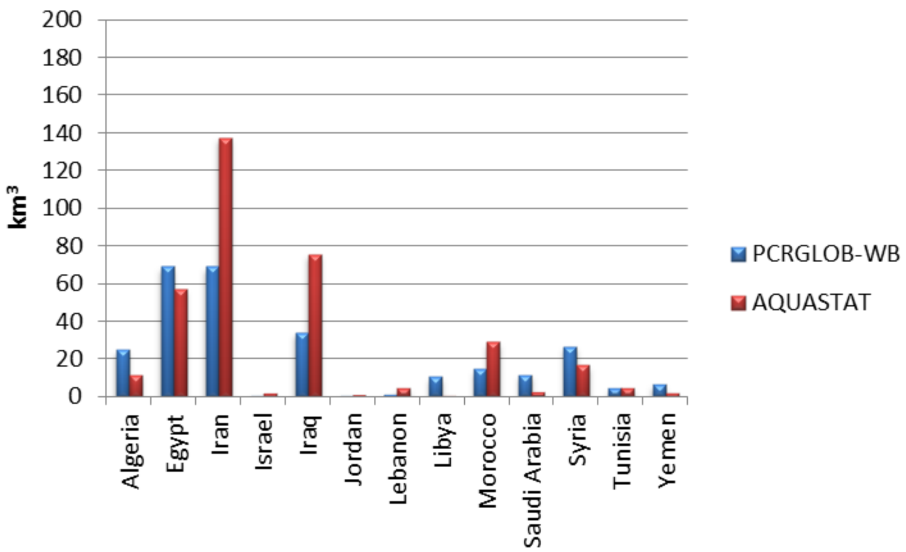

Figure 31. Long term annual total renewable water resources (2000-2009) for some selected countries compared between PCRGLOB-WB, FAO model and AQUASTAT.

5.3 Current water availability

The current MENA water availability is assessed based on model simulation for the period 2000 to 2009. Figure 32 shows the precipitation in mm per country averaged over this period. There is great variation in precipitation across the region ranging from just over 10 mm y^{-1} in Egypt to over 500 mm y^{-1} in Lebanon. On the left side of the figure the total precipitation is shown in absolute amounts (km^3) and then it is observed that Iran is the wettest and on average receives nearly 400 km^3 of precipitation and that Saudi Arabia is also among the wetter countries because of the large area. It is important to take this difference into account.

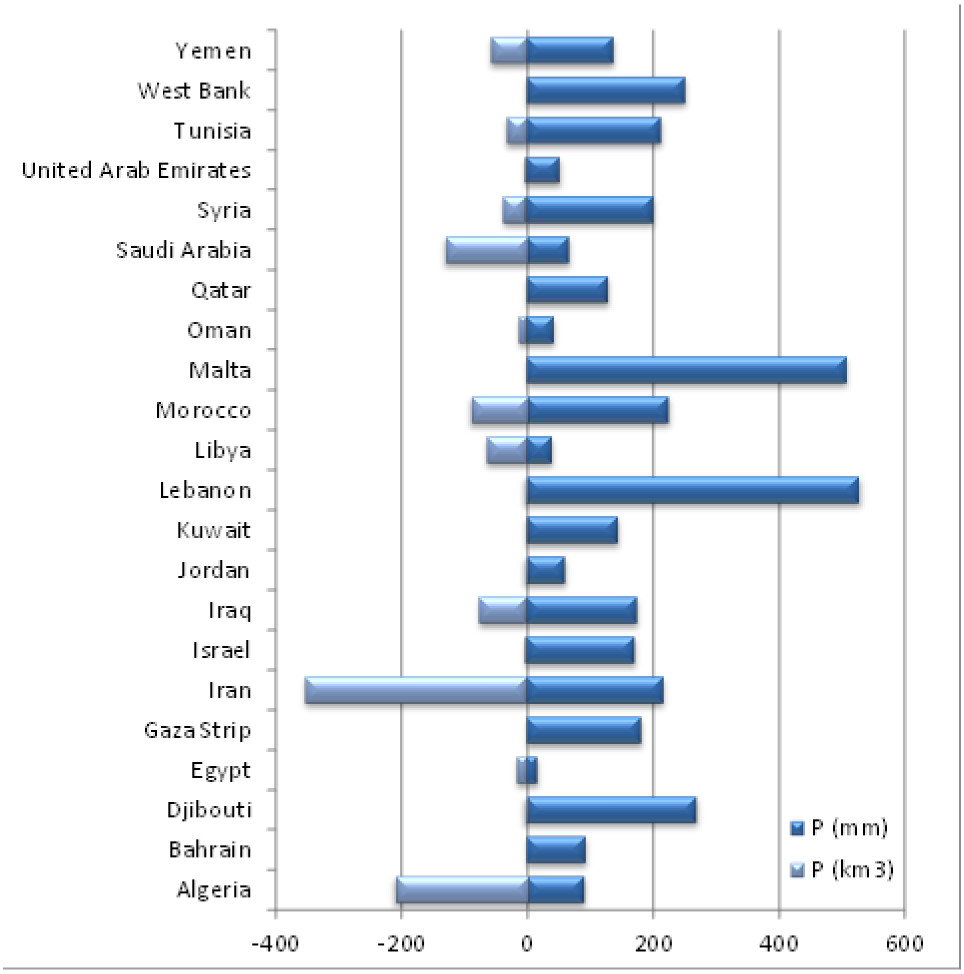

Figure 32 Average annual precipitation in mm (dark blue) and km^3 (light blue) per MENA country.

In addition to total rainfall inter-annual rainfall variability is also a crucial factor in assessing water stress. Figure 33 shows the coefficient of variation (CV) in annual precipitation from 2000 to 2009. On average the CV is around 30%, but some countries show exceptional variation such as Morocco, Tunisia, Oman and Djibouti where the CV is around or above 40%. Countries with a high variation in precipitation require a higher adaptive capacity (e.g. more reservoir storage).

Figure 33. Coefficient of variation in annual precipitation from 2000 to 2009.

The ratio between annual precipitation and the reference evapotranspiration is a measure for the aridity. The reference evapotranspiration determines the water requirements and is a function of temperature, radiation, wind speed and relative humidity. Figure 34 shows the aridity index for the MENA region. Very large parts of the region are hyper arid to very arid. The Mediterranean coast line, Yemen, North-Eastern Iraq and Iran are an exception and are classified as semi-arid.

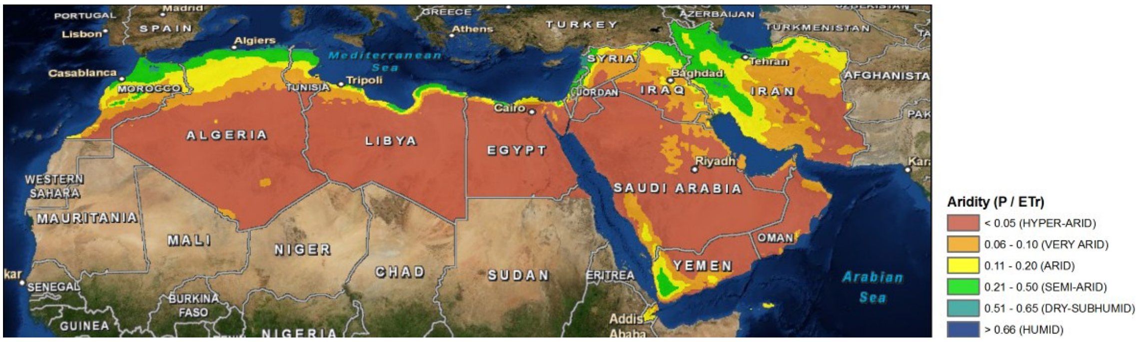

Figure 34. Aridity Index based on 2000 – 2009 climatology.

More relevant than the precipitation is the amount of internal and external renewable water resources that are generated, and which become available to cover the countries water demands. Figure 35 show the total internal renewable water resources for the region. Again a great variation across the region is observed and the highest values are found in Morocco, Yemen and Iran.

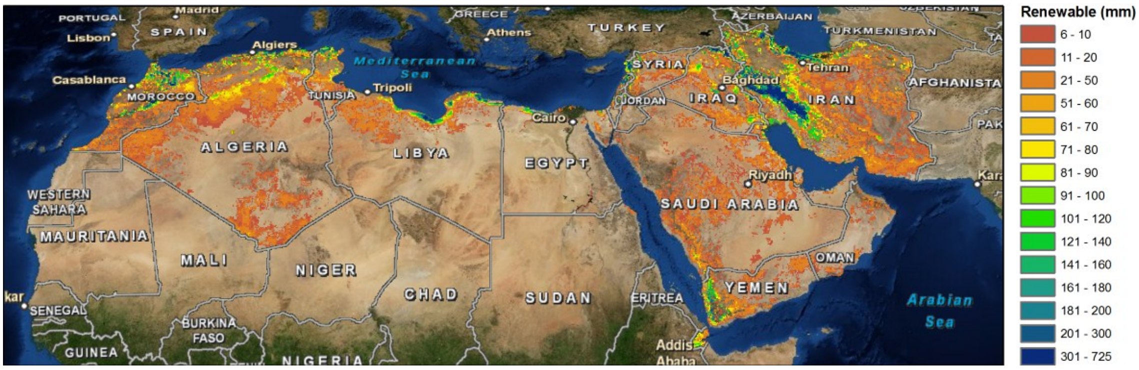

Figure 35. Internal renewable water resources based on 2000-2009 climatology.

In Figure 36 the total renewable water resources are shown per country in mm and in km^3. This includes the trans-boundary inflow into the countries. In particular Egypt (Nile), Syria (Euphrates) and Iraq (Euphrates and Tigris) are for a very large part depending on renewable external water resources. This is particularly critical in Egypt which is completely dependent on the Nile inflow. It should be acknowledged that in the upstream parts of these basins it is likely that investments in dams, irrigation infrastructure and changes in water treaties will have a bearing on the water availability, however it remains unclear to what extent that may happen because the information is lacking or development plans are confidential. It is beyond the scope of this large scale study, but it is recommended that the smaller basin scales are commissioned that attempt to differentiate between the effects of upstream climate changes and water management interventions.

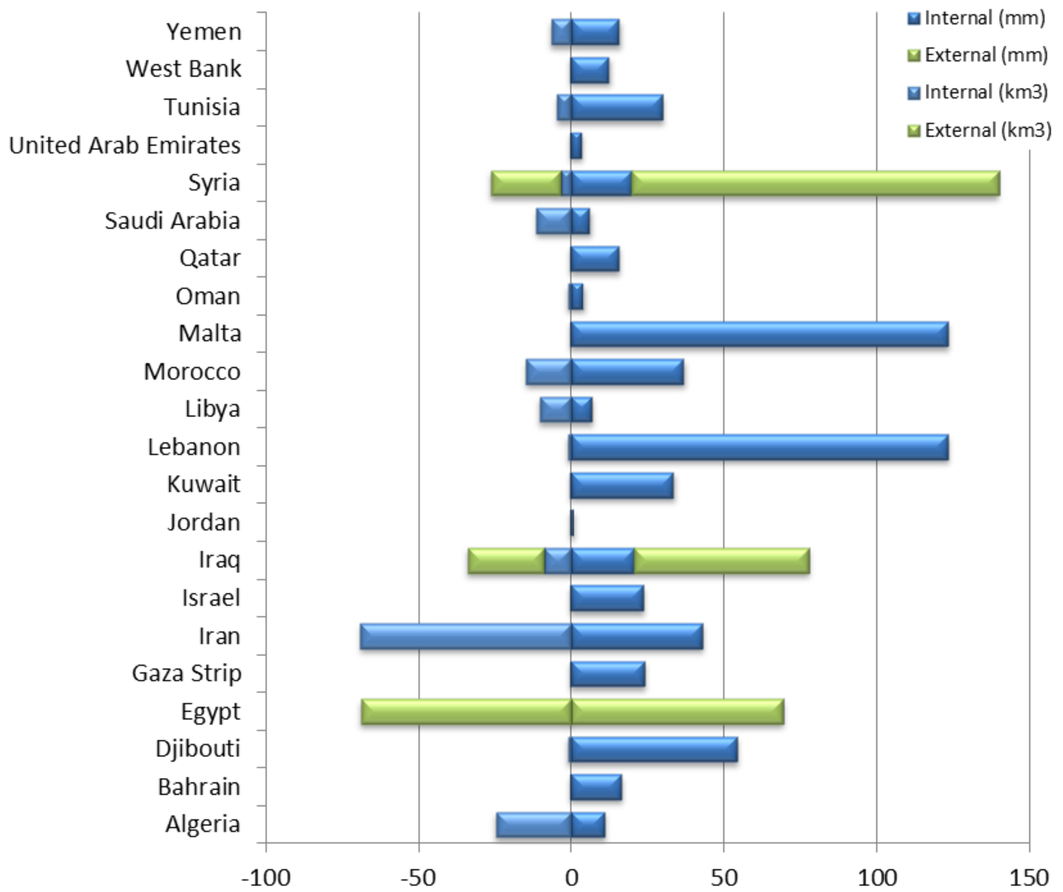

Figure 36. Average annual total renewable water resources in mm (right) and km^3 (left) per MENA country.

Figure 37 shows the per capita total renewable water resources. The Food and Agriculture Organisation (FAO) of the United Nations regards water as a severe constraint on socio-economic development and environmental protection at levels of internal renewable water availability of less than 1 000 m^3/capita. At levels of water availability of less than 2000 m^3/capita, water is regarded as a potentially serious constraint, and a major problem in drought years. Water scarcity provides a measure of the sensitivity of a given situation to drought. In situations where the average availability of water per capita is low, even slight variations can render whole communities unable to cope and create disaster conditions. In the MENA region water availability is a constraint everywhere and the countries in the GCC face the larges per capita water scarcity with an average value of less than 300 m^3 y^{-1} capita^{-1}.

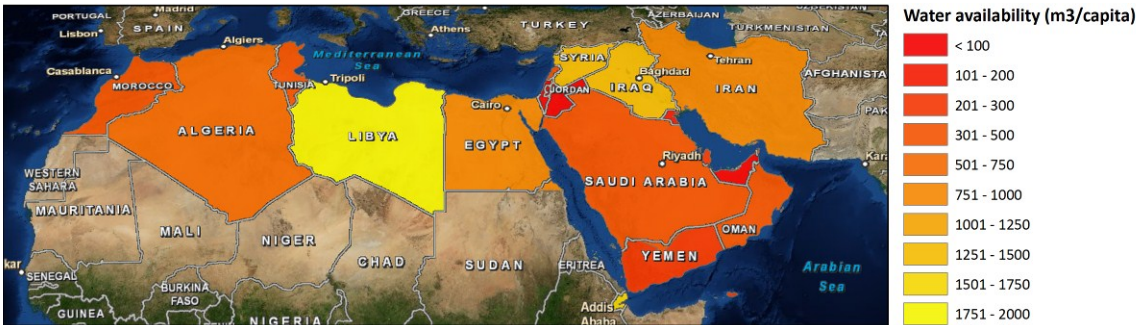

Figure 37. Total annual renewable water resources per capita from 2000-2009 (m^3/capita).

Actual evapotranspiration is the largest water consumer in the MENA region. Water is evapotranspired by both natural surfaces and irrigated agriculture. How water use by irrigated agriculture is determined is described in more detail in chapter 4.1. For the 2000 to 2009 average climate the total actual evapotranspiration and the additional actual evapotranspiration by irrigated agriculture is shown in Figure 38. The figure shows that a very large portion of the precipitation is consumed by evapotranspiration and in many countries actual evapotranspiration exceeds precipitation and trans-boundary water is used or ground water resources are depleted. The entire MENA region receives a total amount of 1122 km^3 of precipitation and 1141 km^3 is consumed annual by evapotranspiration.

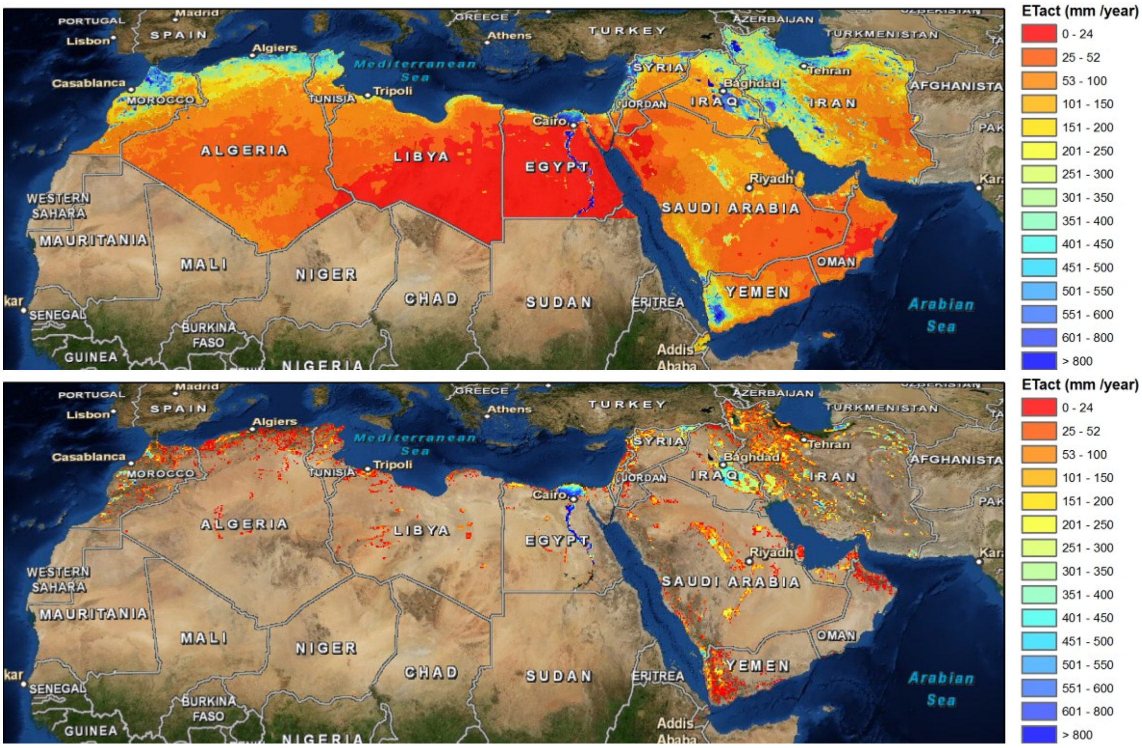

Figure 38. Total actual evapotranspiration and additional actual evapotranspiration by irrigated agriculture in mm / year.

5.4 Future water availability

Figure 39 and Figure 40 show the future water availability for the entire MENA region and a number of important observations can be made. First, the graph shows that the total internal renewable water resources and the recharge show a significant decline. This is the combined effect of the changes in precipitation and evapotranspiration. The total external renewable water resources show a very small increase. This is explained by the fact the majority of the external water resources is provided by the Nile and precipitation increases are projected by most GCMs in Eastern Africa where most Nile water is generated. The combined effect is that the total renewable water resources show a negative trend aggregated over the entire MENA region. The average total MENA renewable water resources from 2000 to 2009 equals about 250 km^3 and this is projected to decline by 0.6 km^3 per year. Secondly the figure shows that there is considerable variation between the different GCMs and that the results should be interpreted with care. Nonetheless it is safe to assume that an overall decrease in water availability is likely to occur in the future.

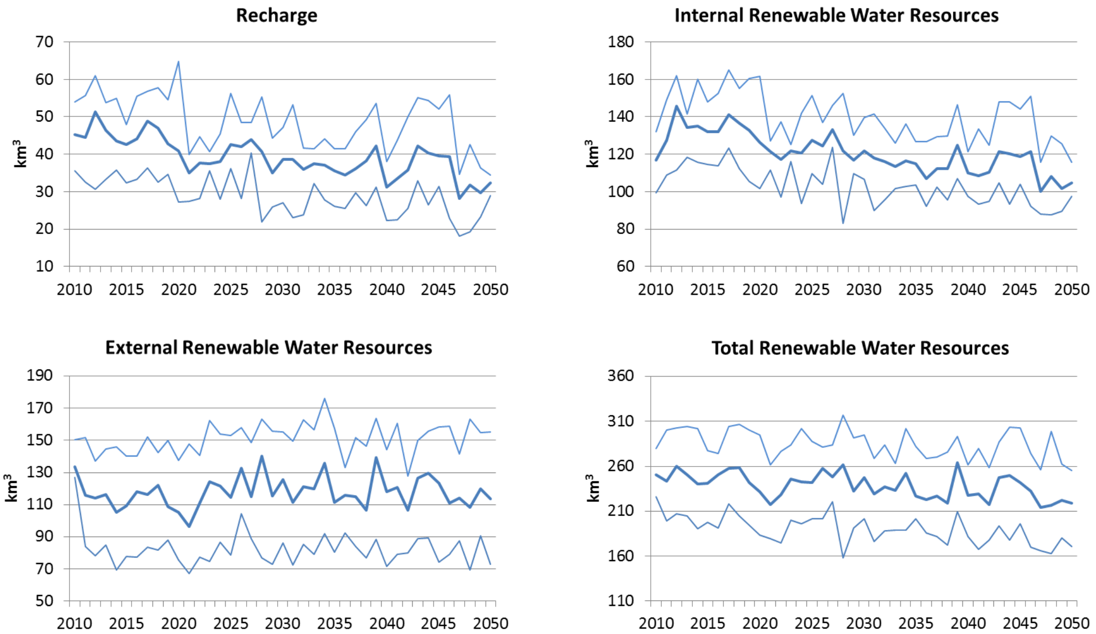

Figure 39. Total gross recharge, internal, external and total renewable water resources from 2010 to 2050. The thick line is the average of the nine GCMs and the thin lines show the second wettest and second driest GCM.

There is great variation between the different MENA countries in the hydrological response to climate change as evidenced by Figure 41. The figure shows the total change in gross recharge, internal renewable water resources and external water resources as percentage over the entire period 2010-2050. The gross recharge shows a very sharp decrease in almost all countries. This decrease is generally much stronger than the projected decrease in precipitation and this can be explained by the non-linearity of hydrological processes. In relative terms some of the gulf states (Oman, UAE, Saudi Arabia) show the largest decline, however also in some of the wetter countries the decline is very considerable (Morocco -38%, Iraq -34%, Iran -22%) and will lead to severe problems. The internal and external renewable water resources also show negative trends throughout the region with the exception of Egypt, Djibouti and Syria. The largest decreases are observed in Jordan (-138%), Oman (-46%), Saudi Arabia (-36%) and

Morocco (-33%). In Syria the internal renewable water resources show an increase but the total renewable water resources show a decrease because the external inflow of the Euphrates into Syria is projected to decrease by 17%.

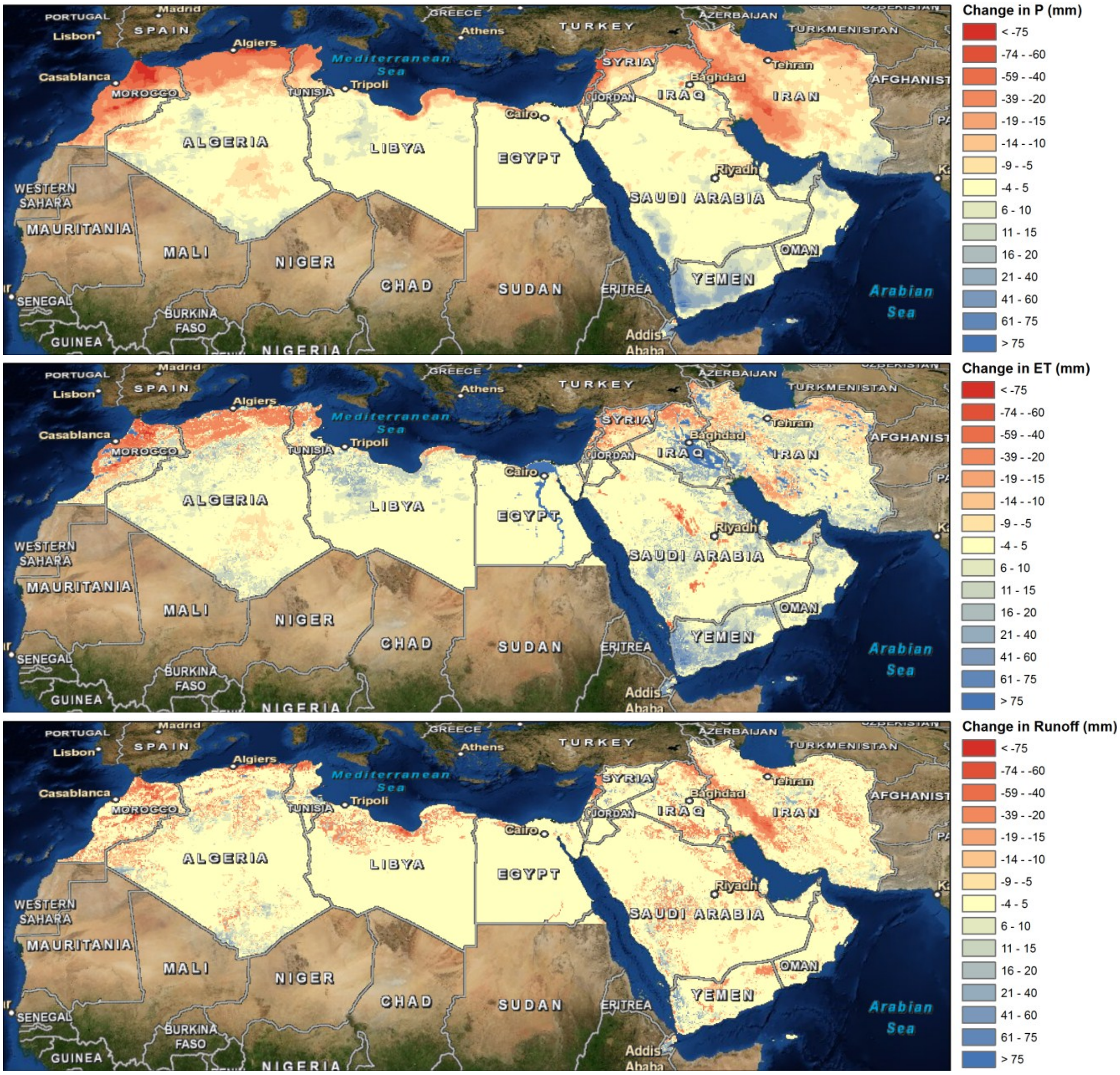

Figure 40. Total change from 2010 to 2050 in mm for precipitation (top), actual evapotranspiration including irrigated areas (middle) and internal renewable water resources (bottom).

In Figure 42 the per capita water availability is shown for 2030 and 2050. The results are striking and the water scarcity is projected to become very severe in the future due to the decrease of renewable water resources and strong increase in population. Countries such as Morocco are for example faced with a decline in per capita water availability from 478 m^3 / capita during 2000-2009 to 76 m^3 /capita in 2020-2030 to 72 m^3/capita in 2040-2050. In total 14 out of 21 countries have less than 200 m^3/capita in 2040-2050 and the GCC states are particularly hard hit.

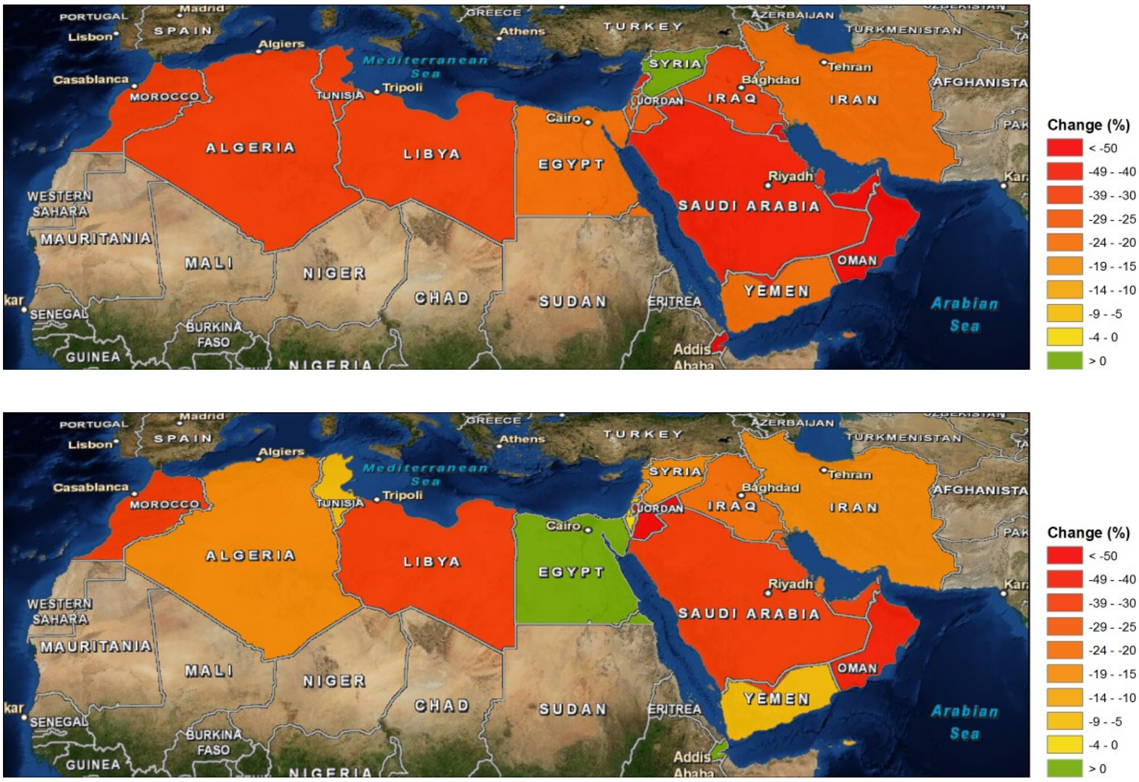

Figure 41. Total change from 2010 to 2050 in % in recharge (top), and total renewable water resources (bottom).

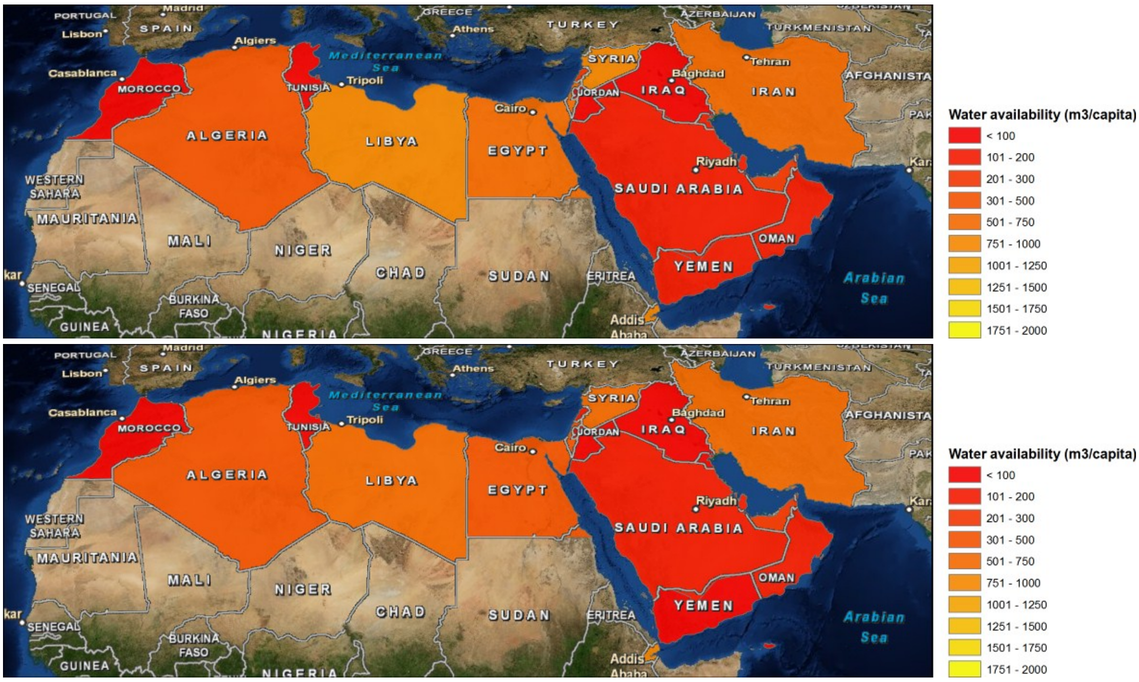

Figure 42. Total annual renewable water resources per capita in from 2020-2030 (top figure) and from 2040-2050 (bottom figure).

6 Water Supply and Demand Analysis

6.1 Introduction

Water supply and demand analysis requires tools, often referred to as simulation models, to support these analyses. In general the two main objectives of model applications are: (i) understanding processes and how they interact, and (ii) scenarios analyses. Understanding processes is something that starts during model development. In order to build our models we must have a clear picture on how processes in the real world function and how we can mimic these in our models. The main challenge is not in trying to build in all processes we understand, which is in fact impossible, but lies in our capability to simplify things and concentrate on the most relevant processes of the model under construction. The PCR-GLOBWB model as presented in the previous section is a clear example of selecting the right modelling tool for the analysis required at the MENA scale level.

The most important aspect of applying models, however, is in their use to explore different scenarios. These scenarios can capture aspects that cannot directly be influenced, such as population growth and climate change (Droogers and Aerts, 2005). These are often referred to as projections. Contrary to this are the management scenarios or interventions or adaptation strategies, where water managers and policy makers can make decisions that will have a direct impact. Examples are changes in reservoir operation rules, water allocation between sectors, investment in infrastructure such as water treatment or desalinization plants, and agricultural/ irrigation practices. In other words: models enable to change focus from a re-active towards a pro-active approach. (Figure 43).

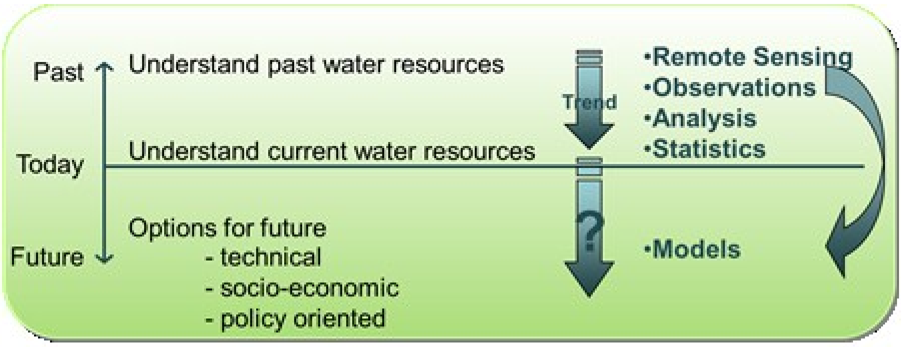

Figure 43. The concept of using simulation models in scenario analysis.

Based on an earlier study (Droogers and Perry, 2008) it was decided that the supply and demand analysis could be best done using the WEAP model. WEAP follows an integrated approach to water development that places water supply projects in the context of multi-sectoral, prioritised demands, and water quality and ecosystem preservation and protection. WEAP incorporates these values into a practical tool for water resources planning and policy analysis. WEAP places demand-side issues such as water use patterns, equipment performance, re-use strategies, costs, and water allocation schemes on an equal footing with supply-side topics such as stream flow, groundwater resources, reservoirs, and water transfers. WEAP is also distinguished by its integrated approach to simulating both the natural (e.g. rainfall, evapo-transpirative demands, runoff, baseflow) and engineered components (e.g. reservoirs, groundwater pumping) of water systems, allowing a more comprehensive view of the broad range of factors that must be considered in managing water resources for present and future use. In summary WEAP is an effective tool for examining alternative water development and management options.

6.2 WEAP modeling framework

6.2.1 Background

WEAP is short for Water Evaluation and Planning System and is a tool for integrated water resources planning. It provides a comprehensive, flexible and user-friendly framework for policy analysis (SEI, 2005).

Many regions face formidable freshwater management challenges. Allocation of limited water resources, environmental quality, and policies for sustainable water use are issues of increasing concern. Conventional supply-oriented simulation models are not always adequate. Over the last decade, an integrated approach to water development has emerged that places water supply projects in the context of demand-side issues, water quality and ecosystem preservation. WEAP aims to incorporate these values into a practical tool for water resources planning.

WEAP is distinguished by its integrated approach to simulating water systems and by its policy orientation. WEAP is a desktop laboratory for examining alternative water development and management strategies (SEI, 2005).

6.2.2 WEAP approach

WEAP is operating on the basic principles of a water balance. WEAP represents the system in terms of its various supply sources (e.g. rainfall, rivers, creeks, groundwater, and reservoirs); withdrawal, transmission and wastewater treatment facilities; ecosystem requirements, water demands and pollution generation. The data structure and level of detail can easily be customised to meet the requirements of a particular analysis, and to reflect the limits imposed by available data.

Operating on these basic principles WEAP is applicable to many scales; municipal and agricultural systems, single catchments or complex transboundary river systems. WEAP not only incorporates water allocation but also water quality and ecosystem preservation modules. This makes the model suitable for simulating many of the fresh water problems that exist in the world nowadays (SEI, 2005).

WEAP applications generally involve several steps. The study definition sets up the time frame, spatial boundary, system components and configuration of the problem. The *Current Accounts*, which can be viewed as a calibration step in the development of an application, provide a snapshot of the actual water demand, pollution loads, resources and supplies for the system. Key assumptions may be built into the *Current Accounts* to represent policies, costs and factors that affect demand, pollution, supply and hydrology. *Scenarios* build on the *Current Accounts* and allow exploration of the impact of alternative assumptions or policies on future water availability and use. Finally, the *Scenarios* are evaluated with regard to water sufficiency, costs and benefits, compatibility with environmental targets, and sensitivity to uncertainty in key variables (SEI, 2005).

WEAP calculates a water and pollution mass balance for every node and link in the system. Water is dispatched to meet instream and consumptive requirements, subject to demand priorities, supply preferences, mass balance and other constraints. Point loads of pollution into receiving bodies of water are computed, and instream concentrations of polluting elements are calculated.

WEAP operates on a monthly time step, from the first month of the *Current Accounts* year through the last month of the last *Scenario* year. Each month is independent of the previous month, except for reservoir and aquifer storage. Thus, all of the water entering the system in a month (e.g. head flow, groundwater recharge, or runoff into reaches) is either stored in an aquifer or reservoir, or leaves the system by the end of the month (e.g. outflow from end of river, demand site consumption, reservoir or river reach evaporation, transmission and return flow link losses). Because the time scale is relatively long (monthly), all flows are assumed to occur instantaneously. Thus, a demand site can withdraw water from the river, consume some, return the rest to a wastewater treatment plant that treats it and returns it to the river. This return flow is available for use in the same month to downstream demands (SEI, 2005).

Each month the calculations (algorithms) follow this order (SEI, 2005):

1. Annual demand and monthly supply requirements for each demand site and flow requirement.
2. Runoff and infiltration from catchments, irrigation.
3. Inflows and outflows of water for every node and link in the system. This includes calculating withdrawals from supply sources to meet demand, and dispatching reservoirs. This step is solved by a linear program (LP), which attempts to optimise coverage of demand site and instream flow requirements, subject to demand priorities, supply preferences, mass balance and other constraints.
4. Pollution generation by demand sites, flows and treatment of pollutants, and loadings on receiving bodies, concentrations in rivers.
5. Hydropower generation.
6. Capital and operating costs and revenues.

6.2.3 Program structure

WEAP consists of five main views: (i) schematic, (ii) data, (iii) results, (iv) overviews, and (v) notes. These views are listed as graphical icons on the “View Bar”, located on the left of the screen. Click an icon in the View Bar to select one of the views. For the Results and Overviews view, WEAP will calculate scenarios before the view is displayed, if any changes have been made to the system or the scenarios.

6.2.3.1 Schematic view

In the Schematic view the basic structure of the model is created (Figure 44). Objects from the item menu are dragged and dropped into the system. First the river is created and the demand sites and supply sites are positioned appropriately in the system. Pictorial files can be added as a background layer. The river, demand sites and supply sites are linked to each other by transmission links, runoff/infiltration links or return flow links.

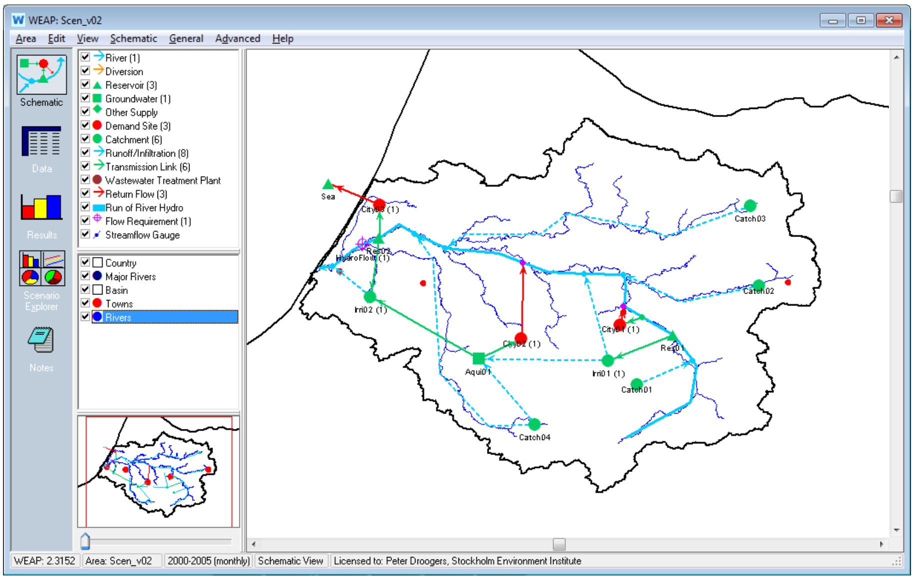

Figure 44. Example of the WEAP Schematic view.

6.2.3.2 Data view

Adding data to the model is done in the Data view. The Data view is structured as a data tree with branches. The main branches are named Key assumptions, Demand sites, Hydrology, Supply and Resources and Water quality.

The objects created in the Schematic view are shown in the branches. Further subdivisions of a demand site can be created by the analyst. The example in Figure 45 shows further sub-division of the demand sites into land use classes.

The Data view allows creation of variables and relationships, entering assumptions and projections using mathematical expressions, and dynamically linking to input files (SEI, 2005).

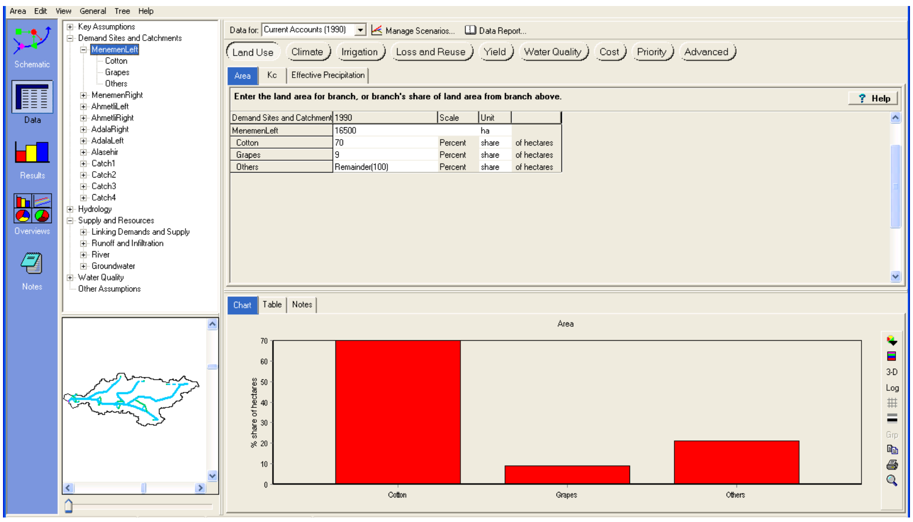

Figure 45. Example of the WEAP Data view.

6.2.3.3 Result view

Clicking the Results view will force WEAP to run its monthly simulation and report projections of all aspects of the system, including demand site requirements and coverage, streamflow, instream flow requirement satisfaction, reservoir and groundwater storage, hydropower generation, evaporation, transmission losses, wastewater treatment, pollution loads, and costs.

The Results view is a general purpose reporting tool for reviewing the results of scenario calculations in either chart or table form, or displayed schematically (Figure 46). Monthly or yearly results can be displayed for any time period within the study horizon. The reports are available either as graphs, tables or maps and can be saved as text, graphic or spreadsheet files. Each report can be customised by changing: the list of nodes displayed (e.g. demand sites), scenarios, time period, graph type, unit, gridlines, color, or background image. Customised reports can be saved as a "favorite" for later retrieval. Up to 25 "favorites" can be displayed side by side by grouping them into an "overview". Using favorites and overviews, the user can easily assemble a customised set of reports that highlight the key results of the analysis (Figure 47).

In addition to its role as WEAP's main reporting tool, the Results view is also important as the main place where intermediate results can be analysed to ensure that data, assumptions and models are valid and consistent.

The reports are grouped into five main categories:

- Demand
- Supply and Resources
- Catchments
- Water Quality
- Financial

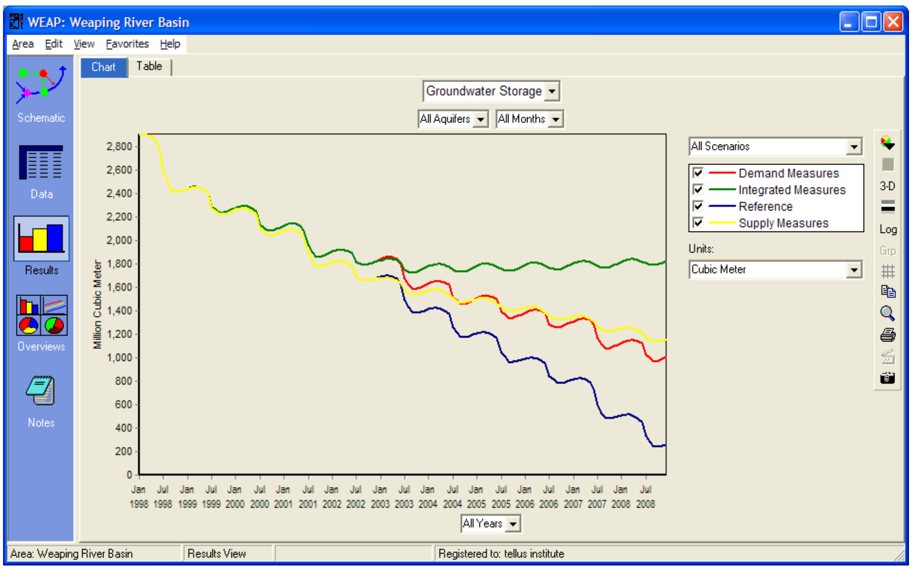

Figure 46. Example of the WEAP Results view.

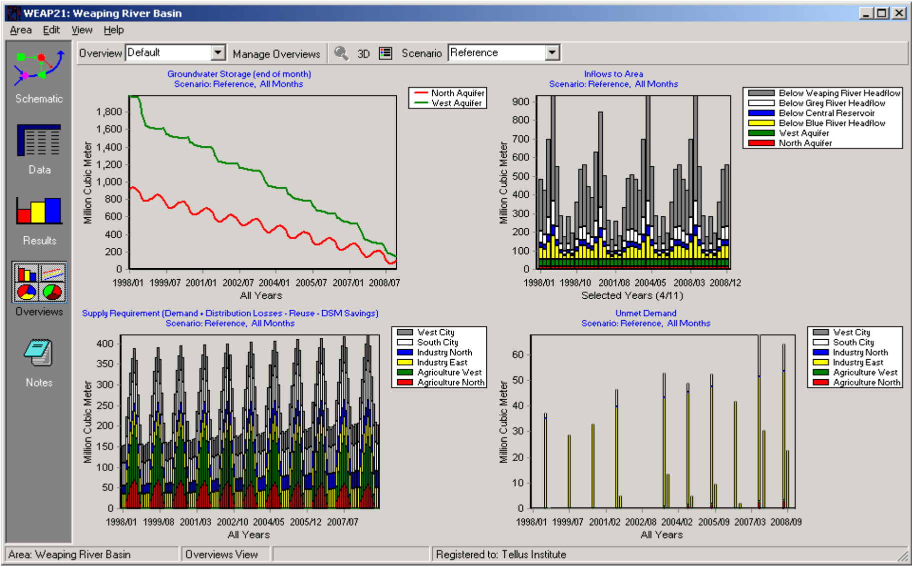

Figure 47. Example of the WEAP Overviews view.

6.3 MENA Water Outlook Framework

6.3.1 Overview

The PCR-GLOBWB model as described in the previous chapter is used to determine changes in water resources availability. The linkage between water resources and water demand is analyzed using the WEAP modeling framework in order to obtain the difference in supply and demand resulting in the water need. Using this approach the Water Outlook for the MENA region can be obtained. WEAP is considered to be amongst the best tools to undertake integrated analysis of different scenarios (e.g. Droogers and Perry, 2008). These scenarios can be constructed to test changes in climate and other water demands (often called “projections”) and changes in management (often referred to as “adaptation” or “intervention”) as well.

Given the nature of the project, large scale and a generalized outlook, a parametric approach was taken using the water supply results from PCR-GLOBWB, which are based on a much more physical based approach.

The conceptual base of MENA Water Outlook Framework, further referred to as MENA-WOF, is shown in Figure 48. It is assumed that within one country the following objects are present: streams, reservoirs, groundwater, industrial demand, domestic demand and irrigation demand. These objects are interconnected with each other and per land a lumped approach is considered. Details for each of these objects are:

- **Streams** represent all the surface water within a country. The inflow into the surface water is originating from the PCR-GLOBWB results. Water can be extracted for domestic, industrial and irrigation needs; water can be stored in the reservoir; and additional outflow to the sea (or any other outlet point of the country) can occur.
- **Reservoirs** are represented by one single lumped object and present total storage capacity in a specific country. Reservoirs can receive water from the streams and water can be released to support the demand.
- **Groundwater** is, similar to the reservoir object, one single lumped object and represents total groundwater storage in a specific country. Groundwater receives water

from natural recharge as calculated by PCR-GLOBWB and additional return flows from irrigated areas. Water is abstracted from the three demand objects (irrigation, domestic, industry).

- **Irrigation** represents all the water requirements for irrigation in a country. Water is obtained from the surface water and the groundwater. Return flows by drainage and surplus irrigation applications return to the groundwater, upstream in the stream (so can be reused) and downstream in the stream (so no reuse).
- **Domestic** represents all water required for domestic supply. Water is obtained from the surface water and the groundwater. Return flows can return upstream in the stream (so can be reused) and downstream in the stream (so no reuse).
- **Industry** represents all water required for industrial supply. Water is obtained from the surface water and the groundwater. Return flows can return upstream in the stream (so can be reused) and downstream in the stream (so no reuse).

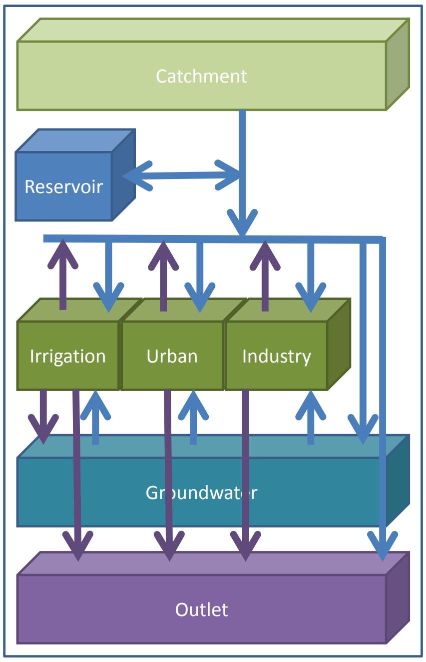

Figure 48. Conceptual framework of the MENA Water Outlook Framework (MENA-WOF).

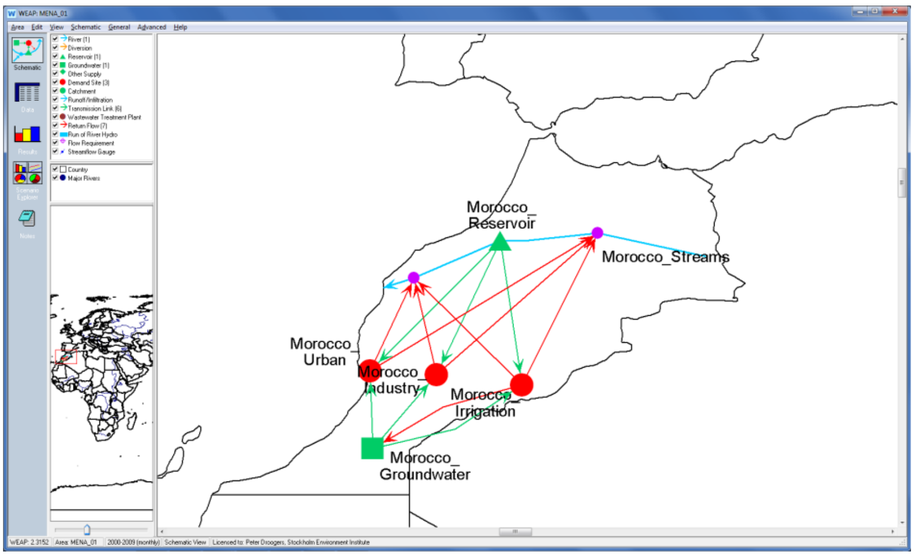

Figure 49. Conceptual framework of MENA-WOF model as implemented in WEAP with Morocco as example.

These concepts are used frequently and have been proven to be very effective in overall scenario analysis to evaluate impact of climate change and adaptation strategies (e.g. Droogers, and Perry, 2008; Immerzeel and Droogers, 2009; Droogers, 2009; Samuel Sandoval-Solis and Daene McKinney, 2010; Yates et al., 2009). An example how this was implemented in the MENA-WOF WEAP model can be seen in Figure 49.

6.3.2 Reservoirs

MEAN-WOF uses the concept of one component representing total reservoir storage capacity in a country. Data are obtained from AQUASTAT and presented in Figure 50. Countries with large reservoir capacity installed include Egypt and Iraq, followed by Iran, Morocco and Syria.

In order to estimate the evaporation losses from the reservoirs the Stage-Volume relationship has to be known. Average depth of reservoirs at full capacity was obtained from the Global Lakes and Wetlands Database (GLWD) as described by Lehner and Döll (2004). Only for six countries data on major reservoirs were available and for the other countries the average depth of 26 meter was assumed (Table 6). The reference evaporation from the reservoirs was calculated with the Hargreaves method, as described earlier.

Reservoir operational rules are quite straightforward. It was assumed that the Top Of Buffer (Figure 51) Is 50% of the storage capacity. As soon as actual storage capacity is in the Conservation Zone a maximum of 20% of this amount can be extracted every month. This is normal practices in reservoir management to avoid severe water shortage at an immediate moment.

Table 6. Average reservoir depth (source: Lehner and Döll, 2004).

Country	Average depth (m)
Algeria	15
Egypt	24
Iran	34
Iraq	27
Morocco	24
Syria	19
Average	**26**

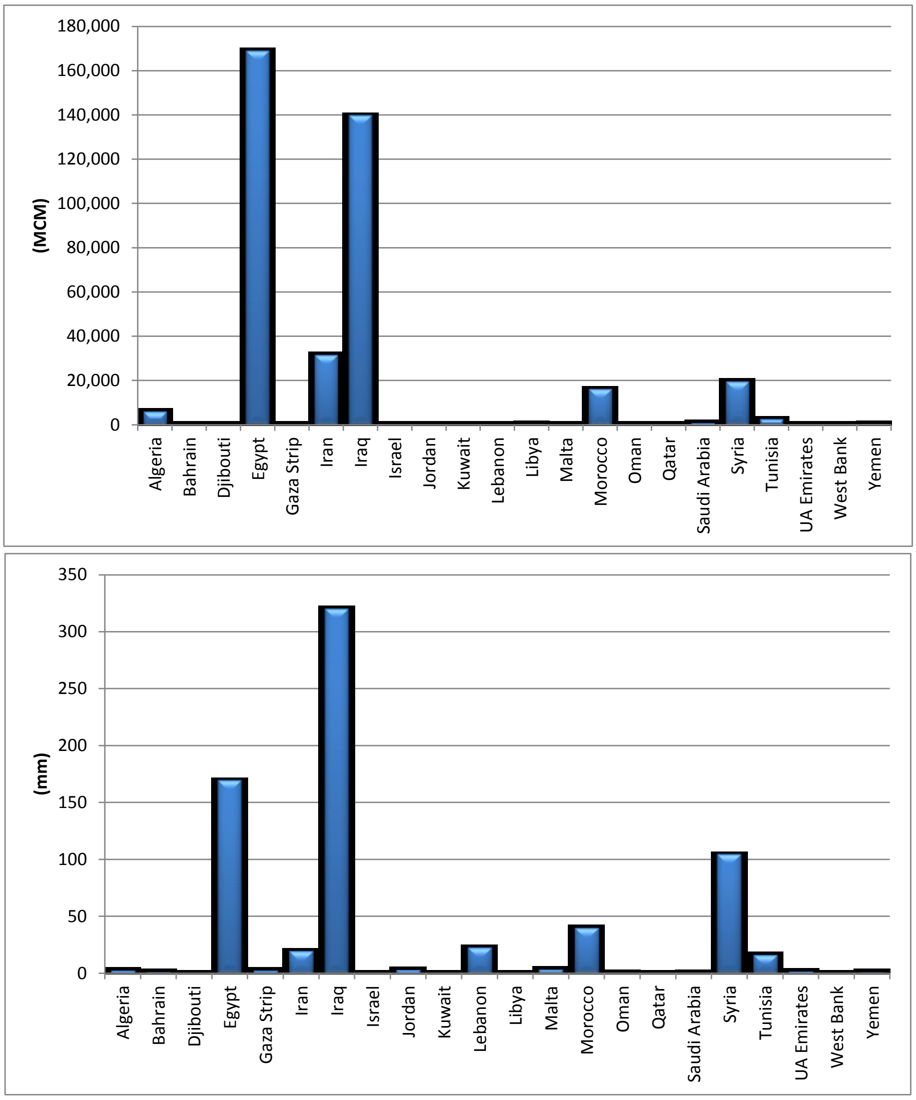

Figure 50. Total reservoir storage capacity per country in million m^3 (top), and converted to mm. (Source: AquaStat)

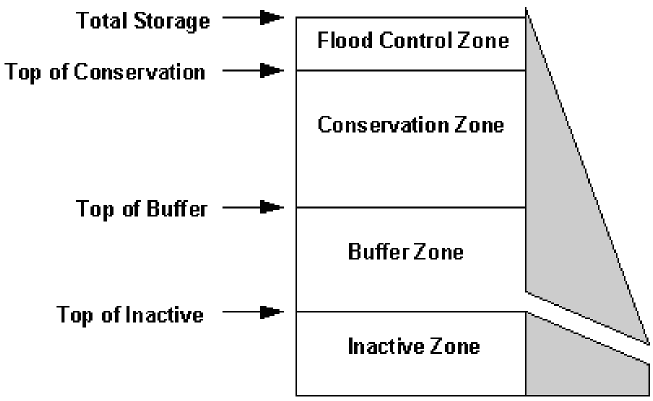

Figure 51. Reservoir stages used to mimic operational rules.

6.3.3 Groundwater

An important aspect of MENA-WOF is the use of groundwater as a source. However, reliable information on groundwater storage capacity at country level is hardly available. For specific countries extensive surveys might have been reported, however, a systematic and universal approach has never been applied and data are therefore not useful in this multi-country study. The International Groundwater Resources Assessment Centre (IGRAC) has the objective to sharing groundwater information on a world-wide scale, but information is much more qualitative and fragmented and therefore also not suitable for this study.

The absolute value of total groundwater resource is therefore not used, but only changes in groundwater storage are considered. In case groundwater resources are becoming scarce, groundwater extraction might become too expensive and limitations in extraction can be expected. To mimic this behavior in MENA-WOF a so-called effective groundwater storage capacity has been assumed. The amount of this effective groundwater storage was assumed to be the sum of ten times the annual gross groundwater recharge and twenty-five times the current overdraft. In this study we will refer to this as the “effective groundwater storage capacity”. It is assumed that the maximum monthly withdrawal from the groundwater is 5% of the “effective groundwater storage capacity”.

This “effective groundwater storage capacity” is plotted in Figure 52. It is important to emphasize that these numbers are not the real groundwater resource. The numbers reflect here are a combination of the current extraction rates and the actual recharge, as explained in the previous paragraph.

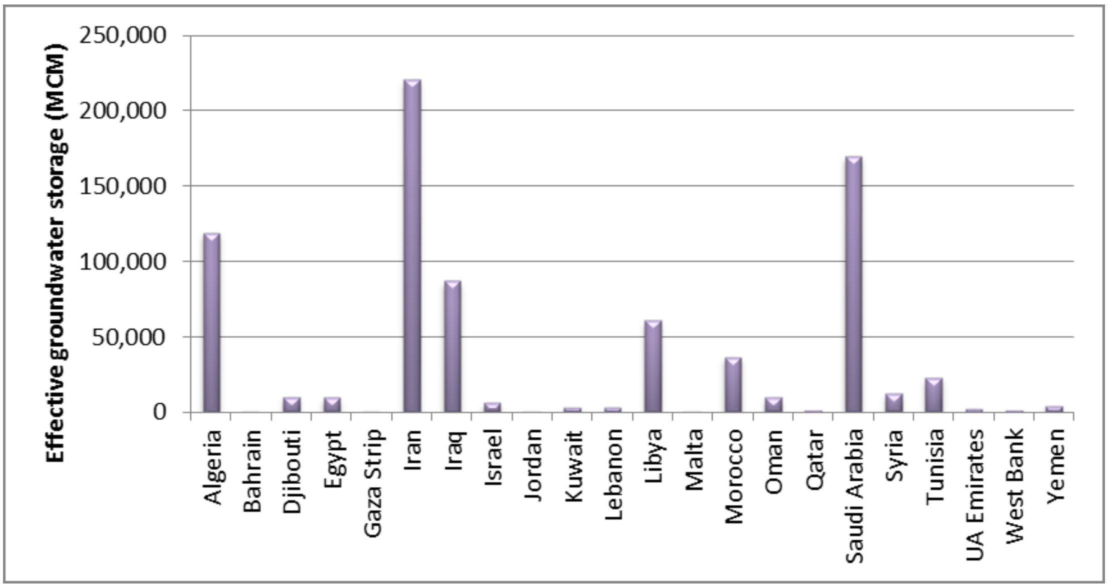

Figure 52. Effective Groundwater Storage Capacity as used in the MENA-WOF model. Note that these are not the real groundwater resource.

6.3.4 Irrigation, domestic, industrial demand and supply

All water demand is based on results of the PCR-GLOBWB model. The MENA-WOF model uses these results to undertake the supply-demand analysis, including losses and/or efficiencies. Additional water requirements due to efficiency losses were considered to be 30% (so irrigation efficiency of 70%). It is assumed that a total of 10% are non-recoverable losses from the system. The remaining 20% are return flows to: (i) recharge the groundwater (20%) and is available for reuse, (ii) flows back in the river (20%) and is available for reuse as well and (iii) drains in the sea (60%). Source of water for irrigation can be from the surface water and reservoirs or from the groundwater. It is assumed that by preference water will be extracted from the surface water, and if insufficient surface water is available the remainder will come from the groundwater.

Similarly as to irrigation, water for domestic and industrial use is withdrawal first from the surface water and if insufficient resource than groundwater will be used. It is assumed that return flows from domestic and industrial does not flow to the groundwater, but drains into the surface water. Distribution of this drainage water is considered of: (i) 20% flows back in the river and is available for reuse, (ii) 80% losses from the system (outflow to sea and/or saline or deep groundwater).

6.4 Results impact analysis

6.4.1 MENA

This section will concentrate on the impact of changes in climate and irrigation, domestic and industrial demand, on water supply and shortage for the entire MENA region. The amount of output generated by MENA-WOF is huge and here most relevant output will be presented, while more details can be obtained from the various Appendices.

In this study the detailed output of the models are presented in a comprehensive way of demands, supplies and unmet demands. Figure 53 presents for the entire MENA region the demand for irrigation, domestic and industry, the water supply (split between groundwater and surface water) and total water shortage. These results are obtained by taking the sum of the 21 countries in the MENA region on an annual base. It is important to realize however that these results are based on monthly calculations to ensure that variations within a year are properly taken into account. The figure also shows the year-to-year variation, which is especially noticeable in surface water availability. Since this year-to-year variation of these climate projections are only meant to be used as an indication that variation is changing, rather than reflecting a specific year, all results will be presented as running averages (Figure 54). Results are also presented in summary tables describing the reference situation (2000-2009), the near future (2020-2030) and the distance future (2040-2050) (Table 7 and Table 8).

From these results it can be seen that the current water shortage in the MENA region is around 42 km^3 per year. Since the period 2000-2009 is based on observed precipitation and temperature records, the annual variation is known as well and ranges between 24 km^3 (2004) and 64 km^3 (2008). This already quite substantial unmet demand is a clear reflection of the conditions in the MENA region where water shortage is already occurring in most of the countries.

Interesting is to compare the values obtained in this study to the ones provided by AquaStat and the Aqua-CSP study. As can be observed in Table 9 a full comparison is not possible as the three studies are not providing similar output variables. The current study provides results for demand, withdrawals, supply, and unmet demand, while the other two studies give only withdrawals and supply. As expected, the withdrawals of the AquaStat and the Aqua-CSP are substantial higher than the ones found in this study. Both AquaStat and Aqua-CSP use an annual approach which can highly overestimate the withdrawals as explained in the previous chapter. In terms of domestic and industrial demand the three studies provide similar results, with the exception of the Aqua-CSP industrial demand. Main reason might be that the CSP study did not included Djibouti and Malta. Other differences can be contributed to different time periods between AquaStat (differs per country and are in the range from 1987 to 2000) and Aqua-CSP and this study (2000-2009).

For the period 2020-2030 changes in water supply, demand and shortage can be seen in Figure 54 and Table 7 and Table 8. As described earlier a total of nine GCMs have been used for the PCR-GLOBWB analysis. In contrast to the normal approach of first ranking the GCMs from dry to wet and then doing the analysis, all GCMs were used in the PCR-GLOBWB analysis and results were ranked from dry to wet. Input for the supply and demand analysis in MENA-WOF was then taken by three results from PCR-GLOBWB: the 2nd driest, the mean and the 2nd wettest. This approach can be considered as first calculate then perform statistics, rather than doing statistics first. These three projections will be referred to as DRY, AVG and WET respectively. Note that in this way the three projections can be from different GCMs for different countries.

It is clear that water shortage will increase substantially in the future, under all climate change projections (Figure 54, Table 7 and Table 8). For the WET climate change projection no substantial increase in water shortage can be expected for the near future (2020-2030), but for the distant future water shortage will increase under all scenarios. Overall one can conclude that water shortage for the entire MENA region will be between about 40 and 200 km^3, depending on the climate change projection for the period 2020-2030. This will increase to about 90 and 280 km^3 per year on average in the period 2040-2050. This is approximately 25 to 50% of the total demand in 2040-2050.

It is important to realize that this projected increase in water shortage is the combined effect of increases in demands and reductions in supplies. For the WET projection this increase in demand is the dominant factor, supply is even slightly higher compared to the current situation. For the AVG and DRY projection, it is the combined effect of increasing demands and reduced supplies.

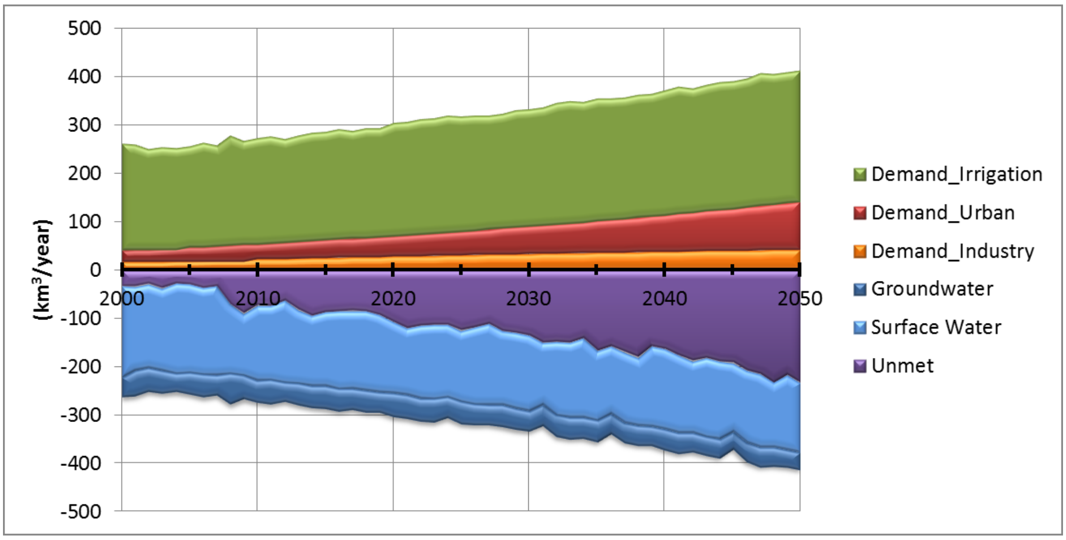

Figure 53. Water demand and supply MENA for the climate scenario AVG.

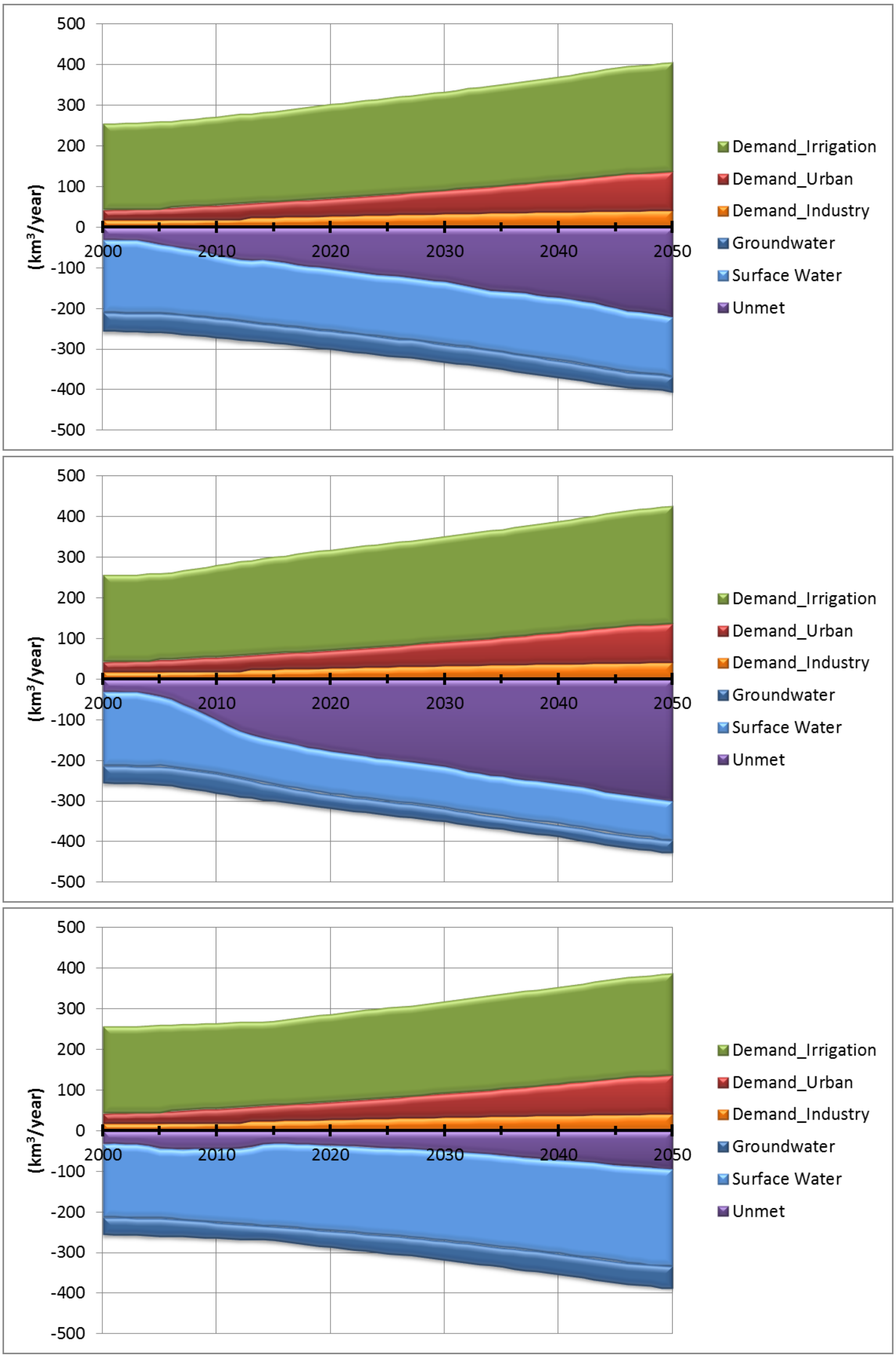

Figure 54. Water demand and supply MENA for the climate scenario AVG (top) and DRY (middle) and WET (bottom).

Table 7. Water Outlook all MENA countries for the three climate scenario for the near future (2020-2030).

KM^3 PER YEAR	2000-2009	CC Scenario AVG 2020-2030	CC Scenario DRY 2020-2030	CC Scenario WET 2020-2030
DEMAND	261	319	336	303
Irrigation	213	237	254	222
Domestic	28	50	50	50
Industry	20	32	32	32
UNMET DEMAND	42	119	199	42
Irrigation	36	91	155	29
Domestic	4	16	25	7
Industry	3	12	19	6
SUPPLY	219	200	136	261
Surface water	171	153	101	215
Groundwater	48	47	35	46

Table 8. Water Outlook all MENA countries for the three climate scenario for the distance future (2040-2050).

KM^3 PER YEAR	2000-2009	CC Scenario AVG 2040-2050	CC Scenario DRY 2040-2050	CC Scenario WET 2040-2050
DEMAND	261	393	412	374
Irrigation	213	265	283	246
Domestic	28	88	88	88
Industry	20	41	41	41
UNMET DEMAND	42	199	283	85
Irrigation	36	136	199	53
Domestic	4	43	56	20
Industry	3	20	27	11
SUPPLY	219	194	129	290
Surface water	171	153	97	237
Groundwater	48	41	31	53

Table 9. Comparison between this study, AquaStat and AquaCSP.

KM³ PER YEAR	This Study	AquaStat	CSP
DEMAND	261		
Irrigation	213		
Urban	28		
Industry	20		
UNMET DEMAND	42		
Irrigation	36		
Urban	4		
Industry	3		
WITHDRAWALS	219	308	289[b]
Irrigation	178	264	252
Urban	24	26	25
Industry	17	18	12
SUPPLY	219	305[a]	275
Surface water	171	53	
Groundwater	48	93	

(a) For many countries no distinction between surface water and groundwater withdrawals has been provided in AquaStat.
(b) The AQUA-CSP study uses the term "demand" while "withdrawals" are meant.

6.4.2 Individual countries

The impact of change in climate and irrigation, domestic and industrial demand is assessed for the 21 countries in the MENA region separately[12]. For each country the water demand, water shortage and supply for the average climate change scenario (AVG) is plotted in Appendix A, while summary results for the near future and distant future are presented in Table 10. Demand will increase for all countries as a result of the higher evaporative demand of irrigated agriculture, and the increase in domestic and industrial needs. Overall, this demand increases by about 25% in 2020-2030 and about 60% in 2040-2050 compared to the current situation. However, large variation occurs where countries with a relatively high demand for domestic and industrial show a larger increase (in percentages) compared to other countries. In actual cubic meters the larger countries with extensive agricultural demands take the major share of the increase in demand.

In terms of unmet demand the situation can be considered as dramatic for all countries. Countries facing currently no or limited water shortage will be confronted with huge deficits in the near and distant future. Countries like Egypt, Iran, Iraq, Morocco and Saudi Arabia will see water shortages increase by 10 to 20 km^3 in 2020-2030 up to 20 to 40 km^3 in 2040-2050.

Uncertainty in these amounts is assessed by undertaking the analysis for a dry and a wet climate projection as well. Changes in total demand as a function of these three projections are limited and increase in water shortage can be mainly attributed to changes in water supply. For a country like Egypt, with its very climate sensitive Nile Basin as the single water source, water shortage will be in the order of 50 to 60 km^3 per year according to the dry projections, but no real shortage in case of the wet projection. For other countries the difference between the climate projections are more modest. For example Morocco, the difference in expected water shortage in 2040-2050 ranges from 8 (WET) to 20 (DRY) km^3 per year, with 15 km^3 per year for the average projection. Other countries show a similar behavior.

[12] Given their detached location, Gaza Strip and West Bank results will be presented separately.

Table 10. Water demand and unmet demand for the current situation and the future for the average climate projection (AVG) (in MCM).[13]

	Demand 2000-2009	Demand 2020-2030	Demand 2040-2050	Unmet 2000-2009	Unmet 2020-2030	Unmet 2040-2050
Algeria	6,356	8,786	12,336	0	0	3,947
Bahrain	226	321	391	195	310	383
Djibouti	28	46	84	0	0	0
Egypt	55,837	70,408	87,681	2,858	22,364	31,648
Gaza Strip	119	194	313	98	183	301
Iran	74,537	84,113	97,107	8,988	21,767	39,939
Iraq	50,160	67,235	83,803	11,001	35,374	54,860
Israel	2,526	3,396	4,212	1,660	2,670	3,418
Jordan	1,113	1,528	2,276	853	1,348	2,088
Kuwait	508	867	1,216	0	313	801
Lebanon	1,202	1,525	1,869	141	472	891
Libya	4,125	4,974	5,982	0	1,382	3,650
Malta	45	62	75	0	22	36
Morocco	15,739	19,357	24,223	2,092	9,110	15,414
Oman	763	1,091	1,709	0	24	1,143
Qatar	325	381	395	83	209	246
Saudi Arabia	20,439	22,674	26,633	9,467	14,412	20,208
Syria	15,311	17,836	21,337	323	3,262	7,111
Tunisia	2,472	3,295	4,452	0	0	837
U.A. Emirates	3,370	3,495	3,389	3,036	3,243	3,189
West Bank	341	486	709	210	408	624
Yemen	5,560	7,069	12,889	1,120	2,573	8,449
MENA	261,099	319,138	393,082	42,125	119,443	199,183

Table 11. Water demand and unmet demand for the current situation and the future for the dry climate projection (DRY) (in MCM).

	Demand 2000-2009	Demand 2020-2030	Demand 2040-2050	Unmet 2000-2009	Unmet 2020-2030	Unmet 2040-2050
Algeria	6,356	9,250	12,818	0	0	574
Bahrain	226	322	392	195	316	389
Djibouti	28	47	85	0	0	0
Egypt	55,837	72,643	90,381	2,858	48,625	61,867
Gaza Strip	119	200	319	98	192	311
Iran	74,537	90,134	103,461	8,988	48,849	65,716
Iraq	50,160	69,893	87,415	11,001	48,615	68,529
Israel	2,526	3,534	4,371	1,660	2,995	3,818
Jordan	1,113	1,587	2,349	853	1,515	2,286
Kuwait	508	870	1,219	0	505	977
Lebanon	1,202	1,627	1,994	141	817	1,259
Libya	4,125	5,241	6,241	0	342	3,931
Malta	45	63	76	0	35	51
Morocco	15,739	20,957	25,939	2,092	13,171	19,554
Oman	763	1,120	1,733	0	300	1,343
Qatar	325	391	405	83	279	314
Saudi Arabia	20,439	23,435	27,424	9,467	16,288	22,717
Syria	15,311	18,939	22,525	323	7,910	12,086
Tunisia	2,472	3,635	4,808	0	252	2,726
U.A. Emirates	3,370	3,605	3,491	3,036	3,464	3,403
West Bank	341	512	741	210	464	696
Yemen	5,560	7,600	13,556	1,120	4,208	10,471
MENA	261,099	335,603	411,743	42,125	199,143	283,019

[13] Given their detached location, Gaza Strip and West Bank results will be presented separately.

Table 12. Water demand and unmet demand for the current situation and the future for the wet climate projection (WET) (in MCM).

	Demand 2000-2009	Demand 2020-2030	Demand 2040-2050	Unmet 2000-2009	Unmet 2020-2030	Unmet 2040-2050
Algeria	6,356	8,351	11,878	0	0	0
Bahrain	226	319	390	195	305	378
Djibouti	28	44	82	0	0	0
Egypt	55,837	68,489	85,235	2,858	0	0
Gaza Strip	119	189	307	98	175	293
Iran	74,537	79,769	90,949	8,988	303	5,262
Iraq	50,160	63,853	80,336	11,001	21,744	38,181
Israel	2,526	3,248	4,047	1,660	2,347	2,946
Jordan	1,113	1,471	2,207	853	1,135	1,808
Kuwait	508	863	1,212	0	0	510
Lebanon	1,202	1,433	1,746	141	274	496
Libya	4,125	4,715	5,727	0	0	73
Malta	45	62	75	0	6	16
Morocco	15,739	17,623	22,443	2,092	424	8,219
Oman	763	1,054	1,668	0	0	458
Qatar	325	366	382	83	89	122
Saudi Arabia	20,439	21,764	25,857	9,467	11,860	17,136
Syria	15,311	16,765	20,028	323	0	437
Tunisia	2,472	2,945	4,000	0	0	0
U.A. Emirates	3,370	3,341	3,212	3,036	3,001	2,851
West Bank	341	461	679	210	352	539
Yemen	5,560	6,323	12,002	1,120	352	4,838
MENA	261,099	303,449	374,463	42,125	42,368	84,561

7 Closing the Water Gap

7.1 Water marginal cost curves

7.1.1 Cost curves

The cost-effectiveness of various measures to close the supply-demand gap will be compared in this study by means of the “water-marginal cost curve”, similar to the approach of the 2030 Water Resources Group (2009). This cost curve shows the cost and potential of a range of different measures- spanning both productivity improvements and supply expansion – to close the gap. Such a water-marginal cost curve is estimated for each MENA country to assess the total costs to close the supply-demand gap projected under various climate change scenarios in 2020-2030 and 2040-2050.

Each of these measures is represented as a block on the curve. The width of the block represents the amount of incremental water that becomes available from adoption of the measure. The wider a measure, the larger its net impact on water availability. The height of the block represents its unit cost[14] in US$ per m^3. The vertical axis measures the financial cost –or savings- per unit of water released by each measure. This is the annualized capital cost, plus the net operating cost compared to business as usual. The unit costs are ordered from the lowest costs to the highest on the cost curve.

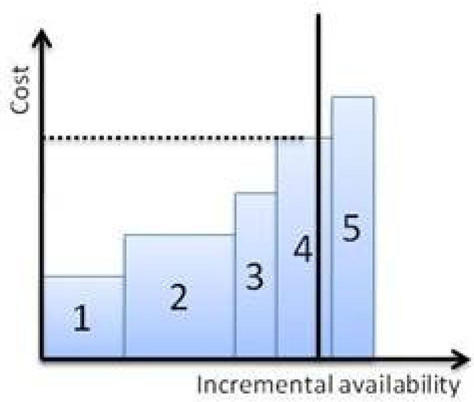

Figure 55. Schematic representation of the cost curve.

In applying the cost curve in the various countries, the net impact of each measure on water availability is estimated, taking into account return flows. This is especially important for drip irrigation, as at farm level it can have massive efficiency impacts but at an aggregate level the impact could be different: by reducing return flows, this measure could actually reduce the supply available to others and therefore diminish the true aggregate impact on closing the gap.

It is important to note that the cost curve’s use is limited to comparing measures’ financial cost and technical potential to close the gap. It does not include or evaluate policies that would be used to enable, incentivize, or enforce the adoption of those measures such as pricing, standards, and behavioral changes. Rather, it provides information on what the cost would be of adopting a set of technical measures, which in turn can be used to inform policy design. Of course, cost is not the only basis on which choices are made, but shedding light on the cost and

[14] All values are annualized and presented as US$ 2010 prices.

technical potential of measures allows these to be compared and evaluated in a common context. The cost curve, then, is not prescriptive: it does not represent what the plan for closing the supply-demand gap ought to be. Rather, it should be considered as a tool to help decision-makers understand and compare different options for closing the gap under a given demand scenario. It is therefore important to emphasize that the estimates generated by the cost curve are not explicit predictions, but approximate guides to decision-making.

7.1.2 Measures to close the supply-demand gap

The challenge for the MENA countries is to become sustainable by closing the gap between projected future water demand and current supply. Three core ways of matching water supply and demand are distinguished:

- increasing the productivity of existing water use;
- expanding supply; and
- reducing demand by shifting the economy towards less water-intensive activities.

Increasing the water productivity of existing activities entails here producing the same output with less water. The following nine potential measures are assessed in this study:

Increasing the productivity:

- A: Improved agricultural practice (including crop varieties)
- B: Increased reuse of water from domestic and industry
- C: Increased reuse of irrigated agriculture

Expanding supply:

- D: Expanding reservoir capacity (small scale)
- E: Expanding reservoir capacity (large scale)
- F: Desalinisation by means of using solar energy
- G: Desalination by means of fossil fuel

Reducing demand:

- H: Reduce irrigated areas
- I: Reduce domestic and industrial demand

7.1.3 Costs of these options

The total annual costs for the combined set of measures can be calculated by multiplying the specified deficit by the unit cost of each block required to close the gap. The considered unit cost of each measure is presented below. As there are a large number of measures and a lot of uncertainty about the costs of these measures in the various countries in the future, some crude assumptions have to be made in this study.

A) For **improved agricultural practices** that increase the productivity of water a unit cost of 0.02 $/m^3$ is considered. There are varies kinds of improved agricultural practices, such as drip and sprinkler irrigation, no-till farming and improved drainage, utilization of the best available germplasm or other seed development, optimizing fertilizer use, innovative crop protection technologies and extension services. Costs of such measures vary, but are relatively cheap compared to the water supply measures. Some of the productivity measures can even result in a net cost saving, when operating savings of the measures outweigh annualized capital costs. The 2030 Water Resource Group shows that the majority of the costs of such measures are in the range of 0.02 $\$/m^3$ to 0.03 $\$/m^3$. Converting this to costs per hectare (assuming on average 1000 mm of water consumption per hectare) is US$ 200 to US$ 300 per hectare per year.

Obviously, these costs can vary and are measure dependent. For example, for the Irrigation Improvement Project (IIP) in Egypt the average IIP improvement costs were exceeding LE 6,000 per feddan on average. This is about US$ 2500 per hectare[15]. Taking into account depreciation costs on investment of 25 years gives annualized capital costs of about US$ 100 per hectare.

B) The unit cost of **increased reuse of domestic and industrial water** depends on the treatment level. According to the 2030 Water Resources Group the unit cost of municipal and industrial waste water reuse is on average 0.30 $\$/m^3$ **(**see Exhibit 24 on Page 77).

C: The unit costs of **increased reuse of irrigation water** are assumed to be 0.04 $\$/m^3$ (2030 Water Resources Group, Exhibit 23 on Page 75). These costs are relatively low as it was assumed that this water is only reused for agricultural purposes so that no additional treatment is necessary. The price of 0.04 $\$/m^3$ is based on

- Reuse of 50 mm = 500 m^3 per ha / year
- Investment costs of $ 1000 /ha
- Annualized capital costs (investment over 10 years) $ 100 / ha / year; for 500 m^3 = 0.02 $\$/m^3$
- Annual operational costs (maintenance, pumping) of 0.02 $\$/m^3$

D and E): The costs of **expanding reservoir capacity** are taken to be 0.03 $\$/m^3$ for small scale infrastructure and 0.05 $\$/m^3$ for large scale infrastructure (2030 Water Resource Group, Exhibit 7, page 48). Obviously these costs can vary from region. For example according to Di Prima (2007), who reviewed experience with sand dams in Kitui District, Kenya, their construction cost is relatively high: currently around US$ 10,000 for each dam to provide an average of 5-8,000 cubic meters of water each season for (potentially) 50 years or more. This means 0.04 $\$/m^3$ (World Bank, 2010)

The Aslantas Dam in Turkey is an example of a large dam. The annual recovery charge on investment of the Aslantas Dam is estimated on $ 350 per ha per year. Assuming a 1000 mm per year (10,000 m^3 per ha) means 0.035 $\$/m^3$ (World Commission on Dams, p. 48)

F) The costs of **desalination by means of concentrating solar power (CSP)** for seawater desalination are assumed to decrease over time from currently 1.50 $\$/m^3$ to 0.90 $\$/m^3$ in 2010 and 2050 (Trieb and Muller-Steinhagen, 2008; Trieb et al., 2011). It is assumed that installed capacity is only sufficient for domestic water in 2030, and for industrial use as well in 2050. The potential additional costs due to externality costs, such as costs used for mitigation against environmental impacts, and subsidies for example of energy cost, are partly taken into consideration but varies from country to country (Trieb et al., 2011).

[15] one Feddan is 4200 m2, one LE is US$ 0.17

G) The costs of **desalination by means of fossil fuel** is assumed to be 1.00 $/m^3 currently and will increase to 1.20 $/m^3 in 2050. In the case of reverse osmosis and fossil fuel half of the costs consist of energy costs (Trieb et al., 2011). There is, however, uncertainty about both the energy price as well as energy requirements in the future among others as a result of the development of crude oil prices and technological breakthrough. It is therefore assumed that this option can be used to fulfill the need for domestic water and for 50% the industrial demand. The potential additional costs due to externality costs, such as costs used for mitigation against environmental impacts, and subsidies for example of energy cost, are partly taken into consideration but varies from country to country (Trieb et al., 2011).

H) The unit cost of **reduced irrigated areas** is assumed to be of 0.10 $/m^3, as the value of irrigation water ranges usually between 0.05 $/m^3 and 0.15 $/m^3 (Hellegers, 2006) and foregone benefits can be considered as unit costs. This value is, of course, strongly dependent on the price of agricultural products, which in turn are strongly affected by interventions of governments and trading blocs.

I) The unit cost of **reduced domestic and industrial demand** is assumed to be 2.00 $/m^3. While drinking water is a necessity of life, its value can be expected to be very high. The other uses of water within households, which make life more comfortable, and industry can be expected to have lower values (Young, 2005) The foregone benefits of moving for instance towards less water-intensive industries can be considered as unit costs of reduced industrial demand.

7.1.4 Conclusions

In many cases desalination -even with expected efficiency improvements- is vastly more expensive than traditional surface water supply measures, which in turn is often much more expensive than productivity measures. Traditional supply measures face a steep marginal cost curve in many parts of the world (2030 Water Resources Group), with many of the supply measures required to close the 2030 gap bearing a cost of more than 0.10 $/m^3, against current costs in most cases, of under 0.10 $/m^3. It may even reach a cost of 0.50 $/m^3 or more. The bigger the gap becomes over time, the more countries have to rely on expensive energy-intensive measures such as desalination.

The water marginal-cost curve can be considered as a decision tool, which allows decision makers to identify cost-effective solutions to close the gap between projected demand and existing supply by comparing the different measures. A combination of the various measures will be utilized to close the demand-supply gap in a country.

If the water gap is not closed, fossil reserves will be depleted, water for environmental needs is drained or some demand will go unmet, so that the associated economic or social benefits will simply not occur.

Obviously, the cost curve's approach has its limitations. Most importantly, it is restricted in comparing measures' financial cost and technical potential to close the gap. It does not include or evaluate policies that would be used to enable, incentivize, or enforce the adoption of those measures such as pricing, standards, and behavioral changes. Rather, it provides information on what the cost would be of adopting a set of technical measures, which in turn can be used to inform policy design. Of course, cost is not the only basis on which choices are made, but shedding light on the cost and technical potential of measures allows these to be compared and evaluated in a common context. The cost curve, then, is not prescriptive: it does not represent what the plan for closing the supply-demand gap ought to be. Rather, it should be considered as a tool to help decision-makers understand and compare different options for closing the gap under a given demand scenario. It is therefore important to emphasize that the estimates generated by the cost curve are not explicit predictions, but approximate guides to decision-making.

In recent years a number of studies have suggested the virtual water trade, introduced by Allen (1997), as one of the ways to improve water use efficiency and mitigated water scarcity at the regional level through adjustments of the structure of cropping patterns and interregional food trade (Chapagain et al., 2006). This concept is an active field of research and there are considerable limitations for implementation, however in the long-term it could be a viable option to alleviate the water crisis. This virtual water trade is implicitly the base of adaptation measure H, which reduces the irrigated areas and thus increases virtual water trade.

7.2 Effectiveness adaptations

The MENA-WOF WEAP model was used to evaluate the impact of changes in climate and domestic and industrial demand, as described in the previous chapter. MENA-WOF was also applied to evaluate the effectiveness of the nine adaptation strategies. This was done for the three climate projections, as these projections will result in different water shortage, but also as the effectiveness of the adaptations might be different.

Summary results for the entire MENA region are displayed in Table 13. The first column REF indicates the situation in 2040-2050 if no adaptation measures will be considered. These values are therefore identical as the one described in Chapter 6. Out of the nine adaptation strategies considered here, three includes a decrease in demand: improved agricultural practice, reduction in irrigated area, and reduction in domestic and industrial demand. The other strategies have a direct impact on supply (reservoir capacity, desalination) or an indirect impact by expanding the reuse.

In terms of effectiveness of the adaptations considered from a water resources perspective it is clear that improved agricultural practice (A) and desalination (F, G) are the preferred options, if costs are not considered. Unmet demand can be reduced by 53 km^3 up to 63 km^3. Increasing the reservoirs capacity (D, E) is not a very effective adaptation. This can be explained by the fact that in 2040-2050 precipitation is projected to be reduced so additional storage capacity is hardly needed.

Similar patterns can be seen for the DRY (Table 14) and the WET (Table 15) climate projections. Obviously, total water shortage for the DRY projection is higher compared to the AVG and WET. For the three projections increasing agricultural practice (A) is still a very effective adaptation.

The effectiveness of the same adaptation measure differs from country to country (Table 16). Expanding reservoir capacity (D, E) is for example much more effective for a country like Iran, compared to other countries. Water supply in Iran is relatively high and reservoirs are a good option to capture this water. Increase the overall agricultural practice is a very attractive measure for Egypt, but relatively unimportant for countries like Bahrain, Kuwait with limited agricultural production.

Table 13. Water demand and unmet demand for MENA region and the nine adaptation scenarios (A to I) for the AVG climate projection. REF reflects values without adaptation; A to I difference compared to REF (in km³).

MENA	Ref 2040-2050	A 2040-2050	B 2040-2050	C 2040-2050	D 2040-2050	E 2040-2050	F 2040-2050	G 2040-2050	H 2040-2050	I 2040-2050
DEMAND	393	-53	0	0	0	0	0	0	-26	-26
Irrigation	265	-53	0	0	0	0	0	0	-26	0
Urban	88	0	0	0	0	0	0	0	0	-18
Industry	41	0	0	0	0	0	0	0	0	-8
UNMET DEMAND	199	-55	-11	-8	-5	-11	-63	-53	-27	-25
Irrigation	136	-47	-6	-6	-3	-8	0	0	-24	-7
Urban	43	-6	-3	-1	-1	-2	-43	-43	-3	-12
Industry	20	-2	-2	-1	0	-1	-20	-10	-1	-5
SUPPLY	192	3	13	8	3	11	63	10	4	2
Surface water	151	0	10	7	4	13	63	10	1	0
Groundwater	41	3	2	1	0	1	0	0	3	2

Table 14. Water demand and unmet demand for MENA region and the nine adaptation scenarios (A to I) for the DRY climate projection. REF reflects values without adaptation; A to I difference compared to REF (in km³).

MENA	Ref 2040-2050	A 2040-2050	B 2040-2050	C 2040-2050	D 2040-2050	E 2040-2050	F 2040-2050	G 2040-2050	H 2040-2050	I 2040-2050
DEMAND	412	-57	0	0	0	0	0	0	-28	-26
Irrigation	283	-57	0	0	0	0	0	0	-28	0
Urban	88	0	0	0	0	0	0	0	0	-18
Industry	41	0	0	0	0	0	0	0	0	-8
UNMET DEMAND	283	-57	-7	-5	-2	-7	-84	-70	-29	-24
Irrigation	199	-52	-4	-4	-2	-5	0	0	-26	-4
Urban	56	-3	-2	-1	0	-1	-56	-56	-2	-14
Industry	27	-1	-1	0	0	-1	-27	-14	-1	-6
SUPPLY	129	0	7	5	2	5	84	14	0	-2
Surface water	97	0	7	5	3	8	84	14	0	-1
Groundwater	31	0	0	0	-1	-3	0	0	0	0

Table 15. Water demand and unmet demand for MENA region and the nine adaptation scenarios (A to I) for the WET climate projection. REF reflects values without adaptation; A to I difference compared to REF (in km³).

MENA	Ref 2040-2050	A 2040-2050	B 2040-2050	C 2040-2050	D 2040-2050	E 2040-2050	F 2040-2050	G 2040-2050	H 2040-2050	I 2040-2050
DEMAND	374	-49	0	0	0	0	0	0	-25	-26
Irrigation	246	-49	0	0	0	0	0	0	-25	0
Urban	88	0	0	0	0	0	0	0	0	-18
Industry	41	0	0	0	0	0	0	0	0	-8
UNMET DEMAND	85	-24	-8	-5	-3	-7	-31	-26	-14	-15
Irrigation	53	-20	-5	-4	-2	-6	0	0	-12	-5
Urban	20	-3	-2	-1	0	-1	-20	-20	-1	-6
Industry	11	-1	-1	0	0	0	-11	-6	-1	-3
SUPPLY	290	1	8	5	3	7	31	6	0	0
Surface water	237	1	10	7	5	15	31	6	0	0
Groundwater	53	1	1	0	0	0	0	0	0	1

Table 16. Unmet demand for 22 MENA countries and the nine adaptation scenarios (A to I) for the AVG climate projection. REF reflects values without adaptation; A to I difference compared to REF (2040-2050) (all in MCM).

(MCM)	REF	A	B	C	D	E	F	G	H	I
Algeria	3,947	-3,492	-2,030	-559	-718	-2,038	-1,800	-1,624	-1,936	-3,021
Bahrain	383	-9	0	0	-3	0	-366	-348	0	-76
Djibouti	0	0	0	0	0	0	0	0	0	0
Egypt	31,648	-10,565	-1,427	-1,618	-423	-1,653	-10,526	-9,264	-4,977	-4,016
Gaza Strip	301	-21	0	0	-2	0	-221	-217	-7	-47
Iran	39,939	-17,582	-2,573	-3,733	-1,958	-4,243	-4,289	-4,073	-9,120	-2,619
Iraq	54,860	-9,740	-2,369	-695	-427	-703	-21,038	-13,920	-4,727	-6,773
Israel	3,418	-445	0	0	-37	-32	-1,599	-1,536	-207	-397
Jordan	2,088	-227	0	-3	-22	-12	-1,149	-1,119	-93	-254
Kuwait	801	-22	-47	-2	-27	-58	-776	-761	0	-235
Lebanon	891	-199	-131	-40	-31	-45	-341	-306	-107	-179
Libya	3,650	-824	-173	-102	-122	-305	-1,128	-1,056	-402	-397
Malta	36	0	-8	0	-1	-1	-36	-36	0	-14
Morocco	15,414	-3,563	-166	-122	-157	-294	-3,214	-3,037	-1,738	-1,062
Oman	1,143	-125	-71	-8	-7	-10	-787	-772	-45	-238
Qatar	246	-29	-20	-3	-6	-11	-164	-161	-12	-54
Saudi Arabia	20,208	-3,143	-384	-126	-10	-66	-8,689	-8,042	-1,369	-2,327
Syria	7,111	-2,576	-468	-353	-233	-584	-969	-866	-1,365	-641
Tunisia	837	-809	-445	-306	-253	-603	-250	-238	-587	-541
U.A. Emirates	3,189	-470	0	0	-5	0	-1,040	-995	-202	-233
West Bank	624	-73	-11	-4	-6	-3	-307	-302	-32	-71
Yemen	8,449	-1,345	-385	-109	-54	-116	-4,462	-4,360	-559	-1,366
MENA	199,183	-55,261	-10,707	-7,782	-4,503	-10,778	-63,149	-53,031	-27,486	-24,562

Comparison of the size of the unmet demand (REF) and the sum of the reductions in unmet demand of the nine adaptation scenarios shows that all countries (except Iraq, Morocco and the United Arab Emirates) have choices in how to close the gap. Insight is therefore provided into the water availability cost curves in the next section. These three countries where the water gap cannot be closed have to take even more drastic measures that the nine adaptation strategies explored here.

7.3 Water-marginal cost curve

The effectiveness of the nine explored adaptation strategies in terms of reduction in water shortage is described in the previous section. The big question is whether these adaptations are cost effective. Combining the costs of these nine adaptation scenarios (presented in section 7.1) with the results of the reductions in unmet demand of the various measures (presented in section 7.2) will result in the water availability cost curves.

The water availability cost curve for the entire MENA region is displayed in Figure 56. It shows the unit costs of the various reductions in unmet demand -presented in Table 13- ordered from the lowest unit cost of 0.02 $/m^3$ to the highest unit cost 2.0 $/m^3$. The order of the unit costs of the scenarios (respectively A, D, C, E, H, B, F, G, I) reflects the cost-effectiveness of the adaptation measures. If the cheapest options are selected the reduction in domestic and industrial demand (I) is not adopted (0 km^3 instead of -28 km^3) and desalination by means of fossil fuel (G) only to a limited extent (-24 km^3 instead of -61 km^3) So, although desalination (F, G) was the preferred option in terms of effectiveness of water availability, it is not the preferred option from a financial point of view. Expanding reservoir capacity, though not a very effective adaptation from a water resources perspective, is much cheaper than desalination.

Similar patterns can be seen for the DRY (Figure 57) and the WET (Figure 58) climate projections, which correspond to the reductions in unmet demand presented in respectively Table 14 and 15.

By overlaying the projected supply and demand gap (unmet demand) for the MENA region in the 2040-2050 REF situation on the cost curve, it can be seen that the region has choices in how to close the gap. If the cheapest options are selected, the total annual costs in 2050 on bridging the unmet water gap of 199 km^3 is about US$ 104 billion (Figure 59, Table 14). Total cumulative costs are calculated by accumulating the costs of incremental water availability. Total cumulative costs to close the unmet water gaps of 283 km^3 for the DRY and 85 km^3 for the WET climate projections are respectively about US$ 212 billion and US$ 27 billion annually in the period 2040-2050 (Figure 59, Table 14). So the total costs to bridge the gap dependent on the projected impact of global climate change in the MENA region.

It is interesting to note that the difference in unmet demand between the AVG and WET projection is 115 km^3 and between the DRY and AVG projection 84 km^3, while the difference in costs are respectively US$ 77 billion (for the incremental 115 km^3) and US$ 108 billion (for the incremental 84 km^3). The average adaptation unit cost in in 2040-2050 for the WET, AVG and DRY climate projections are respectively 0.32 \$/m^3, US$ 0.52 \$/m^3 and 0.75 \$/m^3. The bigger the gap, the more the MENA region has to rely on expensive measures such as desalination.

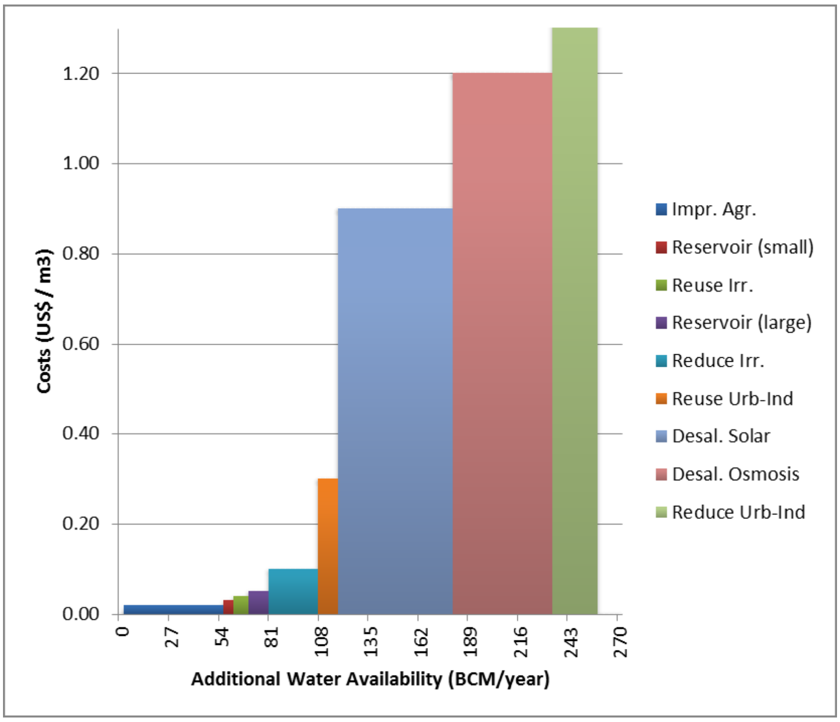

Figure 56. Water marginal cost curve for the AVG climate projection.

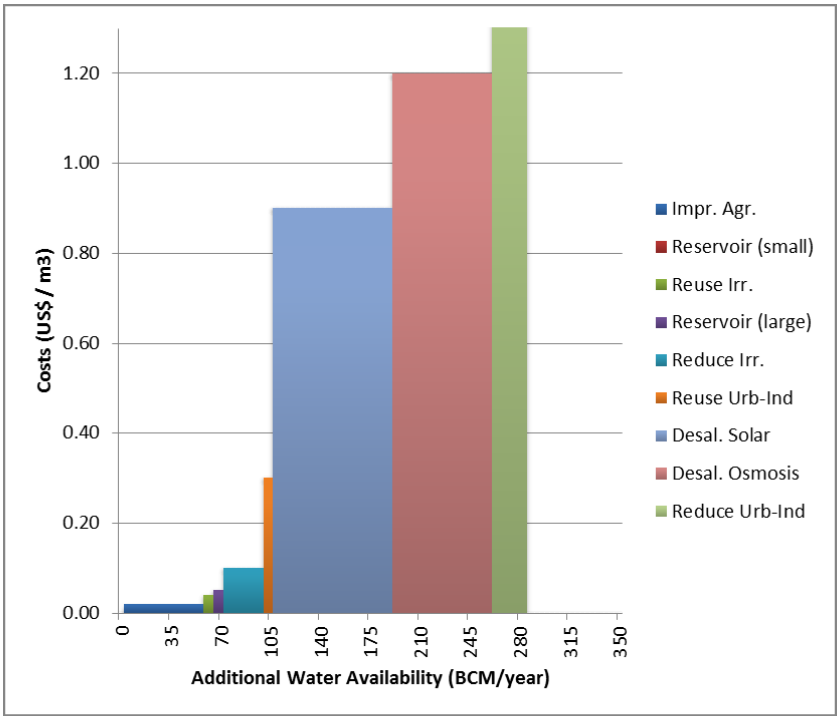

Figure 57. Water marginal cost curve for the DRY climate projection.

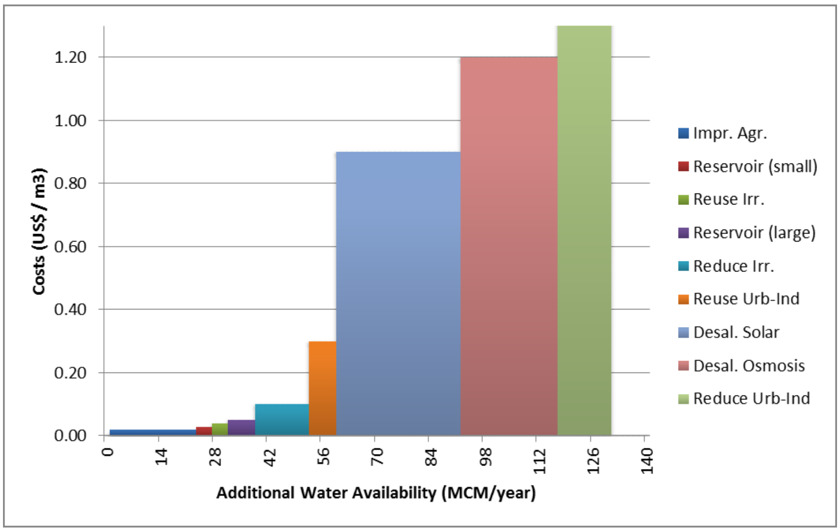

Figure 58. Water marginal cost curve for the WET climate projection.

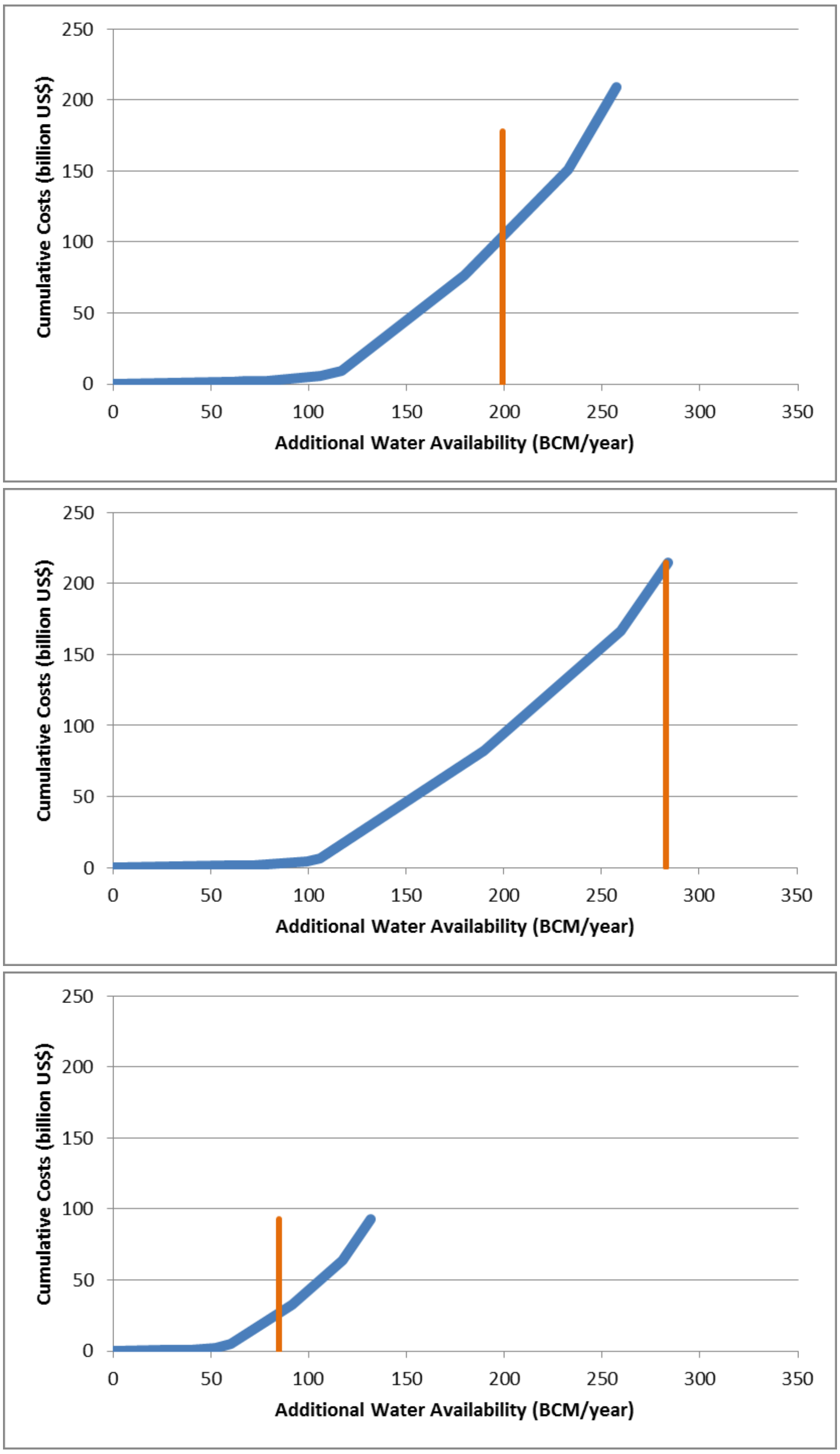

Figure 59. Cumulative water marginal cost curves for the AVG (top), DRY (middle) and WET (bottom) climate projection.

7.4 Individual countries

There is no single water crisis in the MENA region. The general assessment presented in the previous section should therefore be interpreted with great care. Different countries, even in the same region, face different choices and costs regarding how to close the gap. The water availability cost curves for each country for the AVG climate projection are therefore displayed in Appendix C. Total cumulative adaptation costs can be derived from these curves (Table 16).

The average adaptation costs are 0.52 $\$/m^3$ in the MENA region, but vary substantially among countries (Table 16). They are in the range of 0.02 $\$/m^3$ in Algeria (where improved agricultural practice can almost bridge the gap) and 0.98 $\$/m^3$ in the U.A. Emirates (where the gap should be mainly bridged by desalination). These costs are below 0.36 $\$/m^3$ in Algeria, Egypt, Iran, Syria and Tunisia (which means that least-cost measures on the left-hand side of the cost curve dominate) and above 0.64 $\$/m^3$ in Bahrain, Gaza Strip, Israel, Jordan, Kuwait, Malta, Oman, Qatar, Saudi Arabia, United Arab Emirates and West Bank (which means that high-cost measures on the right-hand side of the cost curve dominate).

The incremental water available from the nine adaptation measures assessed in this report is insufficient to close the water demand gap in Iraq, Morocco and the United Arab Emirates (Appendix C). The average adaption unit costs are respectively 0.72 $\$/m^3$, 0.85 $\$/m^3$ and 0.98 $\$/m^3$, and more drastic measures are required, such as additional decrease of irrigated area and/or consumption, to overcome the gap.

More than 83 percent of the burden of US$ 104 billion to bridge the 199 km^3 water demand gap has to be covered by the following five countries: Iraq (covers 38%), Saudi Arabia (15%), Morocco (13%), Egypt (11%) and Yemen (6%). Israel, Iran and the United Arab Emirates are together responsible for 9 percent. This means that the other fourteen countries bear less than 10 percent of the total burden. So the total costs are not equally distributed among the various countries in the MENA region.

The total adapation costs are also not equally distributed among the population living in the MENA region (Figure 61). About 50 percent of the population with the lowest cost per capita (less than US$ 45/capita) bears only 20 percent of the total costs. The 20 percent of the population with the highest cost per capita (more than US$ 100/capita) bears more than 50 percent of the total costs. Average adaptation cost per capita in the MENA region for the AVG climate projection is 148 $/capita in the period 2040-2050 for the AVG projection.

It is interesting to project what percentage of GDP has to be spent in 2040-2050 every year to cover the costs of 104 billion US$ every year to overcome this water shoratge. Total current GDP of the 21 countries in the MENA region is about 1.6×10^{12} US$ (1.6 triljon) , so costs will be about 6% of GDP. This is however unrealistic as we compare water shoratge in 2040-2050 to current GDP. The well-accepted CIESIN GDP projections show an increase to about $ 6.5 triljon (2030-2040) and $ 19 trillion (2040-2050)[16]. Using these GDP projections costs will be between 0.5% and 1.6% of GDP for the entire MENA region. However, depended on the severity of the water shortage and the projected GDP per country, substantial differences can be observed between the countries (Table 17). Countries like Yemen, Iraq, Morocco, Jordan and Egypt have to be prepared to spend a substantial amount of their GDP on overcoming their water shortage in the future. Costs for some countries facing sever water shortages might be limited (relative to their GDP) because of their high GDP projections.

[16] As indicated earlier, all costs are converted to US$ 2010 prices

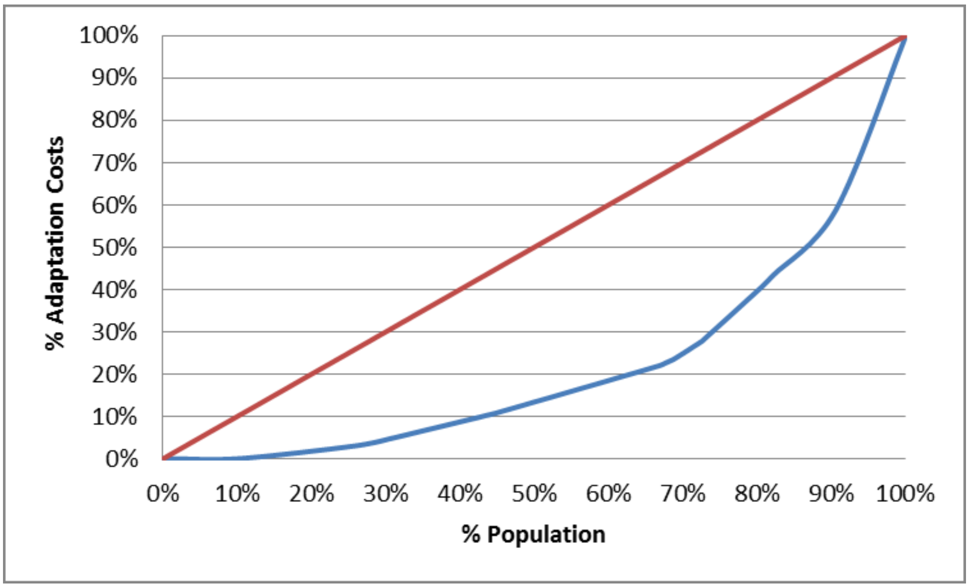

Figure 60. Lorenz curve showing the distribution of costs among the population. The blue line shows that the costs are not equally distributed compared to the red 45 degree line, which shows perfect equality in the distribution of costs among persons

Table 17. Annual adaptation costs to reduce water shortage 2040-2050 for the AVG climate projection.

	MCM Shortage	million US$ Costs	US$/m3 Costs	US$/capita Costs	2020-2030 %GDP	2040-2050 %GDP
Algeria	3,947	83	0.02	1	0.01	0.00
Bahrain	383	335	0.87	248	0.78	0.26
Djibouti	0	0	0.00	0	0.00	0.00
Egypt	31,648	11,321	0.36	76	2.44	0.81
Gaza Strip	301	259	0.86	139	N/A	N/A
Iran	39,939	3,112	0.08	29	0.24	0.08
Iraq	54,860	39,574	0.72	647	7.56	2.52
Israel	3,418	2,788	0.82	265	0.49	0.16
Jordan	2,088	1,746	0.84	164	4.04	1.35
Kuwait	801	600	0.75	112	0.30	0.10
Lebanon	891	363	0.41	72	1.19	0.40
Libya	3,650	1,860	0.51	170	0.56	0.19
Malta	36	26	0.72	57	0.40	0.28
Morocco	15,414	13,104	0.85	236	4.72	1.57
Oman	1,143	846	0.74	116	0.75	0.25
Qatar	246	158	0.64	170	0.20	0.07
Saudi Arabia	20,208	15,849	0.78	271	1.41	0.47
Syria	7,111	1,926	0.27	54	1.45	0.49
Tunisia	837	17	0.02	1	0.00	0.00
U.A. Emirates	3,189	3,116	0.98	716	2.36	0.79
West Bank	624	510	0.82	164	N/A	N/A
Yemen	8,449	5,927	0.70	63	11.82	3.94
MENA	199,183	103,520	0.52	148	1.61	0.54

8 Case Studies

The previous chapters provided analysis and results for the entire MENA region as a whole. Moreover, quite some country specific information was given as well, including details in the various appendices. It would be, however, interesting to give for three specific case studies directions in which way detailed analysis could be helpful in refining policies. It was selected to focus on the following three case studies:

- Economics of domestic water supply in Sana'a
- Economic instrument of irrigated agriculture in Egypt
- Green Water Management Morocco

8.1 Economics of domestic water supply in Sana'a

8.1.1 Introduction

The water supply of the Yemeni capital Sana'a is approaching critical levels quickly. Domestic water supply in the city is mainly depending on the abstraction from fossil groundwater reserves and earlier studies show that in Sana'a basin, total groundwater abstraction is five times larger than the recharge (Hellegers, Perry, & Al-aulaqi, 2009). Data from 2005 shows that in Sana'a basin 209.2 MCM is abstracted for irrigated agriculture, 55.4 MCM is abstracted for domestic use and 4.8 MCM for industrial use annually. The total fossil storage is in the order of 3220 MCM around the year 2000 and given the current abstraction rates storage would be depleted around 2015. The population of Sana'a has grown quickly during the last decade and it is projected to increase strongly in the future from 1.6 million in 2000 to 8.4 million in 2050 and in addition a strong increase in the per capita water withdrawals is foreseen from 17 m^3 / capita / year in 2010 to 96 m^3/ capita / year in 2050. These two factors combined lead to an increase in domestic water demand in Sana'a city of 3300% from 2000 to 2050 (Figure 61). The available renewable water resources are projected to decrease for Sana'a basin from around 50 MCM in 2000 to 40 MCM in 2050 for the AVG scenario and given the limited groundwater reserves and the enormous projected increase in water demand, considerable investments will be required to satisfy the water demands of the population of Sana'a. Obviously strong measures are required in the agricultural sector, which is the largest water consumer; however for this case study focus is on domestic water supply in Sana'a city where a lack of water is a direct threat to the lives of millions of people.

We estimate the required investment per year to close the Sana'a domestic water gap by implementing several relevant adaptation measures; (i) domestic improved waste water re-use, (ii) reduced domestic water demand, (iii) reduced irrigation water demand, (iv) desalination at the red sea coast and transport water to Sana'a. The options (i) to (iii) have also been applied in the country analysis and the same assumptions will be used. The cost estimate for option 4 is described below.

8.1.2 Cost estimates for desalination at the red sea and transport to Sana'a city

Sana'a city is located on an elevation of 2250 meter at a distance of approximately 100 km from the Red Sea and therefore transport costs of water desalinated at the Red Sea coast will be considerable. The costs for transporting 1 m^3 water 100 km horizontally is approximately equal to lifting 1 m^3 by 100 meter at 0.05 US$/$m^3$ (Zhou & Tol, 2005). They base their estimate on an extensive literature review for 12 large cities in the world. For this case study the most cost-effective route from an assumed plant location at the coast to Sana'a was determined using a digital elevation model and cost-distance modeling. First the horizontal costs were determined by calculating the distance from the proposed plant location and then the vertical costs were calculated using the elevation model. By adding the horizontal cost surface to the vertical cost surface the total costs were determined, which was used as an input in the cost-distance modeling. Using this approach the lowest cost path from Sana'a to the coast was determined. This path is shown in Figure 62.

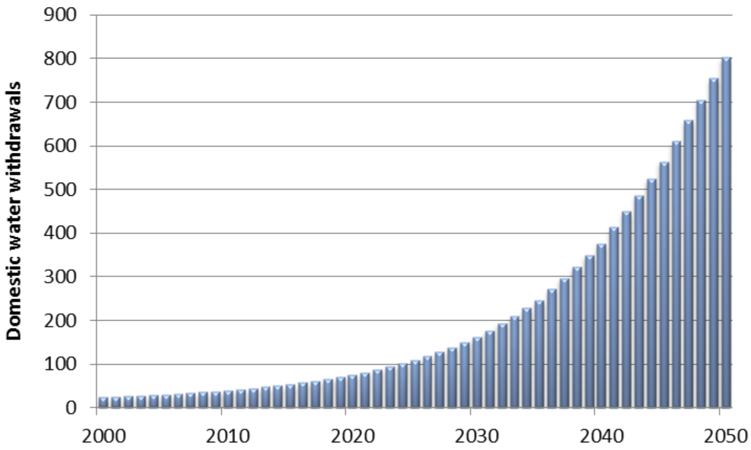

Figure 61. Projected increase in domestic water withdrawals for Sana'a city (MCM).

Figure 62. Lowest cost path from Sana'a to the Red Sea coast

Although Sana'a is located at an elevation of 2250 meter the total height over which the water must be lifted is more, because the terrain elevation is not increasing constantly, but some valleys need to be crossed. This is illustrated in Figure 63. The total elevation gain from the coast to Sana'a equals 3934 meter and the horizontal distance is 139 km. The unit costs for transporting water equals 2.04 US$/$m^3$ in addition to the unit costs of desalination. The costs of desalination are projected to decrease from 1.5 US$/$m^3$ in 2010 to 0.9 US$/$m^3$ in 2050. This means that the total unit cost for this option including transport will range from 3.54 US$/$m^3$ in 2010 to 2.98 US$/$m^3$ in 2050, thus this option is expensive and should be considered as a last option.

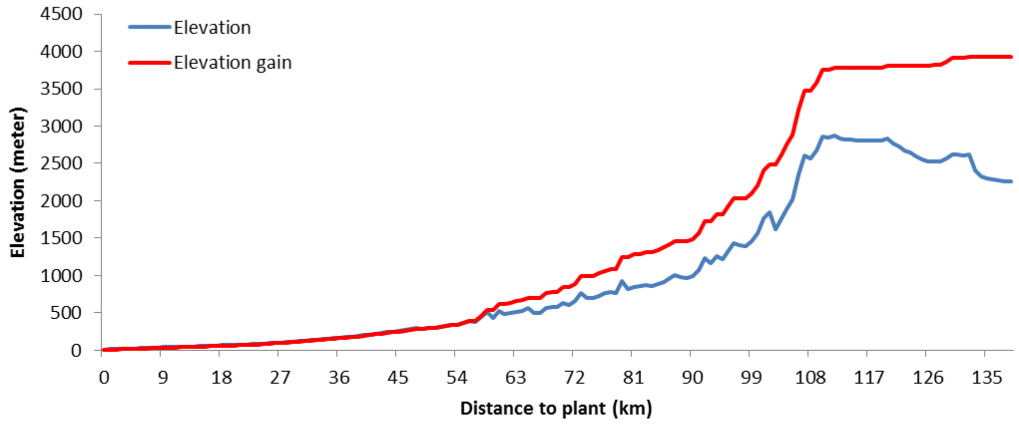

Figure 63. Elevation profile of the lowest cost path from Sana'a to the Red Sea coast

8.1.3 Cost analysis

We first estimate which part of the total domestic demand is covered by which source of water on an annual basis (Figure 64). We determine the relative contribution of each source of water by taking into account the physical feasibility (e.g. how much water can realistically be supplied by a certain source) and by taking into account the units costs of each measure.

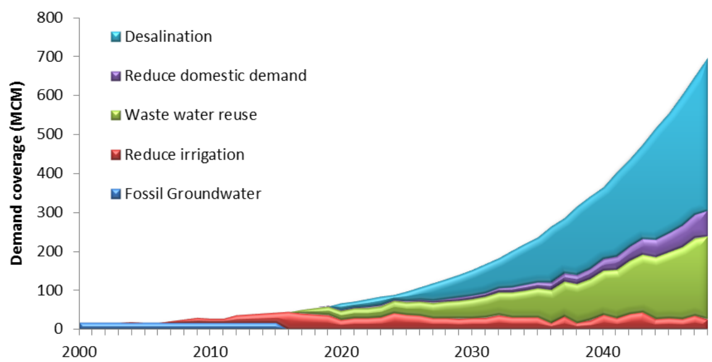

Figure 64. Coverage of domestic water demand from different sources based on cost optimization and physical feasibility.

The following key assumptions are made in our analysis:

- It is likely that the current use of the fossil groundwater will continue until the aquifer has been completely depleted. The average cost of pumping groundwater is 0.25 US$/m^3 (Hellegers et al., 2009). In theory reducing irrigated agriculture and using the water for domestic purpose would be cheaper (0.10 US$/m^3), but due to social constraints and the reliance on qat production this is not a likely scenario in the near future.
- The decrease in fossil groundwater reserves will most likely result in a reduction in irrigation for agriculture and the renewable water resources that are currently used to augment irrigation will become readily available for domestic water use at a cost of 0.10 US$/m^3. The total amount of water that can be diverted from agriculture to domestic water uses is maximized by the total amount of renewable water resources.
- Domestic waste water reuse is a third option and treatment costs are estimated at 0.30 US$/m^3. We estimate that 30% of the domestic water demand is recoverable and can be treated to be reused.

- Considerable savings may also be achieved by reducing the domestic demand through more efficient technologies or by creating awareness about the importance of saving water (e.g. swimming pools, watering gardens and washing cars). However the per capita water demand in Yemen is projected to increase from 17 m^3/capita/year in 2010 to 96 m^3/capita/year in 2100, which is still relative low compared to the developed world. It is therefore likely that water is used for essential life supporting purposes only and that scope for large savings are limited. We assume that the savings increase with per capita water demand from 0% in 2000 to 10% in 2050 at an average cost of 1 US$/$m^3$.
- The residual of the total water demand will need to be covered by using desalinated water that is transported from the Red Sea coast as discussed above. This is the most expensive option at a unit cost between 3.54 US$/$m^3$ in 2010 to 2.98 US$/$m^3$ in 2050, but it is the only option to quench Sana'a's thirst.

Figure 64 shows that up to 2020 desalination is not required to sustain the domestic water needs, but from then onwards the demand increase rapidly and other measures are insufficient to sustain these. Around 2050 more than half of the water demands are covered by desalination.

Based on the results in combination we can derive the total costs of sustaining the domestic water demand. Figure 65 shows that costs are limited up to 2020 (69 million US$), but they increase to 1304 million US$ in 2050 when there is a strong reliance on desalinated water. The per capita costs to cover domestic water demand increases from 20 US$ in 2020 to 163 US$ in 2050.

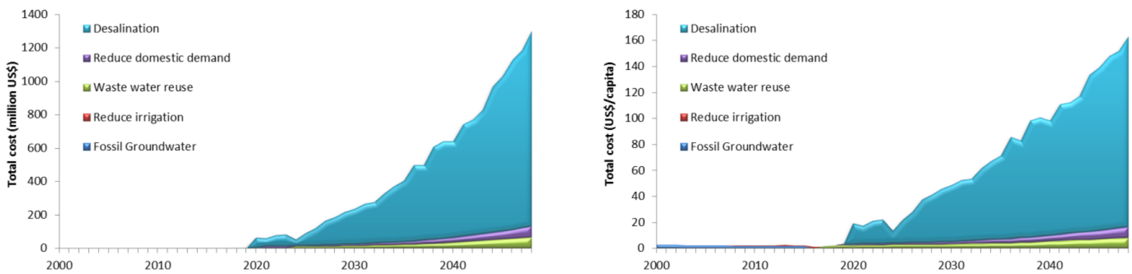

Figure 65. Annual total costs and per capita costs to cover the domestic water supply

8.1.4 Conclusions

The following main conclusions are drawn:

- Domestic water demand in Sana'a city is projected to increase dramatically from 40 MCM in 2010 to 705 MCM in 2050 due to strong population and economic growth.
- We estimate that the unit cost of desalinated sea water including transport to Sana'a is between 3.54 US$/$m^3$ in 2010 to 2.98 US$/$m^3$ in 2050. This much higher than then the economic water productivity of irrigated crops and therefore it is likely that irrigated agriculture will disappear from the Sana'a basin, except when it would be strongly subsidized.
- The fossil groundwater reserves are likely to be depleted around 2015 and this will reduce the possibility of irrigated agriculture. The only option to completely sustain the domestic water demand for Sana'a city is by transporting desalinated water from the Red Sea. Around 2050 we estimate that more than 50% of the domestic water will be covered by desalinated water.

- The total cost to supply the domestic water will increase from 69 million US$ in 2020 to 1304 million US$ in 2050, and the per capita cost will increase from 20 US$ in 2020 to 163 US$ in 2050.
- It is recommended to initiate as soon as possible an appraisal study for a desalination plant and pipeline from the Red Sea coast to Sana'a.

8.2 Sensitivity of marginal costs of adaptation measures in Egypt

8.2.1 Introduction

In this study the marginal costs for the nine adaptation measures are based on literature review and average marginal costs have been used in the economic analysis. Obviously the estimates for the marginal costs are subject to uncertainties (Hellegers and Perry, 2004; WRG, 2009; Hellegers, 2006) and the question arises what the impact of this uncertainty is on the estimates of the total costs of adaptation to climate change and how this relates to uncertainty in the climate change impact projections itself.

8.2.2 Approach

To estimate the impact of uncertainty in marginal costs we assume that the marginal costs follow a normal Gaussian distribution that is defined using the standard deviation and average marginal costs for each adaptation measure

Table 18 Overview of average marginal costs per adaptation measure

Measure	Cost (US$/m^3)
Improved agricultural practice (including crop varieties)	0.02
Expanding reservoir capacity (small scale)	0.03
Increased reuse of irrigated agriculture	0.04
Expanding reservoir capacity (large scale)	0.05
Reduce irrigated areas	0.10
Increased reuse of water from domestic and industry	0.30
Desalination by means of using solar energy	0.90
Desalination by means of fossil fuel	1.20
Reduce domestic and industrial demand	2.00

In Table 18 the average costs prices are summarized. It should be noted that the costs for desalination vary over time as earlier discussed. Based on these average costs we estimate the distribution of the marginal costs using five different coefficients of variation (CV). The coefficient of variation is defined as the standard deviation divided by the average. A low CV means that the cost estimate is relatively certain and a high CV means that the cost estimate is uncertain. This is further illustrated in Figure 66 where different marginal cost distributions for the measure that considers reducing irrigated areas. The average cost of this measure is 0.1 US$ / m^3, but the uncertainty in this average cost is depicted by the width of the curves. The surface under each curve is always equal to 1. When the CV is 10% (standard deviation = 0.01 US$ / m^3) the curve is rather narrow and there is a 95% certainty that the cost prices ranges between 0.08 US$ / m^3 and 0.12 US$ / m^3. However when the CV = 50% (standard deviation = 0.05 US$ / m^3) the distribution curve widens and the 95% range increases from 0.00 US$ / m^3

to 0.20 US$ / m³. These costs curves are generated for each of the nine adaptation measures using three different assumptions for the CV (10%, 20% and 50%).

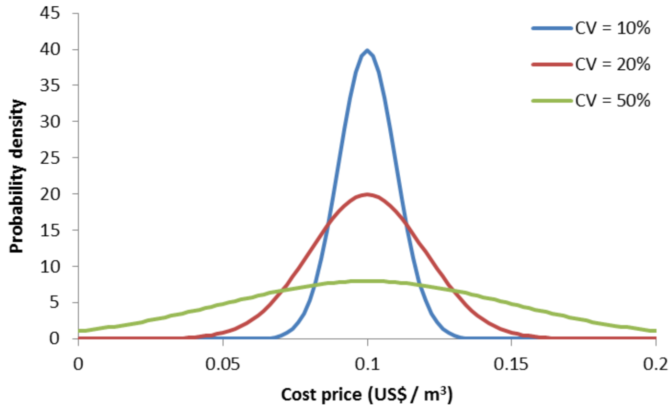

Figure 66 Probability density for the marginal costs of reducing irrigated areas assuming a coefficient of variation of 10%, 20% and 50%

Based on these distributions we perform a Monte Carlo analysis for CVs of 10%, 20%, 30%, 40% and 50% respectively by taking the following steps:

- Step 1: We randomly sample from the marginal cost distribution that belong to the selected CV and this results in 9 marginal cost prices for each measure.
- Step 2: We determine the total cost of adaptation to close the water gap for the AVG scenario using these prices.
- Step 3: We repeat the first two steps 25 times and based on this we can estimate the uncertainty in the total cost of adaptation for a certain CV.

8.2.3 Discussion and results

In the MENA region there is very considerable variation between different GCMs and the resulting impact on the water resources. This is particularly true for Egypt which is highly depending on trans-boundary water from the Nile and its upstream basin covers a large part of Africa. Table 19 shows the differences between the three climate projections. In the DRY projection the unmet demand is a factor 2 higher than the AVG projection. The total costs are however a factor 4 higher because the average unit cost has doubled. These costs have doubled because more expensive measures are required to close the water gap.

Table 19 Differences in unmet demand, total cost of adaptation and average unit costs for the three different climate change projections (DRY, AVG, WET)

Scenario	Unmet demand (MCM)	Total cost of adaptation (million US$)	Average unit cost (US$/m³)
DRY	61,867	46,581	0.75
AVG	31,647	11,321	0.36
WET	0	0	-

In Table 20 the results of the sensitivity analysis are shown in Table 20. The table shows how the uncertainty in marginal costs reflects in the uncertainty in total costs for adaptation for the AVG projection. The table shows that the coefficient of variation in total costs for adaptation is less than the coefficient of variation in the marginal costs. This is caused by the fact that some costs will in reality be higher than the assumed average and some will be lower. The situation that the costs for all measures are simultaneously higher or lower is not likely to occur and therefore the CV in total cost for adaptation is lower. The average total cost for adaptation for Egypt is 11321 million US$ and if a CV of 10% is assumed in the marginal costs than there is a 95% chance that the total adaptation costs are in the range between 9731 million US$ and 12911 million US$. If the marginal costs are highly uncertain (CV = 50%) than the range is between 1872 million US$ and 20770 million US$.

Table 20 Results of the sensitivity analysis for the AVG projection

CV marginal costs (%)	CV total costs for adaptation (%)	95% range in total adaptation costs (million US$)	
10	7	9,731	12,911
20	16	7,765	14,877
30	22	6,264	16,378
40	32	4,022	18,620
50	42	1,872	20,770

It is interesting to compare this uncertainty in total costs for adaptation with the uncertainty in the climate change projections. The data in Table 19 shows that the CV in total costs for adaptation between different climate change projections equals 214% (standard deviation = 24294 million US$) and thus the uncertainty in climate change projections is far larger than the uncertainty in marginal costs. Even if we assume a very high uncertainty in marginal costs (CV = 50%) than the resulting uncertainty in total costs of adaptation is more than 5 times smaller than the uncertainty that results from the climate change projections.

8.2.4 Conclusions

The following key conclusions are drawn based on this case study:

- The uncertainty in total costs for adaptation resulting from uncertainty in climate change projections is much higher than the uncertainty in unit costs for adaptation measures.
- The uncertainty in total costs for adaptation is less than the uncertainty in the marginal costs estimates, because the marginal costs for individual adaptation measures are normally distributed and in reality never all consistently higher or lower.

8.3 Green Water Management in Morocco

8.3.1 Introduction

From the results presented in this report it is clear that all countries will be negatively affected by climate change and increases in water demand over the coming 40 years. Morocco is one of the countries that can be expected to experience severe water shortages and has limited options to overcome these shortages. The options explored to overcome the projected water shortage in this study have been divided in three types of measures:

- increasing the productivity of current water use
- expanding supply
- reducing demand by shifting the economy towards less water-consuming activities

There is however an alternative measure receiving quite some attention over the last years called “Green Water Management” (GWM). Some countries, for example Kenya and Morocco, are currently exploring these options in the context of an IFAD (International Fund for Agricultural Development) supported project referred to as “Green Water Credits”[17]. It is believed that of all water resources, green water is probably the most under-valued resource. Yet it is responsible for by far the largest part of the world's food and biomass production. The concept of green water was first introduced by Falkenmark et al. (1998), to distinguish it from blue water, which is the water that occurs in rivers and lakes. The storage medium for green water is the soil. The process through which green water is consumed is transpiration. Hence the total amount of green water resources available over a given period of time equals the accumulated amount of transpiration over that period. Green water is transpiration resulting directly from rainfall, hence we are talking about rainfed agriculture, pasture, forestry, etc. Green water excludes transpiration due to irrigation.

Green water management is claimed to have substantial benefits. Water productivity can be significantly increased, the hazards of flood and drought mitigated, and rural livelihoods secured by two fundamental improvements in soil management: increasing infiltration of rainfall into the soil, thereby cutting storm runoff, and shifting unproductive evaporation to productive water use. More infiltration means banking water in soils and aquifers which feed river base flow; less storm runoff means less soil and bank erosion, less flooding, and less siltation of streams and reservoirs.

A detailed discussion on which and how these measures can be implemented and their potential impact is described in WOCAT (World Overview of Conservation Approaches and Technologies)[18]. A full analysis of the impact of Green Water Management is beyond the scope of this demonstration pilot, but the focus here will be on the potential it will have on overcoming water shortages in the future.

8.3.2 Methodology

For this case study it was assumed that by implementing Green Water Management less water will be consumed. In order to explore how these measures will have a positive impact on reducing water shortage now and in the future we explored the following four scenarios:

- A: reduction of 1% in actual evapotranspiration on arable land and permanent crops
- B: reduction of 5% in actual evapotranspiration on arable land and permanent crops
- C: reduction of 1% in actual evapotranspiration on arable land, permanent crops, and meadows and pastures
- D: reduction of 5% in actual evapotranspiration on arable land, permanent crops, and permanent crops and meadows and pastures

[17] http://www.isric.org/UK/About+ISRIC/Projects/Current+Projects/Green+Water+Credits.htm

[18] http://www.wocat.net/

The total area of land in Morocco is about 45 million ha and the distribution for the most relevant land classes is shown in Figure 67. The areas where these Green Water Measures will be implemented, based on the previous four scenarios, are:

- Arable and permanent crops: 9 million ha (19% of land area)
- Arable, permanent crops, and meadows and pastures: 29 million ha (64% of land area)

These assumptions are used on the PCR-GLOBWB results from Morocco and implemented in the Morocco component of the MENA-WOF model as described in Chapter 6.

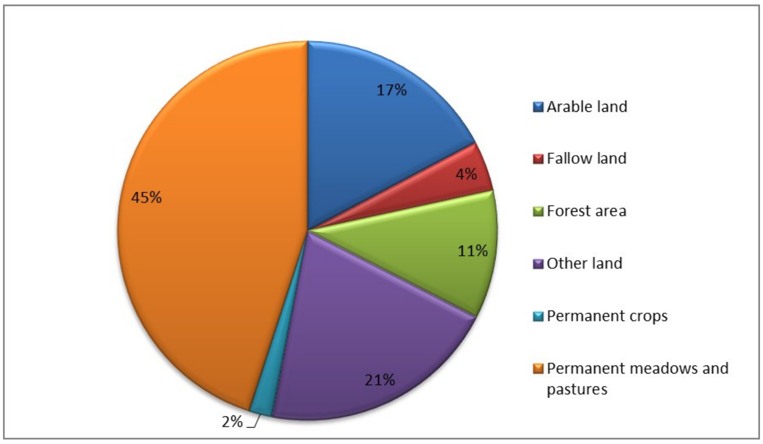

Figure 67. Land cover Morocco (*source: FAOStat*).

8.3.3 Results and Discussion

The total water shortage (Unmet Demand) for Morocco was estimated to be about 15,500 million m^3 (MCM) per year in 2040-2050 (Figure 68). Implementing one of the four Green Water Measures as defined in the previous section will reduce this water shortage by 140 to 2,502 MCM each year (Figure 69), which is substantial and worthwhile to explore further in more detailed analysis.

Obviously, costs are associated to implementing these Green Water Measures. These costs vary considerably among different types of measures and among the specific conditions at the location. Some first rough estimates vary from US$ 5 up to US$ 50 per hectare (Hof et al., 2007). When relating these costs to estimated effectiveness the unit costs vary between US$ 0.06 and 0.90 per m^3 of water. It is clear that if the lower cost range options are feasible, these Green Water Management options are very attractive to be further explored.

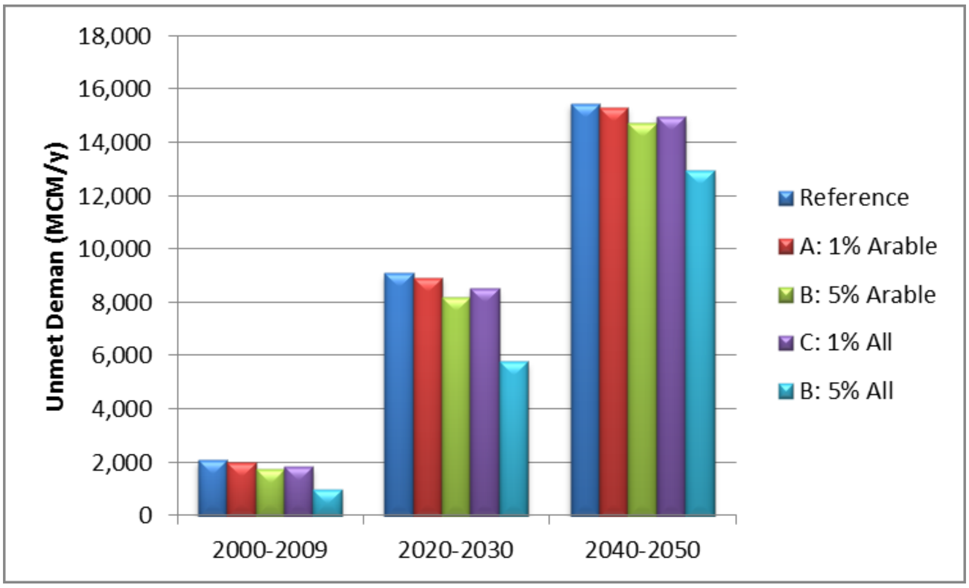

Figure 68. Unmet demand for Morocco using the four Green Water Measure options.

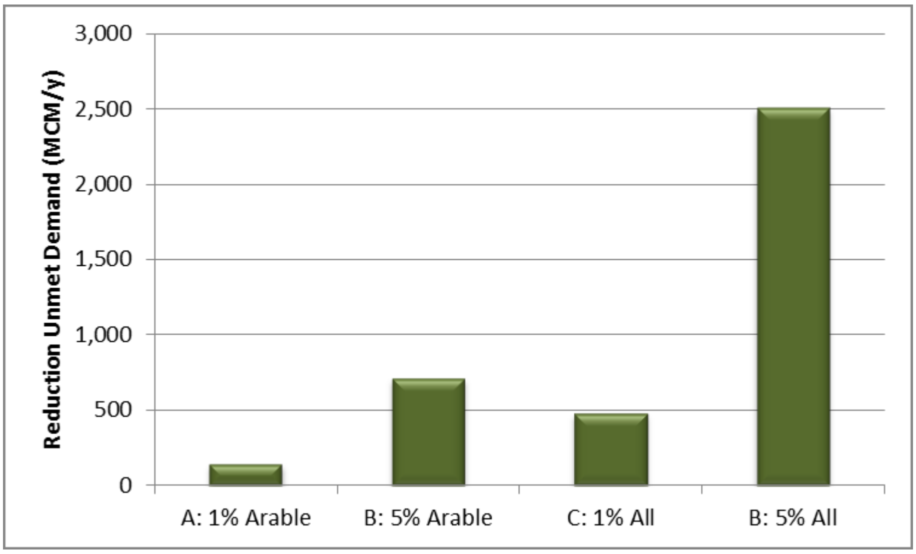

Figure 69. Reduction in unmet demand for the four Green Water Measure options (2040-2050).

9 Conclusion and Discussions

The current study shows that the total annual adaptation costs to bridge the water demand gap in the MENA region are very high. Annual costs during 2040-2050 for bridging the water gap of 199 km^3 per year are t US$ 103 billion ever year (at 2010 prices) for the average climate projection. Costs to close the water gap of 283 km^3 for the dry climate projection and 85 km^3 for the wet climate projection are respectively US$ 212 billion and US$ 27 billion per year (at 2010 prices).

Results indicate that the distribution of these costs among the various countries in the MENA region is very skewed. More than 57% of the burden of US$ 103 billion has to be covered by three countries; Iraq (27%), Saudi Arabia (19%) and Morocco (11%). Egypt, Iran and Yemen have to bear in total about 28% of the burden. However, the per capita costs are highest for U.A. Emirates, Iraq, Israel, Qatar and Saudi Arabia.

An important issue is the percentage of GDP countries have to spend every year on overcoming this looming water crisis. This percentage of GDP is a combination of actual water shortage in 2050, available options to reduce water shortage and, very relevant, the projected GDP for the specific country. Countries that will have to spend a large portion of their GDP include Yemen, Iraq, Morocco, and Jordan.

The water availability cost curve's use is limited to comparing measures' financial costs to close the gap. It is important to note that these might be different from the economic costs for society as a whole, which includes also externality costs, opportunity costs, subsidies etc. By not taking such costs into consideration, measures with low financial cost but high economic costs –like measures that use highly subsidized energy- might seem to be cost-effective whereas in reality they are not attractive for society as a whole. The cost curve is, however, not prescriptive, but should be considered as a guide for comparing the financial costs of measures for decision-making. Of course, financial cost is not the only basis on which choices are made. As the 21 countries, even in the same region, face different economic costs regarding the various measures, this study focuses for clarity only on the financial costs. The general assessment presented in this paper should therefore be interpreted with care. It is recommended for future research to study the economic costs in a number of countries in more detail.

The water gap as found in this study is a combination of climate change impacts and autonomous developments such as an increase in population and economic development. It is interesting to estimate which percentage of the costs can be attributed to climate change and which costs can be attributed to increased demand owing to economic development and population growth. For the average climate projection 16% of the water shortage can be attributed to climate change in 2050. In 2030 the total water shortage due to climate change is lower compared to 2050, but the increase in water demand due to autonomous developments outpaces climate change impacts in 2050. Therefore the percentage of shortage attributed to climate change for 2030 is higher (25%). For the dry projection 37% of total shortage can be attributed to climate change in 2050, while for the wet projection it is negligible compared to the increase in demand because of changes in population and GDP.

It is interesting to compare these figures with three recently published studies:

- The Economics of Adaptation to Climate Change (World Bank, 2010)
- "2030 Water Resources Group" (2009)

- Making the Most of Scarcity (World Bank, 2007)

The study “Economics of adaptation to climate change” (World Bank, 2010) comes to the conclusion that developing countries have to spend 0.12% of their GDP in 2050 to overcome the negative impact of climate change. Although costs in 2030 will be lower compared to 2050, in terms of GDP the number is higher (0.2%) as the economies are projected to grow substantially between 2030 and 2050. Actual amounts to be spent are provided for the MENA region separately and are estimated to be in the range of US$ 2.5 to 3.6 billion per year in 2050. These numbers are substantially lower than the about US$ 100 billion found in the current study. One reason is that the EACC study considered only climate change, while the current study includes also changes in demand by irrigation, domestic and industry. If we consider that the current study indicates that climate contributes for about 16% of additional water shortage, estimates of costs provided by the current study are still considerably higher. One of the underlying reasons for this is that the costs of overcoming water shortage are not linear; the larger the water gap the more one relies on expensive measures.

The “2030 Water Resources Group” (2009) concluded that for the MENA region the increase in demand would be 99 km^3 in 2030. The current study indicates that the increase in demand would be 74 km^3 in 2030. It is however not completely clear what the “2030 WRG” study means by “increase in demand”. The study sometimes refers to this “increase in demand” when water shortage is meant, which are obviously different issues. The current study makes a clear distinction between total demand in 2030 (335 km^3); increase in demand in 2030 (74 km^3); total unmet demand in 2030 (134 km^3); and increase in unmet demand in 2030 (91 km^3).

The study “Making the Most of Scarcity” (World Bank, 2007) was not specifically focussing on climate change but provides some general estimates on the costs of water as a whole. The study indicates that the required investment (both capital and operating costs) ranges between 1 and 3 percent of GDP per year.

The current study as presented in this report is a clear response to these previous studies which poses the questions on which reforms and interventions can be best considered to overcome water shortage. The main conclusion of the current study is that the water crisis will be amplified substantially over the coming decades over all climate projections. Appropriate actions as explored in this study are able to overcome this water gap at expected costs of about US$ 100 billion per year in 2050, which is about 0.5% of the projected GDP in 2050 for the MENA region as a whole. Based on this figure it will be feasible to bear the burden of adaptation measures in 2050, however, policies should be put in place now to act timely.

The World Bank support study of the “2030 Water Resources Group” concluded that “*meeting all competing demands for water is in fact possible at reasonable cost*”. The study also conclude that: “*This outcome will not emerge naturally from existing market dynamics, but will require a concerted effort by all stakeholders, the willingness to adopt a total resource view where water is seen as a key, cross-sectoral input for development and growth, a mix of technical approaches, and the courage to undertake and fund water sector reforms*.” The current study provides the initial direction towards a selection of adaptation measures. The current study indicates that a mix of approaches is required and that these are country specific. Country-specific studies are needed to explore these approaches more in-depth in close collaboration with policy makers and planners and take steps towards concrete actions.

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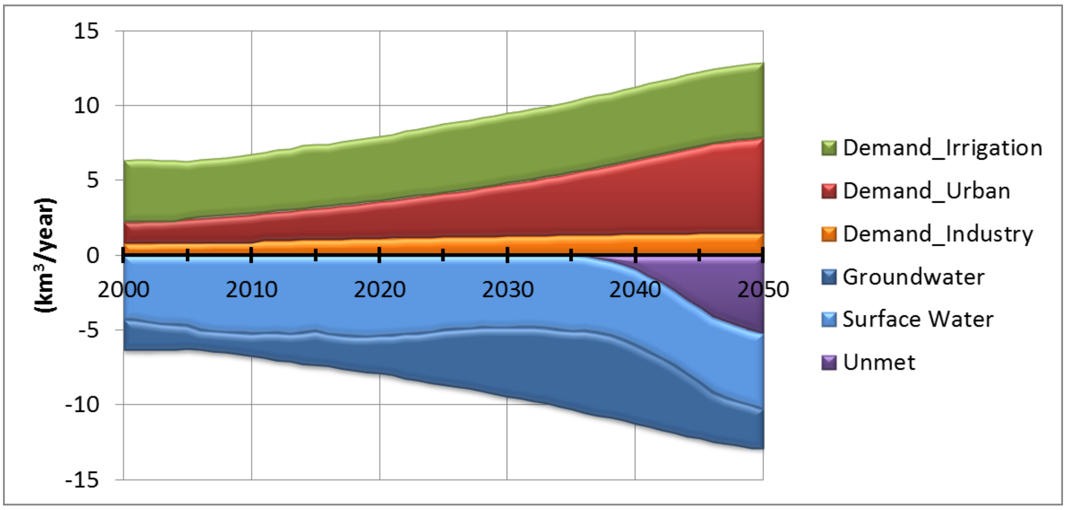
Appendix A: Impact climate change individual countries, graphical for the average climate projection.

Algeria (DZ)



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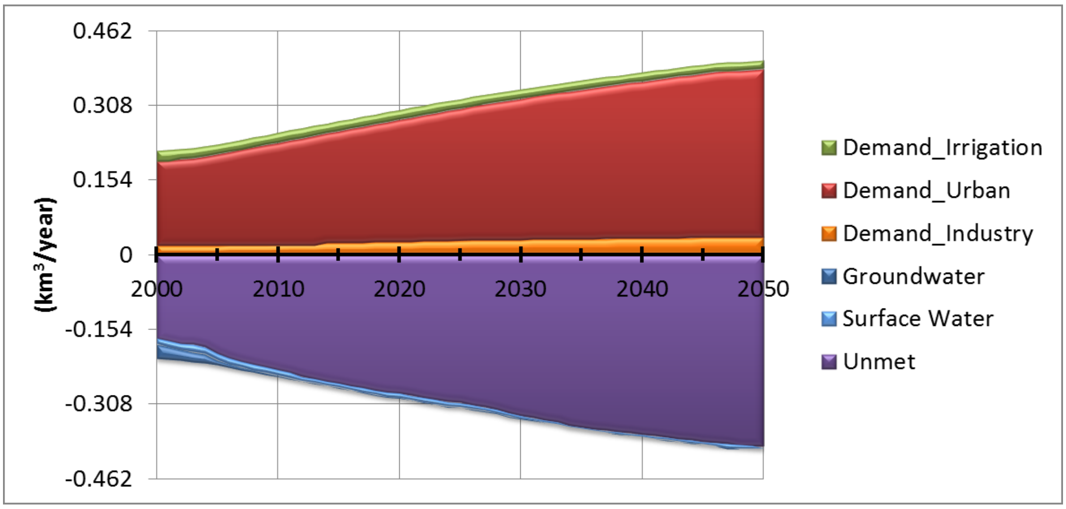
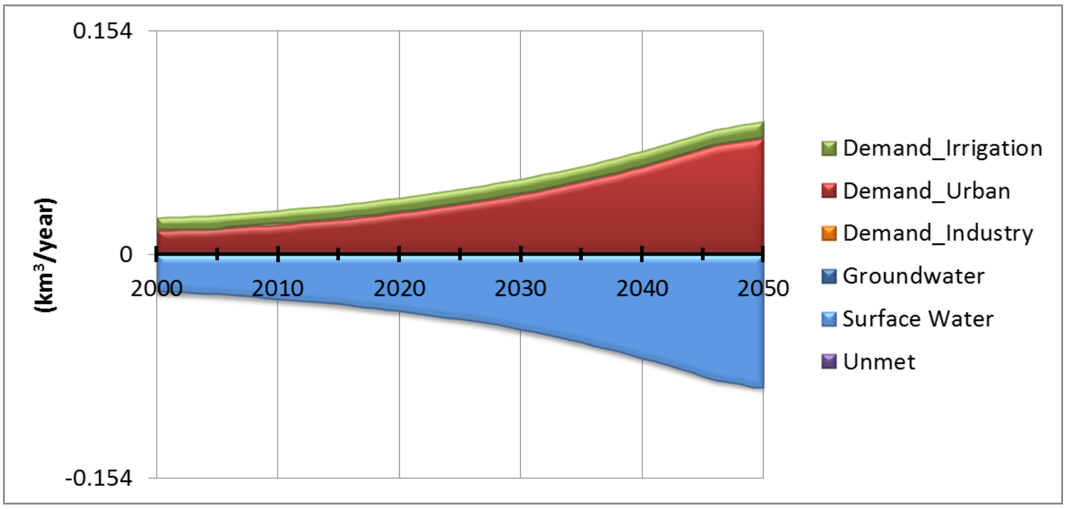
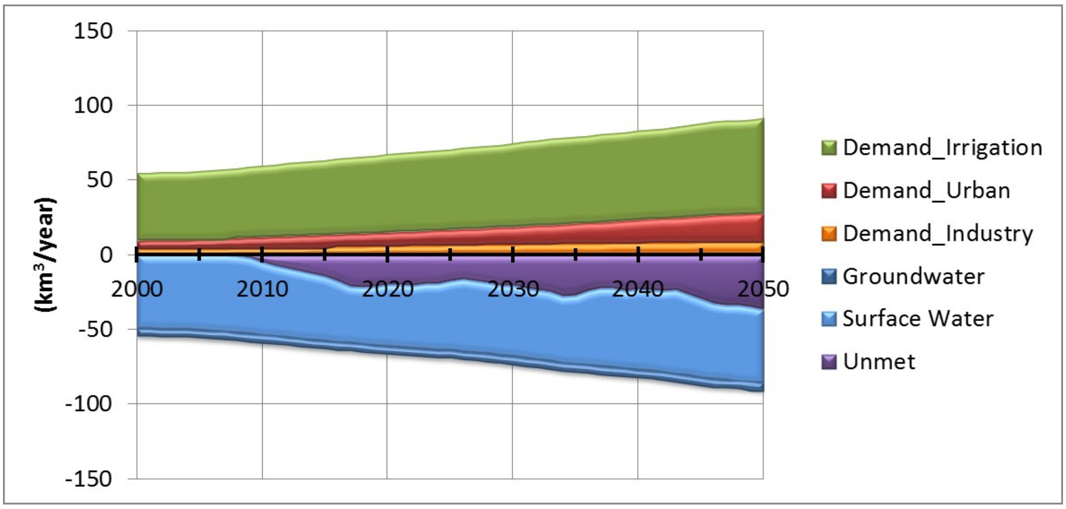


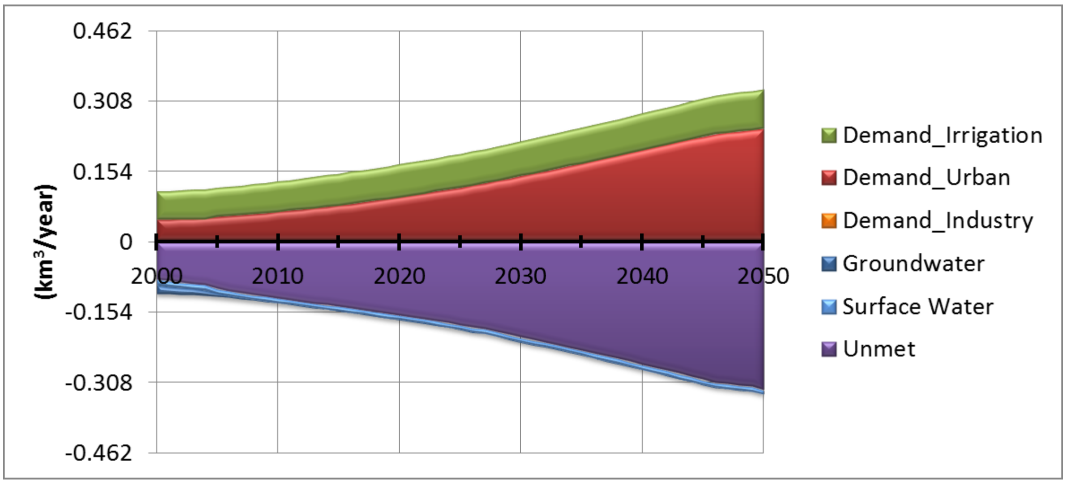
Djibouti (DJ)



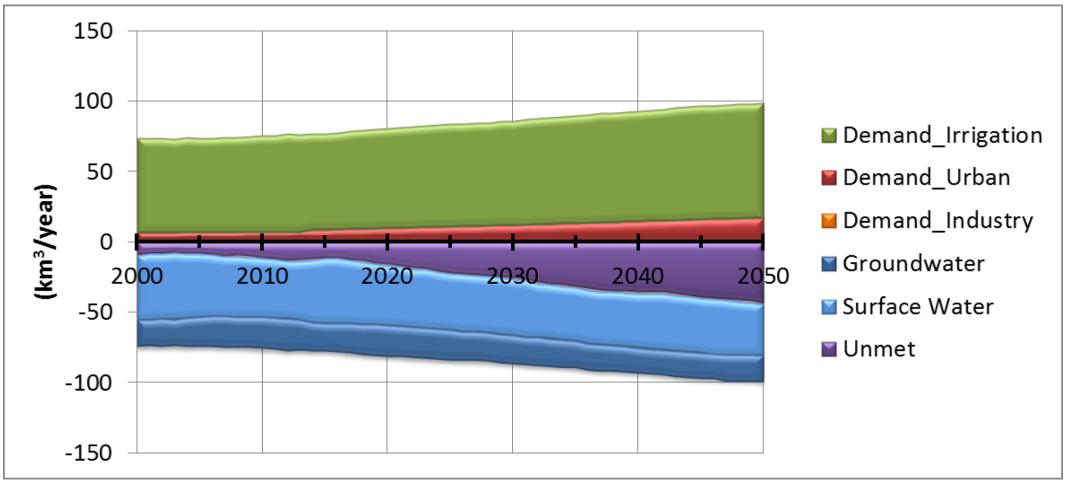
Egypt (EG)



Gaza Strip (GS)[19]

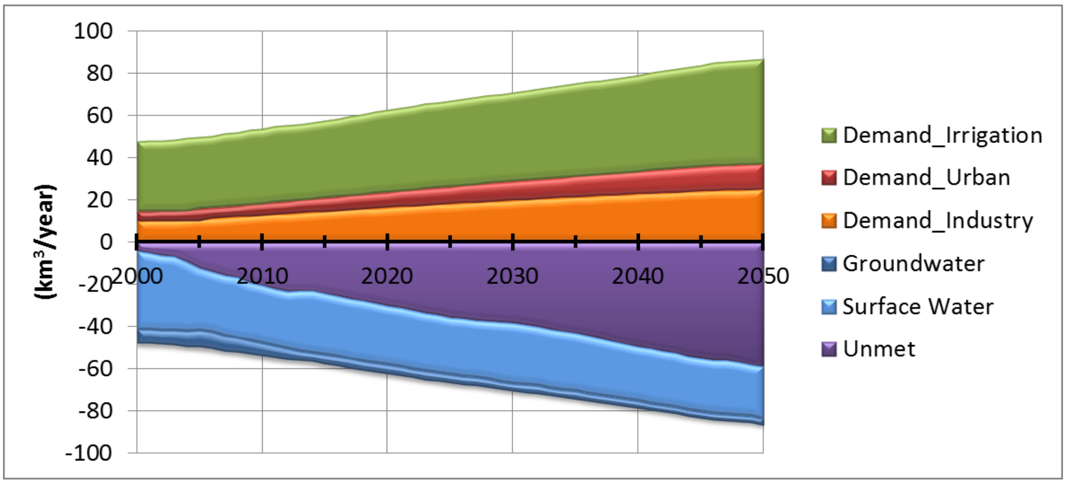


Iran (IR)

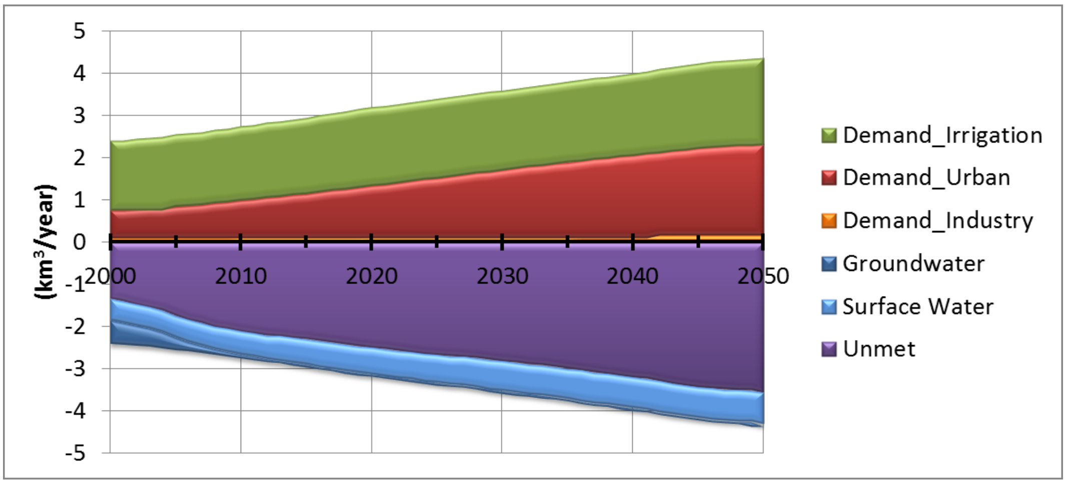


[19] Given their detached location, Gaza Strip and West Bank results will be presented separately.

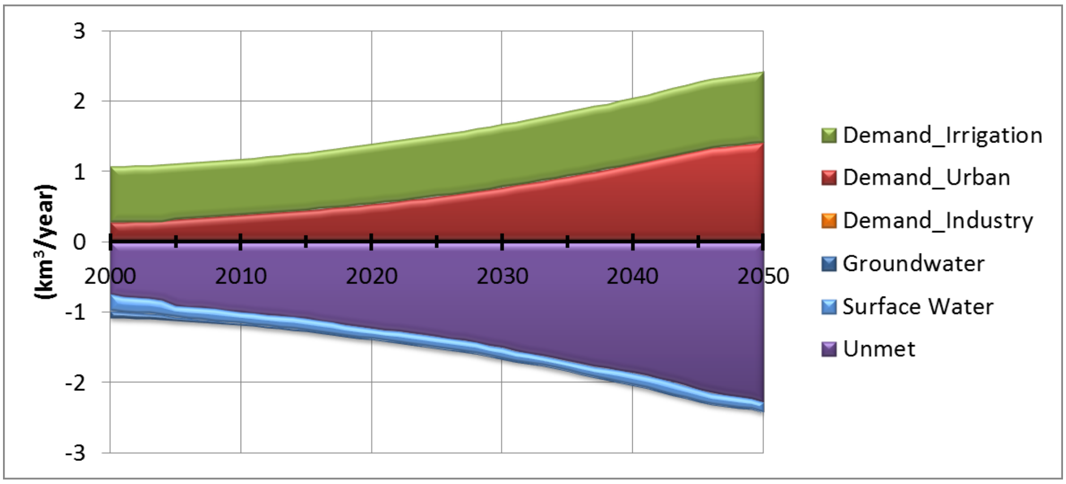
Iraq (IQ)



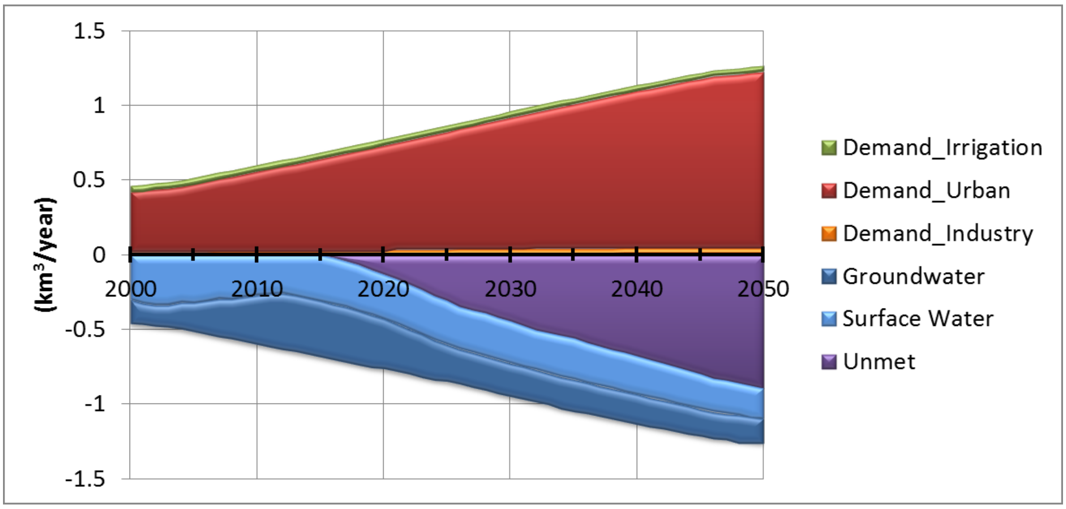
Israël (IL)



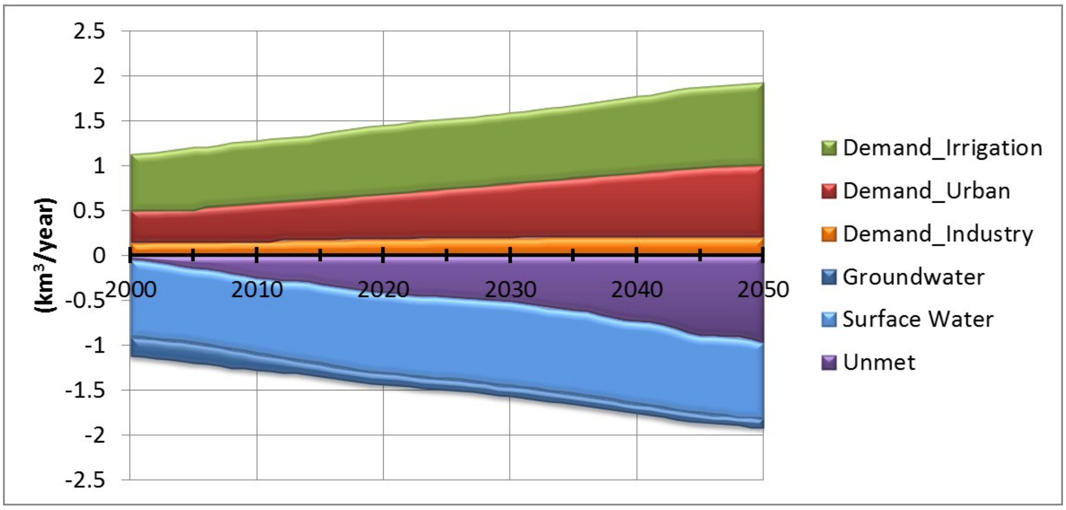
Jordan (JO)



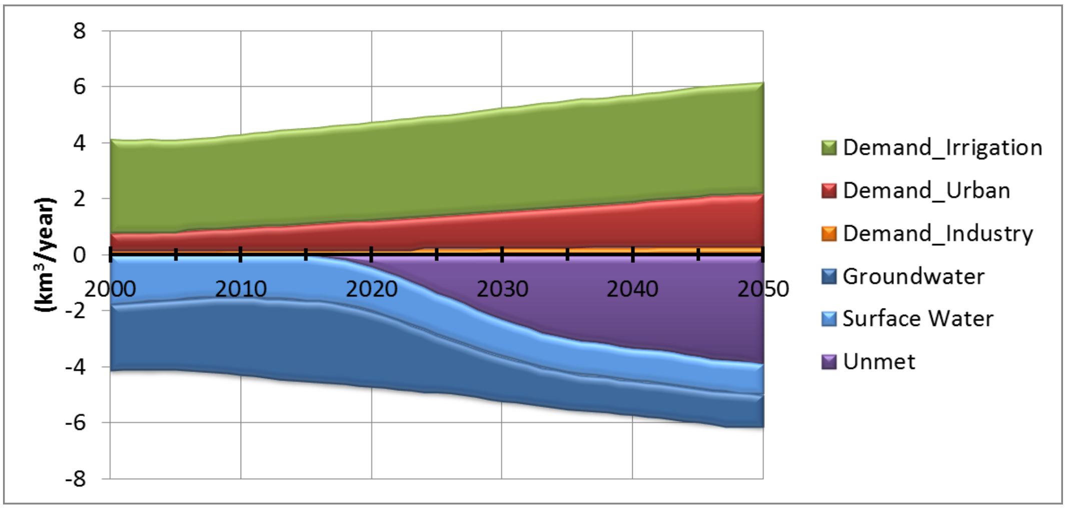
Kuwait (KW)



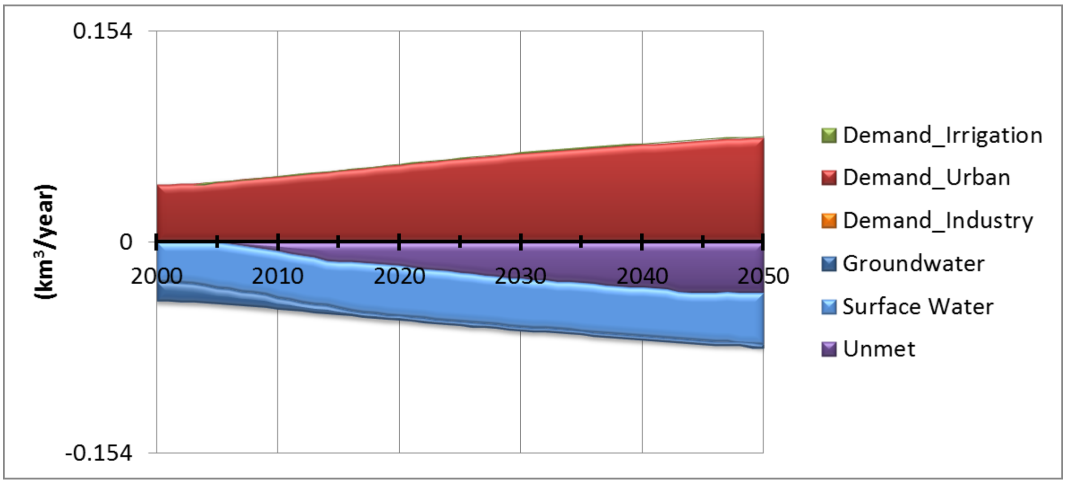
Lebanon (LB)



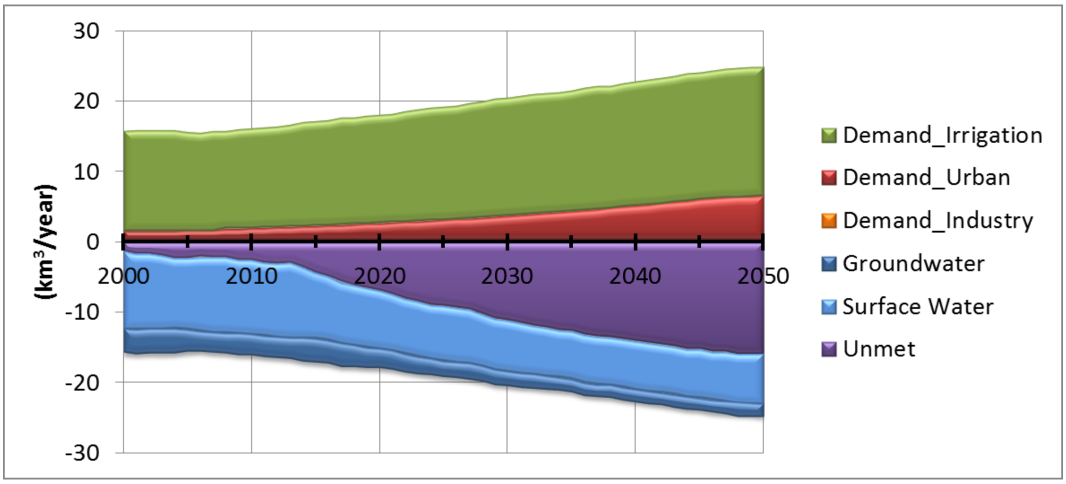
Libya (LY)



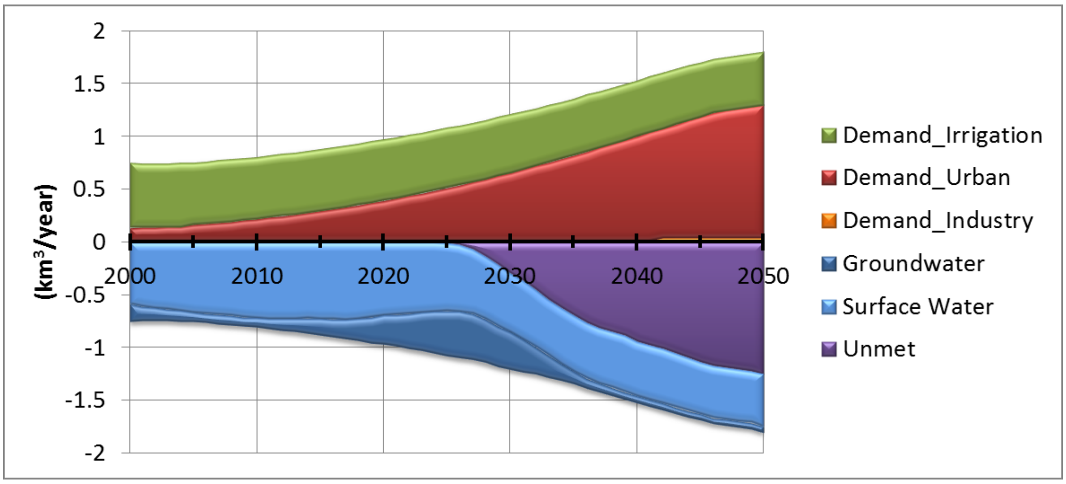
Malta (MT)



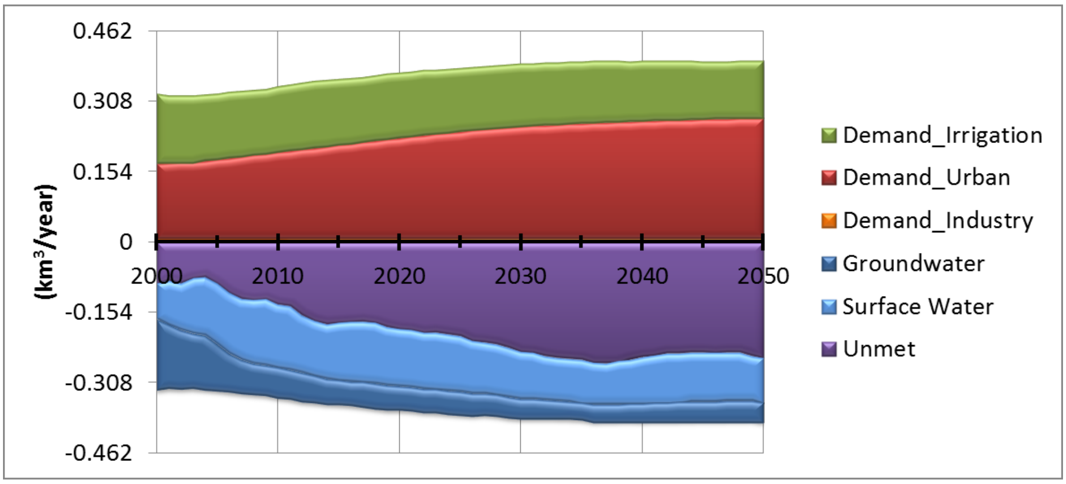
Morocco (MA)



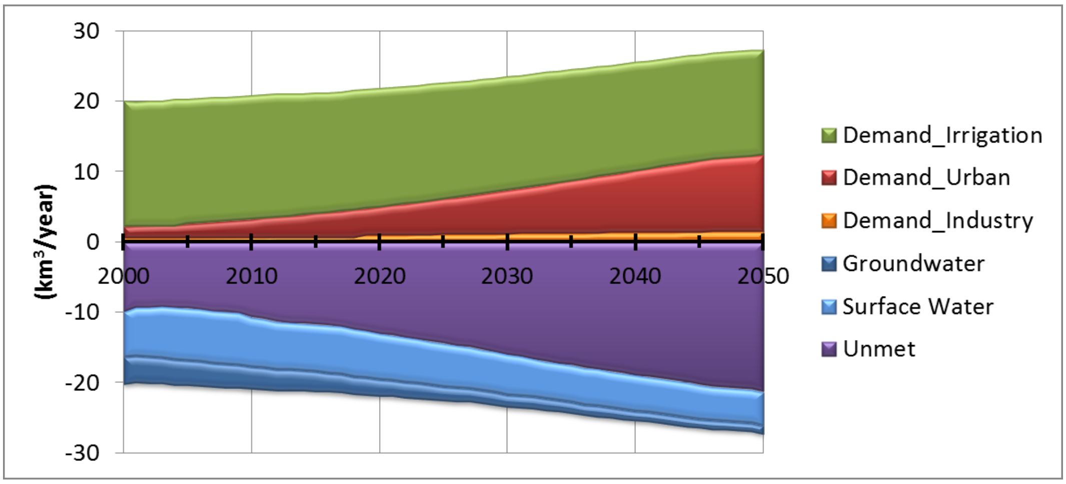
Oman (OM)



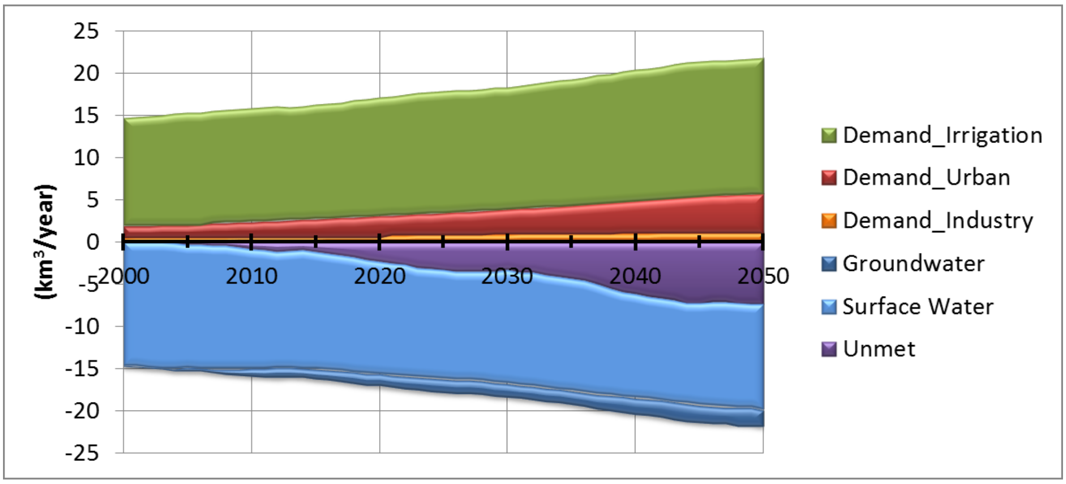
Qatar (QA)



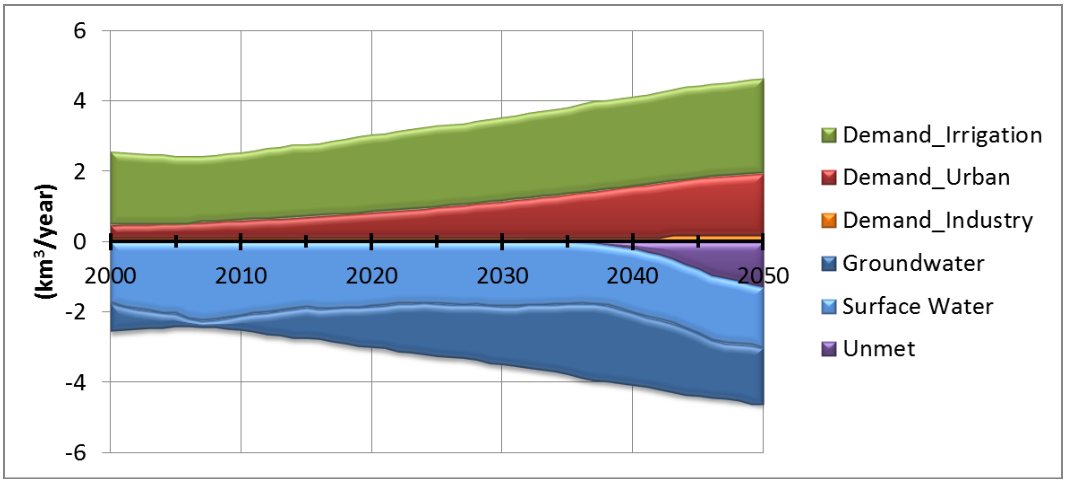
Saudi Arabia (SA)



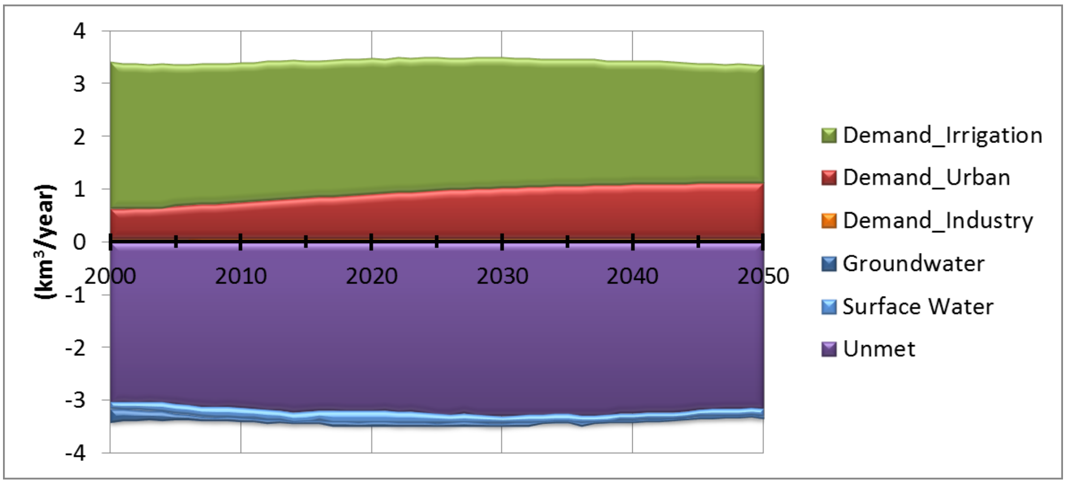
Syria (SY)



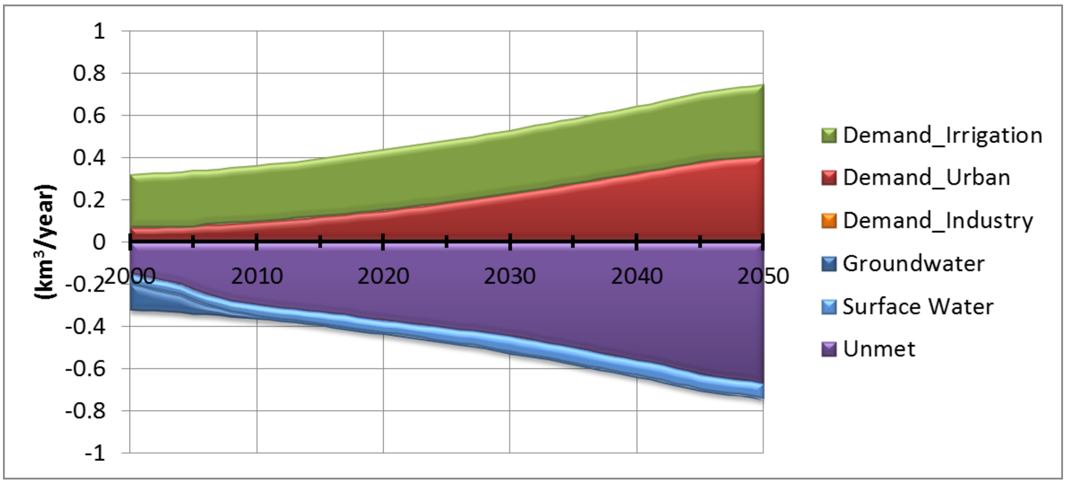
Tunisia (TN)



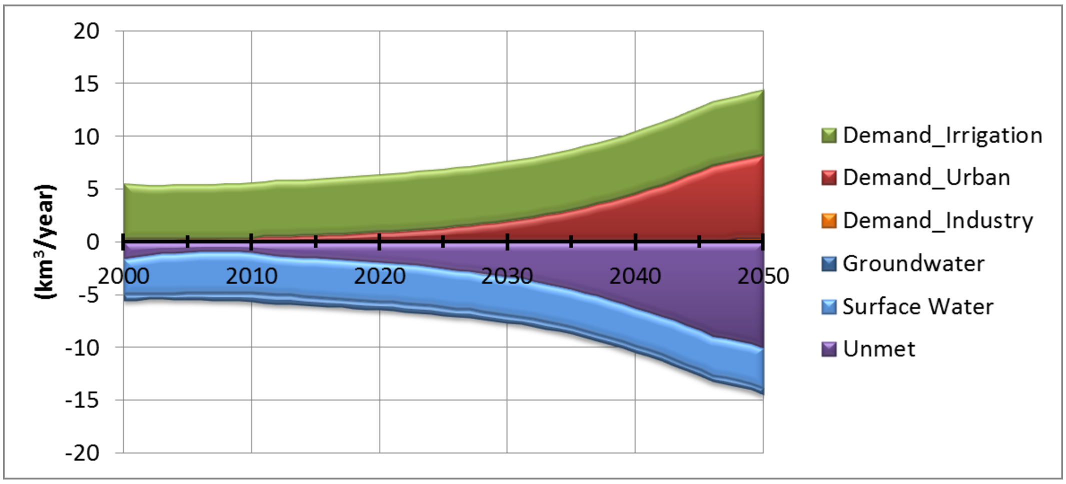
United Arab Emirates (AE)



West Bank (WB)



Yemen (YE)



20
15
10
5
0
-5
-10
-15
-20
(km³/year)
2000
2010
2020
2030
2040
2050
Demand_Irrigation
Demand_Urban
Demand_Industry
Groundwater
Surface Water
Unmet

Appendix B: Impact climate change individual countries for the average climate change projection (AVG)

Water demand, unmet demand and supply for all MENA countries. All data in MCM (million m^3 per year), MENA as a whole in km^3 *(billion m^3 per year).*

(BCM) MENA	2000-2009	2020-2030	2040-2050
DEMAND	261	319	393
Irrigation	213	237	265
Urban	28	50	88
Industry	20	32	41
UNMET DEMAND	42	119	199
Irrigation	36	91	136
Urban	4	16	43
Industry	3	12	20
SUPPLY	219	200	194
Surface water	171	153	153
Groundwater	48	47	41

(MCM) Algeria	2000-2009	2020-2030	2040-2050
DEMAND	6,356	8,786	12,336
Irrigation	3,955	4,621	5,059
Urban	1,523	2,944	5,814
Industry	878	1,221	1,463
UNMET DEMAND	0	0	3,947
Irrigation	0	0	2,148
Urban	0	0	1,448
Industry	0	0	352
SUPPLY	6,356	8,786	8,389
Surface water	4,622	5,037	4,903
Groundwater	1,733	3,749	3,487

(MCM) Bahrain	2000-2009	2020-2030	2040-2050
DEMAND	226	321	391
Irrigation	20	19	17
Urban	184	271	337
Industry	21	30	36
UNMET DEMAND	195	310	383
Irrigation	18	18	17

Urban	160	262	331
Industry	18	29	36
SUPPLY	30	11	8
Surface water	14	10	7
Groundwater	16	2	1

(MCM) Djibouti	2000-2009	2020-2030	2040-2050
DEMAND	28	46	84
Irrigation	9	11	11
Urban	18	34	72
Industry	1	1	1
UNMET DEMAND	0	0	0
Irrigation	0	0	0
Urban	0	0	0
Industry	0	0	0
SUPPLY	28	46	84
Surface water	28	46	84
Groundwater	0	0	0

(MCM) Egypt	2000-2009	2020-2030	2040-2050
DEMAND	55,837	70,408	87,681
Irrigation	45,371	53,478	61,712
Urban	6,003	10,284	17,525
Industry	4,462	6,646	8,443
UNMET DEMAND	2,858	22,364	31,648
Irrigation	2,595	17,692	21,122
Urban	59	2,697	8,002
Industry	204	1,975	2,524
SUPPLY	52,979	48,045	56,033
Surface water	47,470	42,343	50,154
Groundwater	5,509	5,702	5,879

(MCM) Gaza Strip	2000-2009	2020-2030	2040-2050
DEMAND	119	194	313
Irrigation	63	73	82
Urban	50	113	222
Industry	7	8	9
UNMET DEMAND	98	183	301
Irrigation	53	70	80
Urban	39	105	213
Industry	5	8	8
SUPPLY	21	11	12
Surface water	11	10	11

Groundwater	11	1	1

(MCM) Iran	2000-2009	2020-2030	2040-2050
DEMAND	74,537	84,113	97,107
Irrigation	67,153	72,983	80,828
Urban	6,275	9,663	14,627
Industry	1,109	1,467	1,652
UNMET DEMAND	8,988	21,767	39,939
Irrigation	8,563	20,229	35,650
Urban	361	1,336	3,856
Industry	64	202	433
SUPPLY	65,550	62,347	57,168
Surface water	44,135	40,706	38,740
Groundwater	21,414	21,641	18,428

(MCM) Iraq	2000-2009	2020-2030	2040-2050
DEMAND	50,160	67,235	83,803
Irrigation	34,084	40,521	47,901
Urban	4,942	8,304	11,606
Industry	11,134	18,409	24,296
UNMET DEMAND	11,001	35,374	54,860
Irrigation	8,008	23,065	33,822
Urban	920	3,827	6,803
Industry	2,073	8,483	14,235
SUPPLY	39,160	31,860	28,944
Surface water	31,634	27,650	25,423
Groundwater	7,526	4,210	3,521

(MCM) Israel	2000-2009	2020-2030	2040-2050
DEMAND	2,526	3,396	4,212
Irrigation	1,683	1,865	1,992
Urban	728	1,377	2,044
Industry	114	154	176
UNMET DEMAND	1,660	2,670	3,418
Irrigation	1,254	1,667	1,819
Urban	351	902	1,472
Industry	54	101	126
SUPPLY	866	726	794
Surface water	519	676	745
Groundwater	347	50	49

(MCM) Jordan	2000-2009	2020-2030	2040-2050

DEMAND	1,113	1,528	2,276
Irrigation	789	871	975
Urban	286	600	1,233
Industry	38	56	68
UNMET DEMAND	853	1,348	2,088
Irrigation	641	816	939
Urban	188	486	1,089
Industry	25	45	60
SUPPLY	259	180	188
Surface water	193	160	170
Groundwater	67	20	18

(MCM) Kuwait	2000-2009	2020-2030	2040-2050
DEMAND	508	867	1,216
Irrigation	44	42	38
Urban	442	789	1,133
Industry	23	36	44
UNMET DEMAND	0	313	801
Irrigation	0	15	25
Urban	0	286	747
Industry	0	13	29
SUPPLY	508	553	415
Surface water	306	290	231
Groundwater	203	263	183

(MCM) Lebanon	2000-2009	2020-2030	2040-2050
DEMAND	1,202	1,525	1,869
Irrigation	677	781	893
Urban	376	557	776
Industry	149	187	200
UNMET DEMAND	141	472	891
Irrigation	105	320	550
Urban	26	114	271
Industry	10	38	70
SUPPLY	1,060	1,052	978
Surface water	829	927	869
Groundwater	231	125	110

(MCM) Libya	2000-2009	2020-2030	2040-2050
DEMAND	4,125	4,974	5,982
Irrigation	3,287	3,597	3,917
Urban	691	1,163	1,799
Industry	147	214	265

UNMET DEMAND	0	1,382	3,650
Irrigation	0	1,105	2,522
Urban	0	234	983
Industry	0	42	145
SUPPLY	4,125	3,592	2,331
Surface water	1,612	1,481	1,117
Groundwater	2,512	2,110	1,214

(MCM) Malta	2000-2009	2020-2030	2040-2050
DEMAND	45	62	75
Irrigation	1	1	1
Urban	43	60	74
Industry	1	1	1
UNMET DEMAND	0	22	36
Irrigation	0	0	1
Urban	0	21	35
Industry	0	0	0
SUPPLY	44	40	39
Surface water	32	37	36
Groundwater	12	4	3

(MCM) Morocco	2000-2009	2020-2030	2040-2050
DEMAND	15,739	19,357	24,223
Irrigation	13,942	16,115	18,173
Urban	1,403	2,691	5,386
Industry	395	551	665
UNMET DEMAND	2,092	9,110	15,414
Irrigation	1,933	7,949	12,200
Urban	124	964	2,861
Industry	35	196	353
SUPPLY	13,647	10,247	8,809
Surface water	10,440	7,829	6,899
Groundwater	3,208	2,417	1,911

(MCM) Oman	2000-2009	2020-2030	2040-2050
DEMAND	763	1,091	1,709
Irrigation	596	571	521
Urban	148	487	1,143
Industry	20	34	45
UNMET DEMAND	0	24	1,143
Irrigation	0	14	356
Urban	0	10	757
Industry	0	1	30

SUPPLY	763	1,067	567
Surface water	663	650	505
Groundwater	101	417	61

(MCM) Qatar	2000-2009	2020-2030	2040-2050
DEMAND	325	381	395
Irrigation	144	139	127
Urban	173	231	257
Industry	8	11	12
UNMET DEMAND	83	209	246
Irrigation	41	80	82
Urban	40	123	157
Industry	2	6	7
SUPPLY	242	172	149
Surface water	125	119	105
Groundwater	116	53	44

(MCM) Saudi Arabia	2000-2009	2020-2030	2040-2050
DEMAND	20,439	22,674	26,633
Irrigation	17,788	16,450	15,062
Urban	1,972	5,108	10,098
Industry	678	1,116	1,474
UNMET DEMAND	9,467	14,412	20,208
Irrigation	8,441	10,591	11,519
Urban	745	2,961	7,394
Industry	280	860	1,295
SUPPLY	10,972	8,262	6,425
Surface water	7,285	6,107	5,025
Groundwater	3,687	2,155	1,400

(MCM) Syria	2000-2009	2020-2030	2040-2050
DEMAND	15,311	17,836	21,337
Irrigation	13,202	14,358	15,973
Urban	1,490	2,544	4,222
Industry	619	934	1,142
UNMET DEMAND	323	3,262	7,111
Irrigation	292	2,897	6,142
Urban	22	267	763
Industry	9	98	206
SUPPLY	14,988	14,575	14,226
Surface water	14,612	12,961	12,181
Groundwater	376	1,613	2,045

(MCM) Tunisia	2000-2009	2020-2030	2040-2050
DEMAND	2,472	3,295	4,452
Irrigation	1,938	2,304	2,648
Urban	417	841	1,634
Industry	117	151	170
UNMET DEMAND	0	0	837
Irrigation	0	0	587
Urban	0	0	227
Industry	0	0	23
SUPPLY	2,472	3,295	3,616
Surface water	2,059	1,803	1,800
Groundwater	413	1,492	1,816

(MCM) U.A. Emirates	2000-2009	2020-2030	2040-2050
DEMAND	3,370	3,495	3,389
Irrigation	2,691	2,517	2,279
Urban	610	886	1,014
Industry	68	91	96
UNMET DEMAND	3,036	3,243	3,189
Irrigation	2,435	2,346	2,149
Urban	541	813	950
Industry	61	84	90
SUPPLY	334	252	199
Surface water	169	178	144
Groundwater	164	74	55

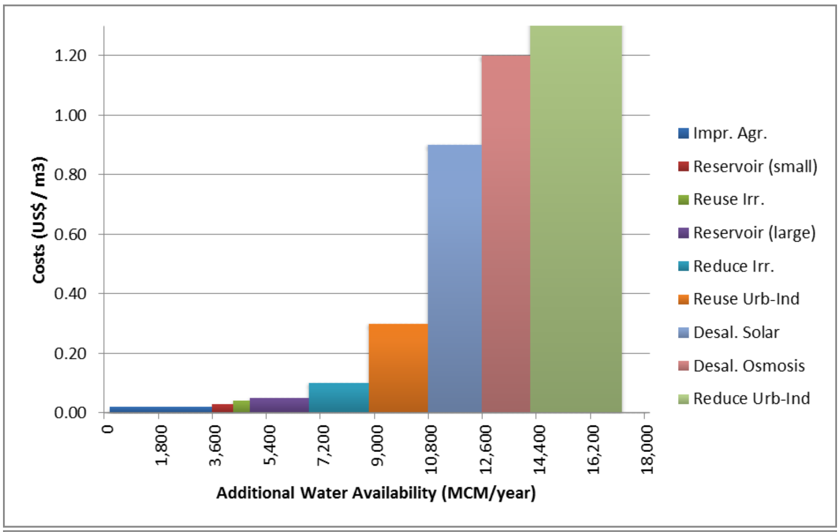
(MCM) West Bank	2000-2009	2020-2030	2040-2050
DEMAND	341	486	709
Irrigation	260	297	331
Urban	72	178	365
Industry	9	12	13
UNMET DEMAND	210	408	624
Irrigation	173	274	317
Urban	33	125	297
Industry	4	8	10
SUPPLY	130	79	85
Surface water	50	69	77
Groundwater	80	10	8

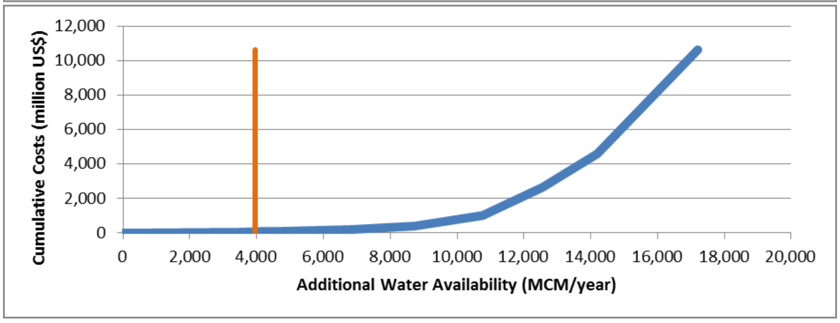
(MCM) Yemen	2000-2009	2020-2030	2040-2050
DEMAND	5,560	7,069	12,889
Irrigation	5,137	5,623	6,081

Urban	341	1,270	6,492
Industry	82	177	316
UNMET DEMAND	1,120	2,573	8,449
Irrigation	1,069	2,120	3,987
Urban	41	398	4,257
Industry	10	54	205
SUPPLY	4,440	4,497	4,440
Surface water	3,777	3,679	3,780
Groundwater	663	818	660

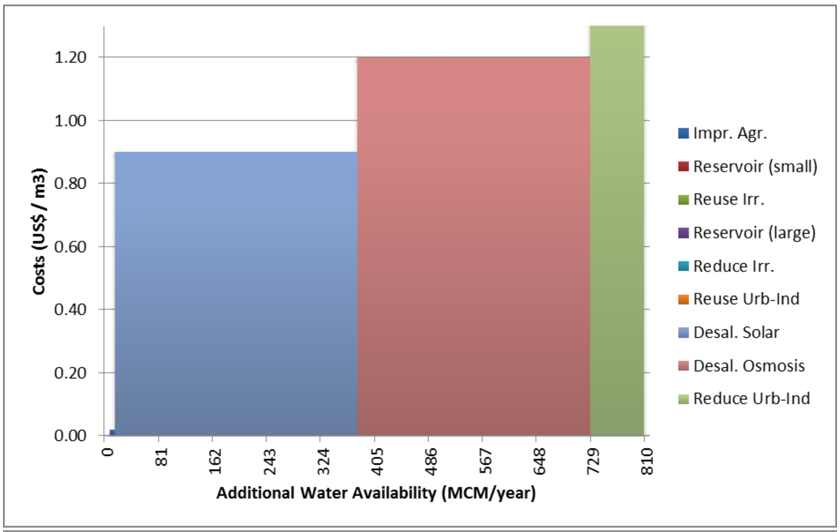
Appendix C: Cost Adaptation Curves

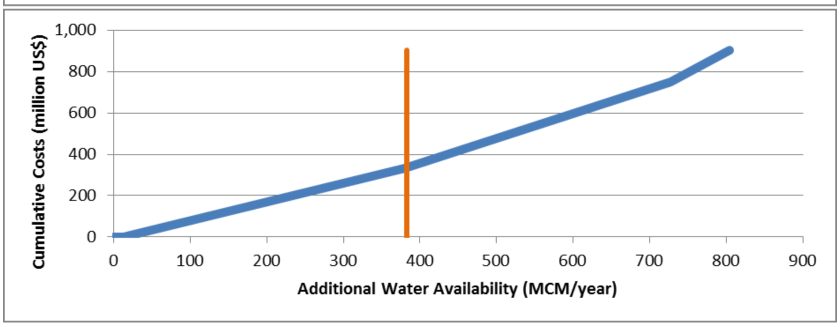
Algeria (DZ)





Bahrain (BH)

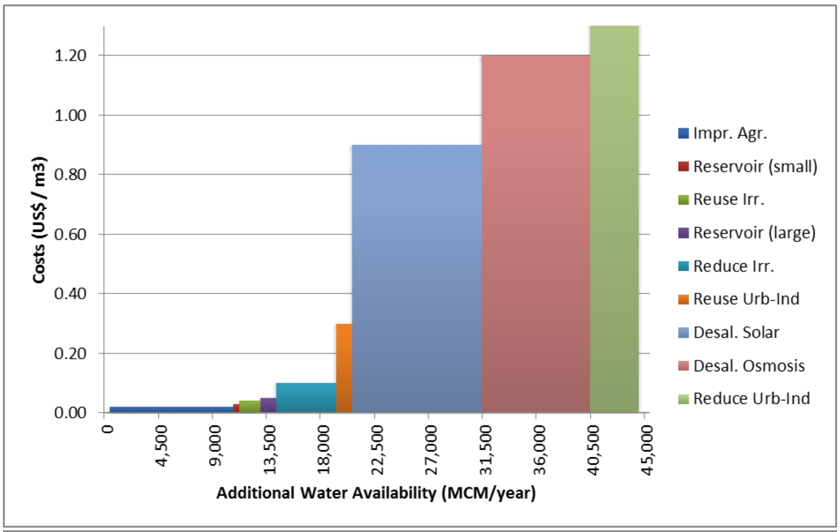


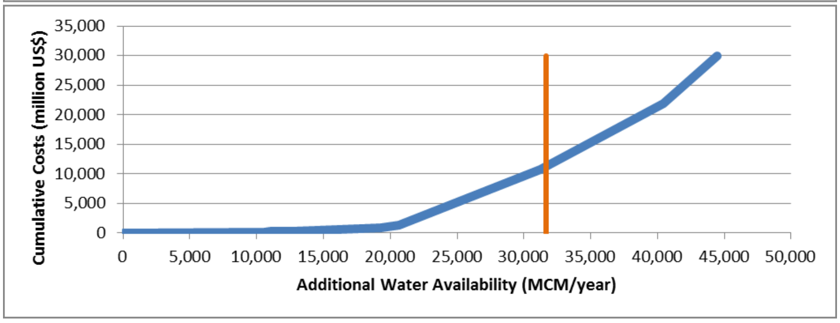


Djibouti (DJ)

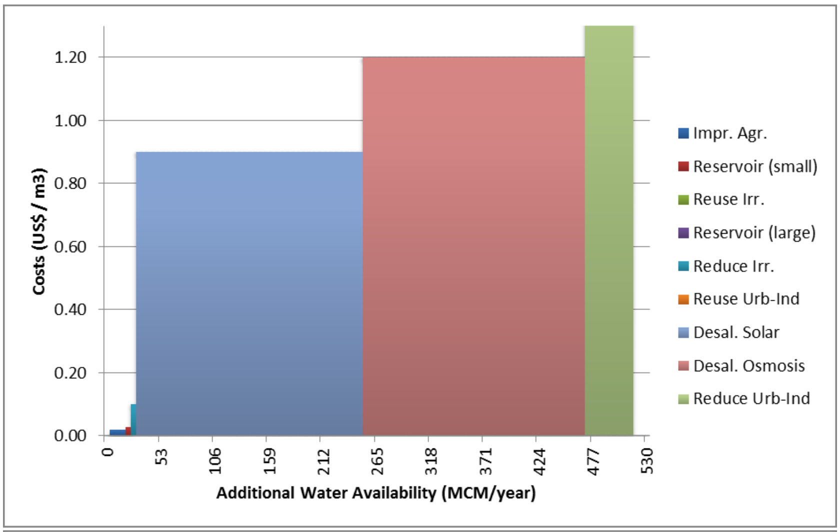
No cost curves, no sever water shortage

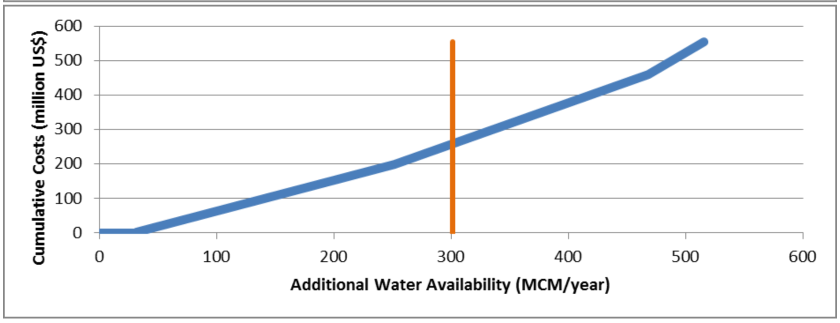
Egypt (EG)



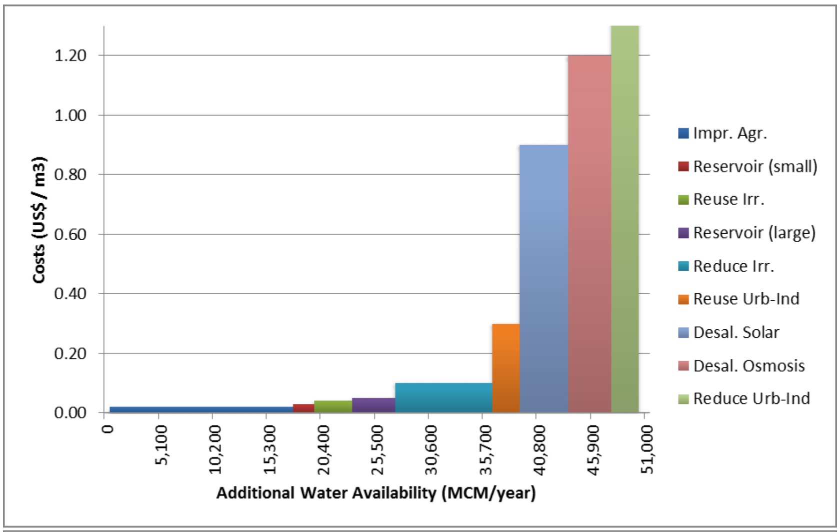


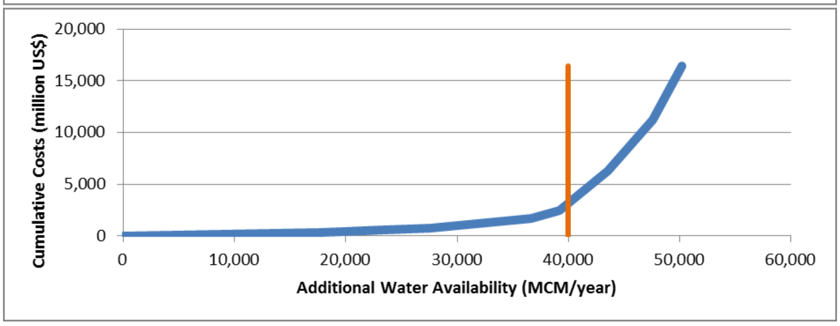
Gaza Strip (GS)



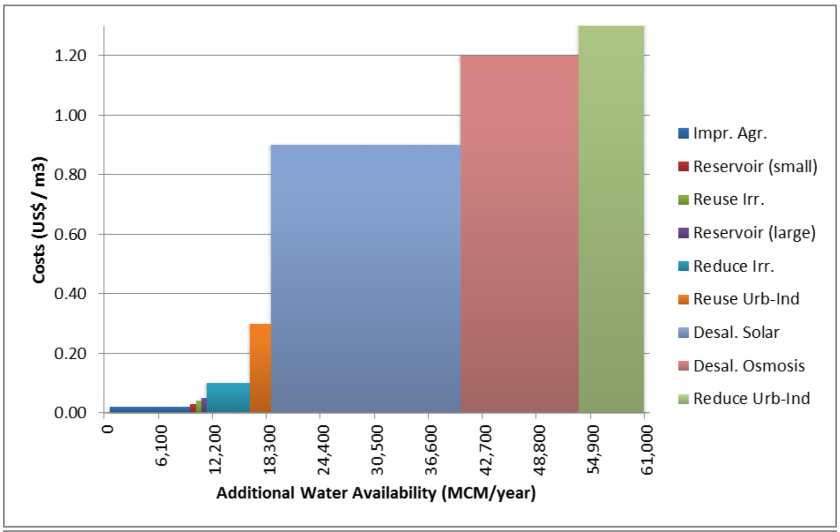


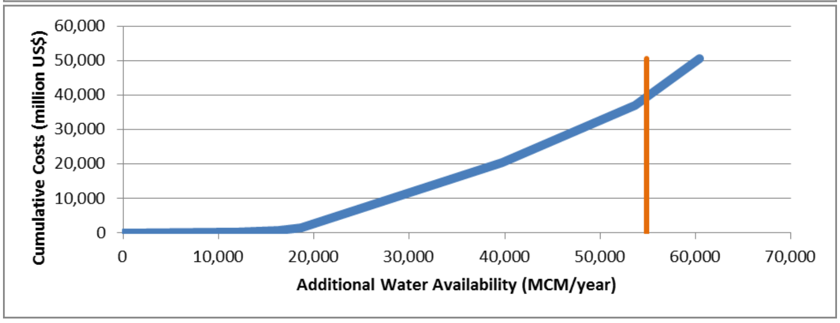
Iran (IR)



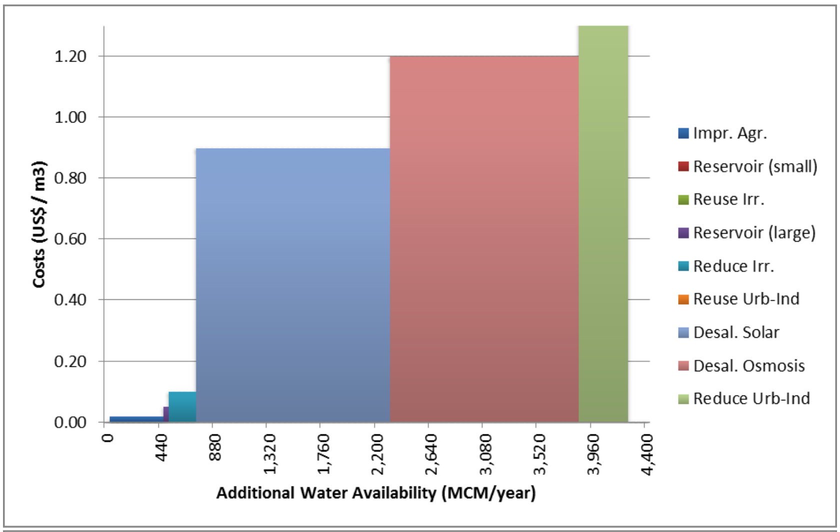


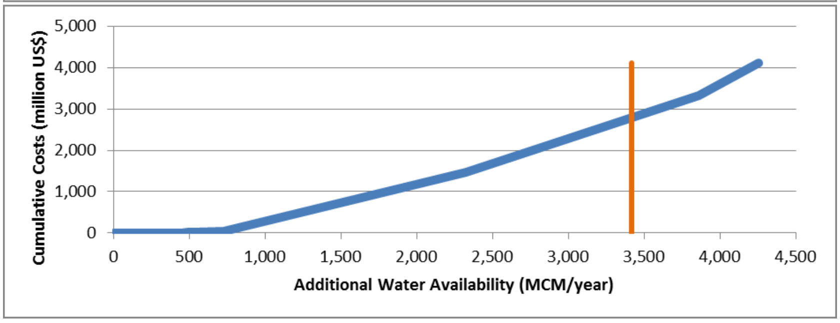
Iraq (IQ)



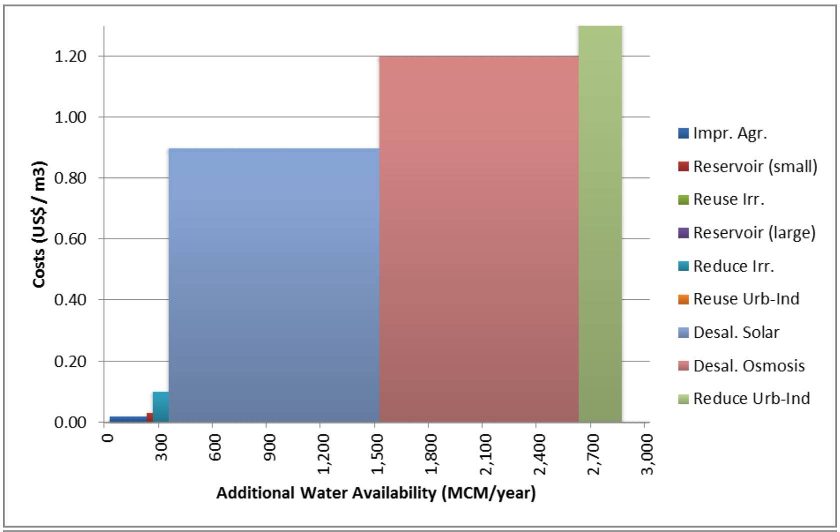


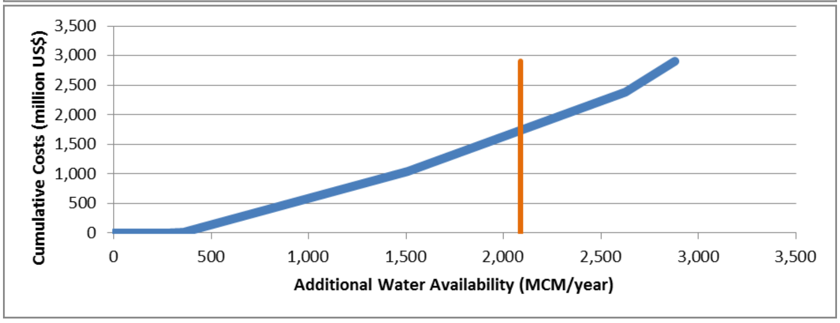
Israël (IL)



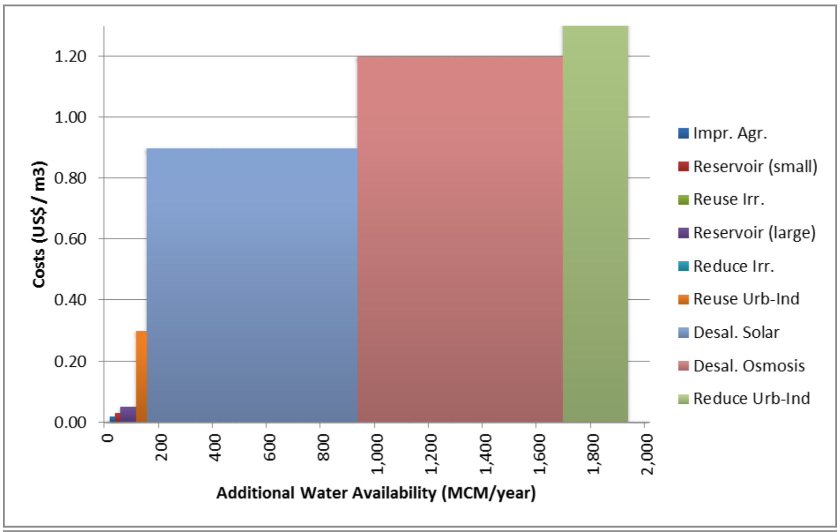


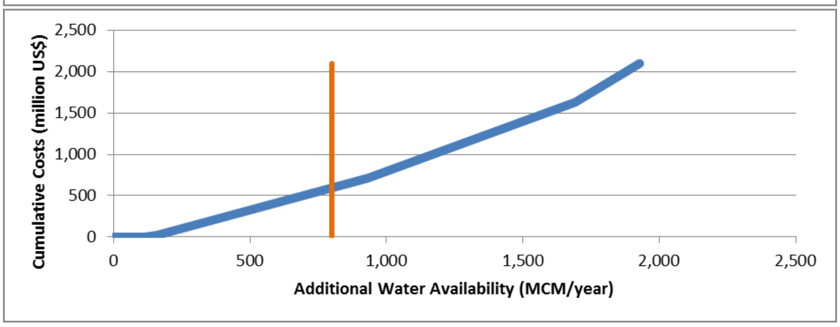
Jordan (JO)



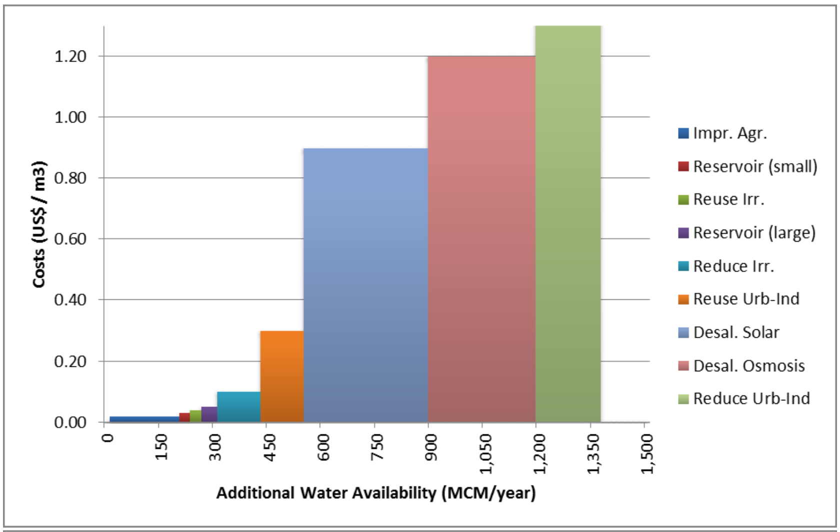


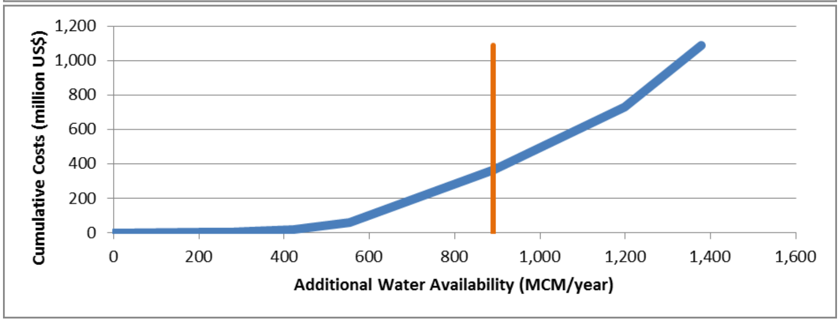
Kuwait (KW)



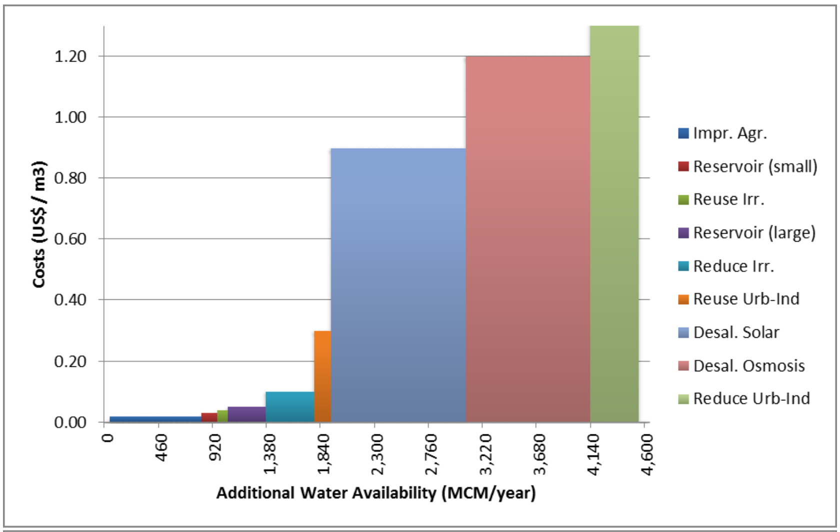


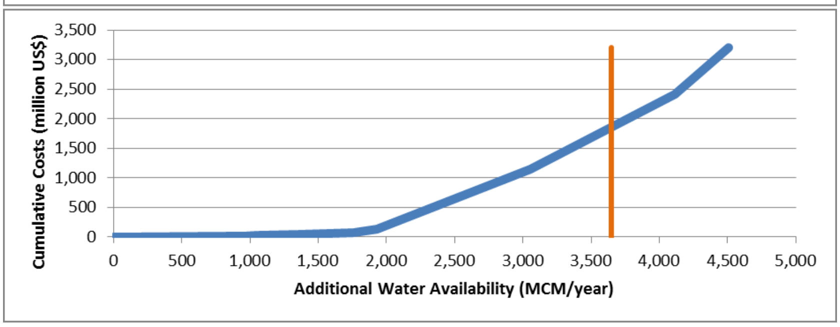
Lebanon (LB)



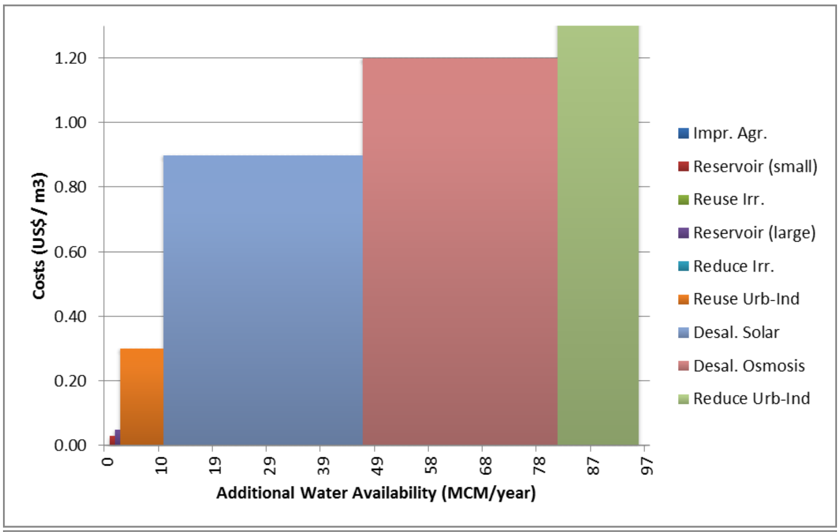


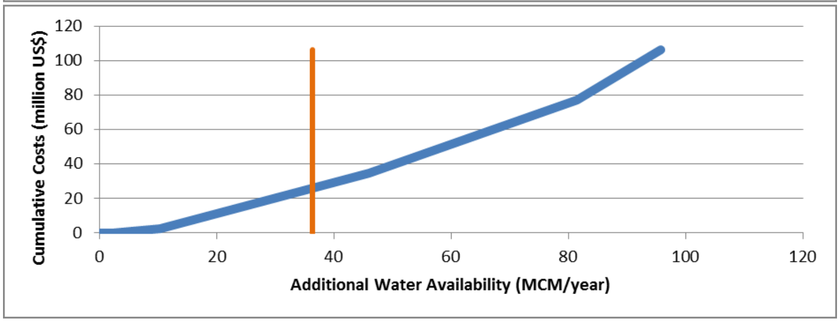
Libya (LY)



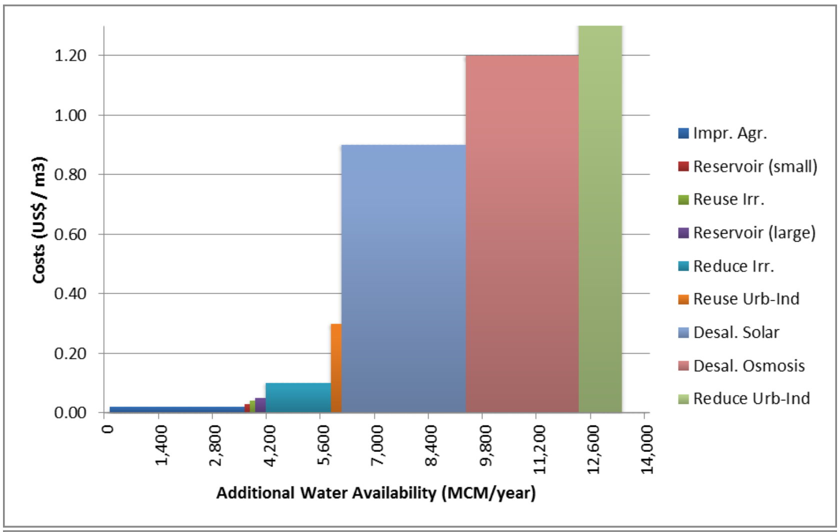


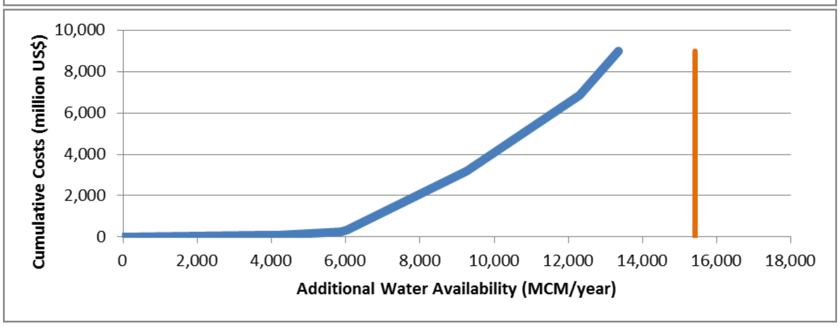
Malta (MT)



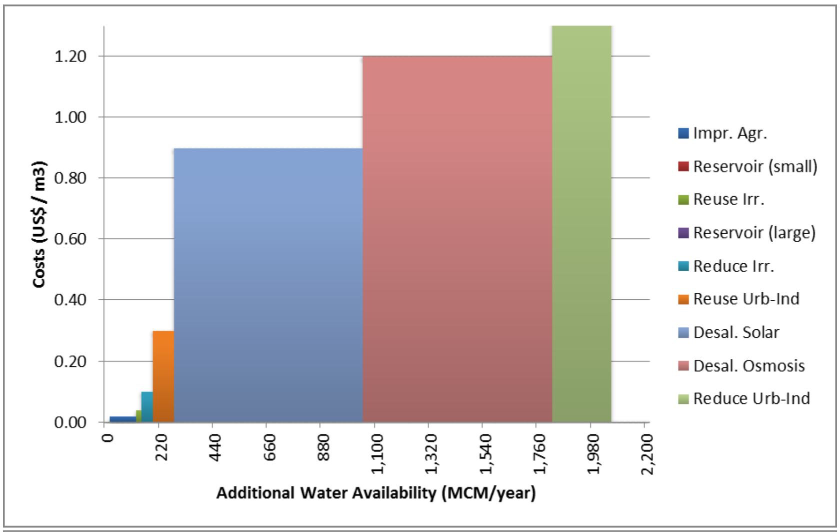


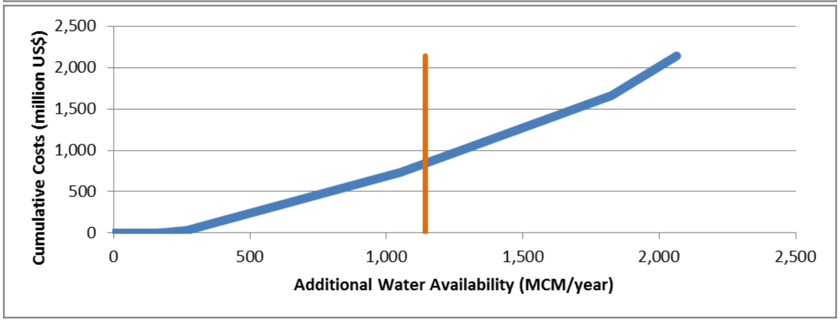
Morocco (MA)



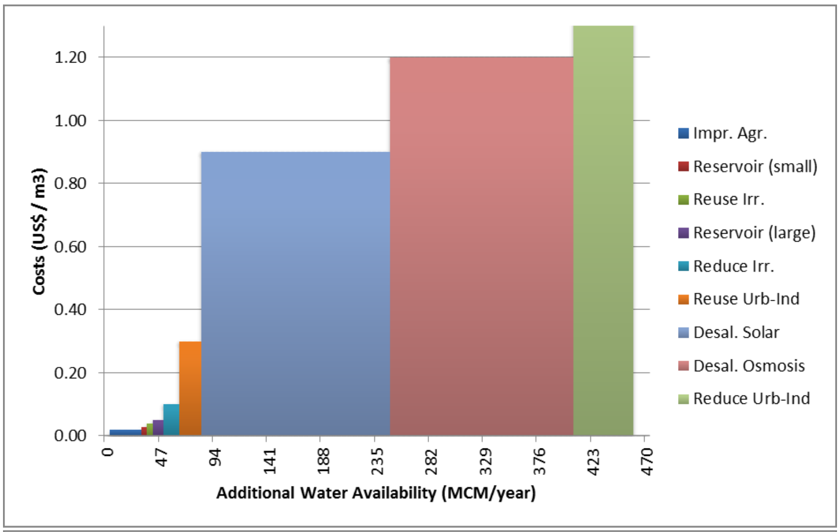


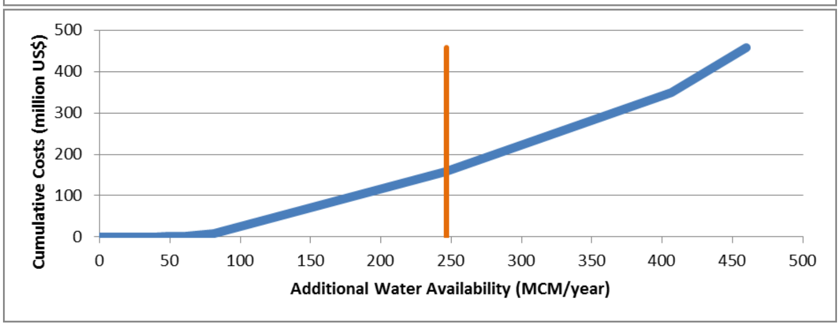
Oman (OM)



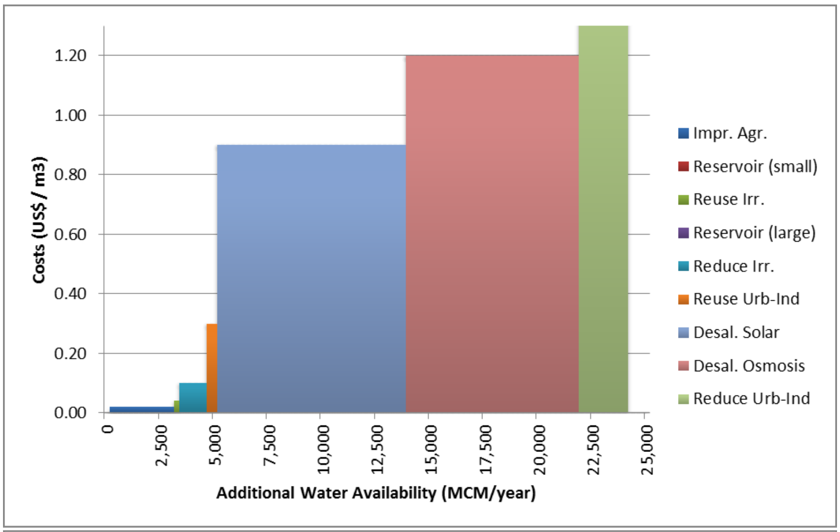


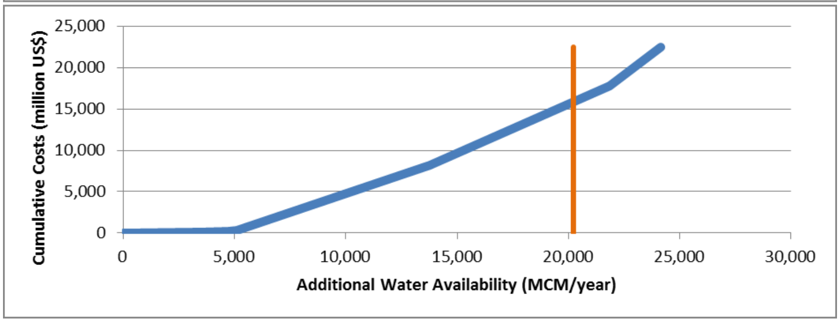
Qatar (QA)



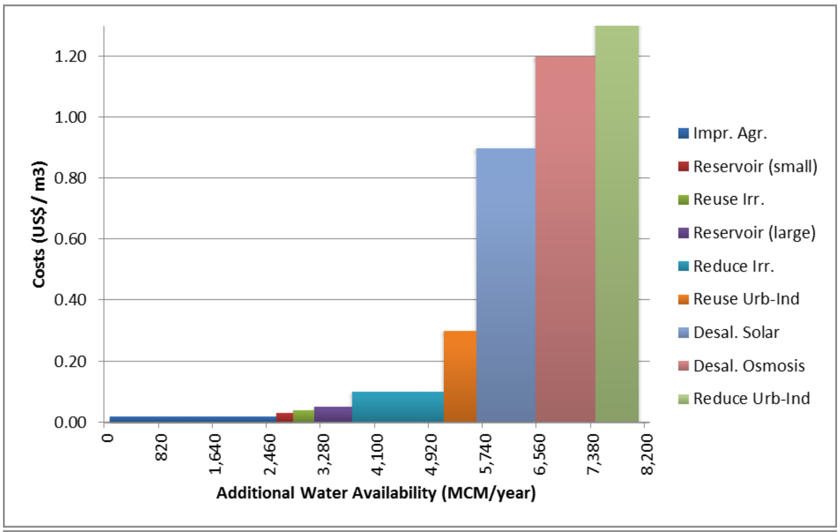


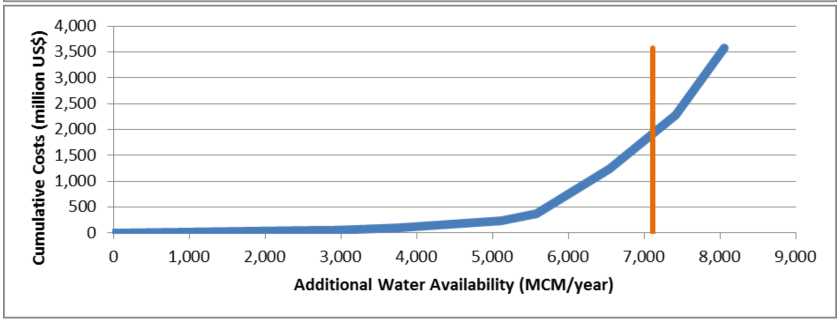
Saudi Arabia (SA)



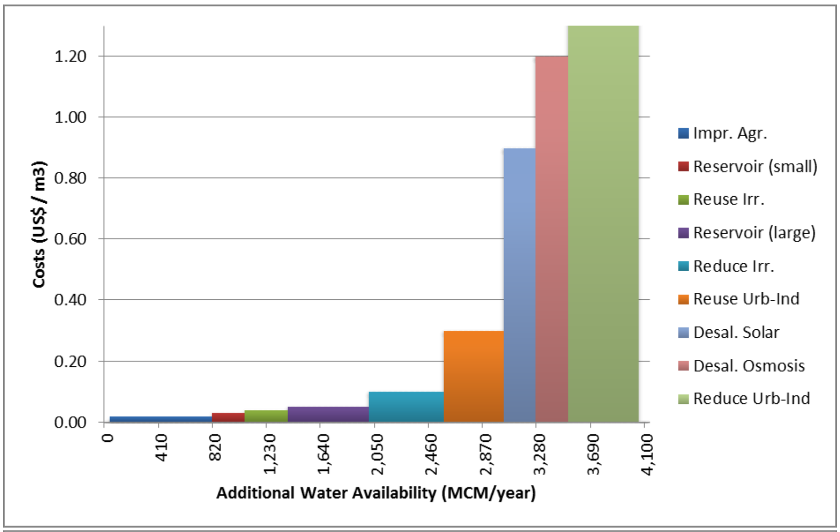


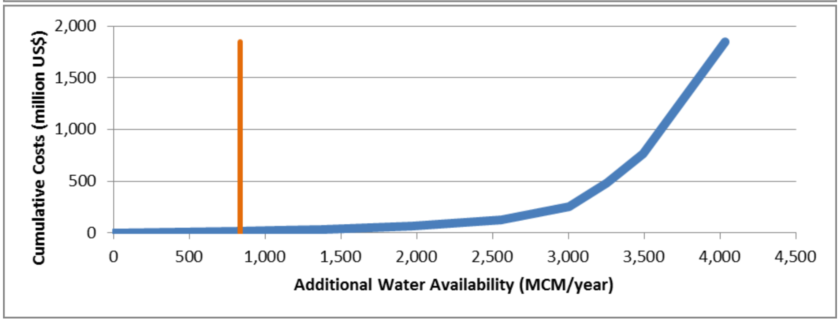
Syria (SY)



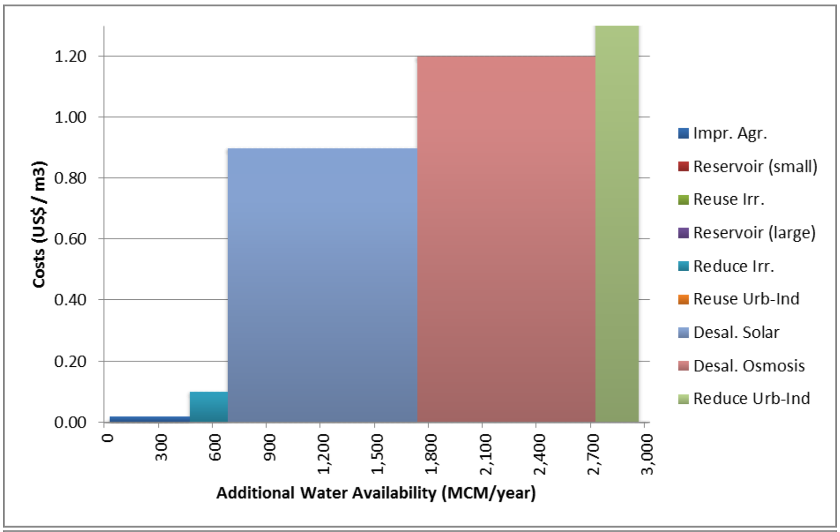


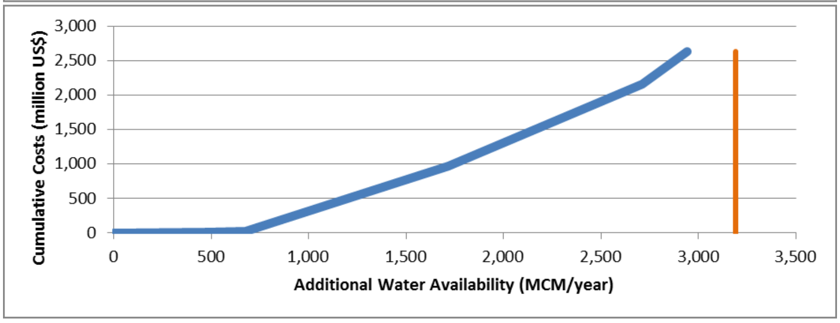
Tunisia (TN)



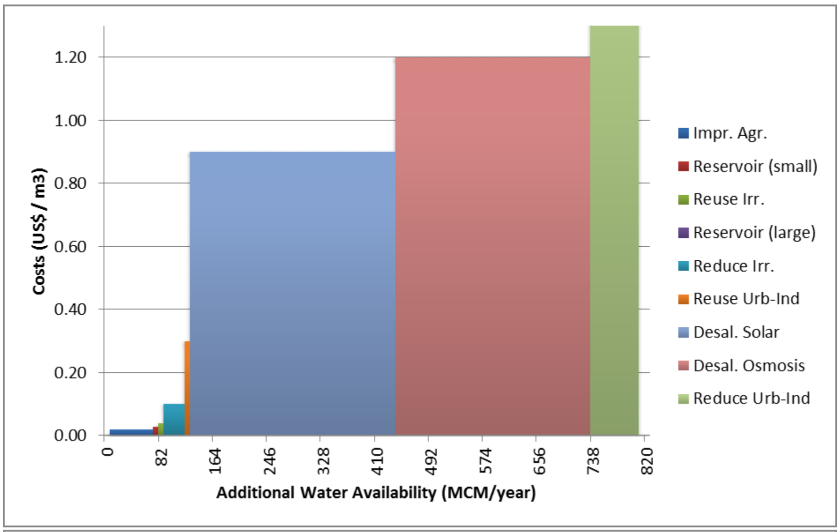


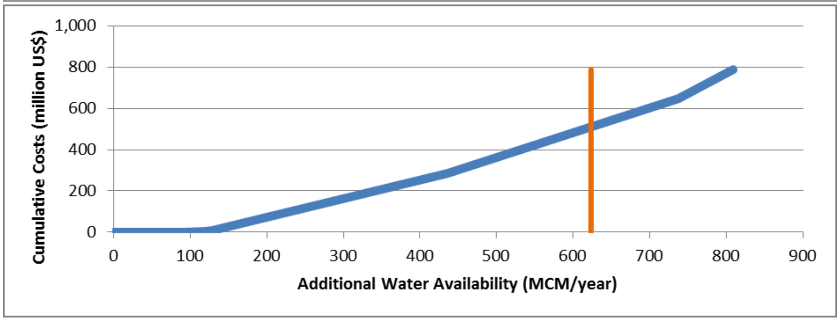
United Arab Emirates (AE)





West Bank (WB)





Yemen (YE)