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Economic concepts to address future water supply–demand imbalances in Iran, Morocco and Saudi Arabia

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SUMMARY

In Middle East and North Africa (MENA) countries, renewable groundwater and surface water supply are limited while demand for water is growing rapidly. Climate change is expected to increase water demand even further. The main aim of this paper is to evaluate the water supply–demand imbalances in Iran, Morocco and Saudi Arabia in 2040–2050 under dry, average and wet climate change projections and to show on the basis of the marginal cost and marginal value of water the optimum mix of supply-side and demand-side adjustments to address the imbalance. A hydrological model has been used to estimate the water supply–demand imbalance. Water supply and demand curves have been used to explore for which (marginal value of) water usage the marginal cost of supply-enhancement becomes too expensive. The results indicate that in the future in all cases, except in Iran under the wet climate projection, the quantity of water demanded has to be reduced considerably to address the imbalance, which is indeed what is currently happening already.

1. Introduction

Serious water problems are already apparent in the Middle East and North Africa (MENA) region. Aquifers are over-drafted, water quality is deteriorating, and water supply and irrigation services are often rationed, with consequences for human health, agricultural productivity and the environment.

The MENA region's population continues to grow, and is projected to double over the next 40 years (CIESIN, 2002). One of the major challenges in the MENA region is to increase agricultural production for the rapidly growing population. According to the Food and Agricultural Organization (FAO, 2006), water will be a crucial constraint in this respect.

A proportion of agricultural production in the MENA region currently depends on unsustainably high groundwater use. Some countries, including Saudi Arabia, are already exploring the possibilities for making groundwater extraction sustainable in the future, for instance by reducing the area of land under wheat and by importing wheat.

In the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007) strong changes in climate across the MENA region are projected. Temperature increases combined with substantially decreasing precipitation are expected. The higher temperature results in a higher evapotranspiration demand and, in combination with a decrease in precipitation, will put severe pressure on the water resources in the region. The region may see more frequent and severe droughts and floods if climate change affects the weather as predicted. The World Bank (2010) estimates that the total cost of all kinds of adaptations to a world that is approximately 2 °C warmer by 2050 is in the range of $2.5 billion to $3.5 billion a year between 2010 and 2050 in the MENA region.

There is an urgent need to address the water supply–demand imbalance, defined here as unconstrained projections of water demand exceeding renewable water supply under a static policy regime-, however a clear vision of what kinds of measures is lacking. A broad range of measures to address the imbalance already exists, from productivity improvements (Al-Said et al., 2012; Molden et al., 2010) to expansion of the quantity supplied and reductions in the quantity demanded (Haddada and Lindner, 2001; World Bank, 2012).

A World Bank study on better water management in MENA countries (World Bank, 2007) raises the question whether countries in the MENA region can adapt to overcome these combined challenges. The study argues that they will have to adapt, because if they do not the social, economic and budgetary consequences would be enormous. Drinking water supplies will become more erratic than they already are. Cities will need to rely on more expensive desalination and more frequently on emergency supplies brought in by tankers or barges. In irrigated agriculture, unreliable water supplies will depress farmers' incomes. The economic and

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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, will put increasing pressure on public budgets and may exacerbate tensions within and between communities.

In this paper water supply–demand imbalances in Iran, Morocco and Saudi Arabia are evaluated in a reference period (between 2000 and 2009), and in the future (2040–2050) under dry, average and wet climate change projections. Iran, Morocco and Saudi Arabia have been selected for this study because these countries are currently responsible for more than 42% of the total water demand in the MENA region and for almost 50% of the water supply–demand imbalance in the MENA region (Droogers et al., 2012). At a later stage, water supply and demand curves are introduced to explore when the marginal cost of supply-enhancement becomes too expensive compared to the marginal value of water usage and to determine the optimum mix of supply-side and demand-side adjustments to address the imbalance.

In Section 2 the MENA Water Outlook Framework is presented as well as the way climate change scenarios are generated. Economic concepts to determine the optimum groundwater extraction rate and the optimum mix of adjustment to address the supply–demand imbalance are also discussed. Water supply–demand imbalances are analysed in Section 3 in a conceptual manner by comparing future water demand with renewable water supply. In Section 4, water supply and demand curves are derived to show the optimum mix of adjustments needed to address water supply–demand imbalances. Finally, the approach and results are discussed and conclusions are drawn in Section 5.

2. Methodology

The conceptual base of the MENA Water Outlook Framework, hereafter referred to as MENA-WOF, is shown in Fig. 1. Projected water demand consists of irrigation, domestic demand and industrial demand. Irrigation demand is calculated using a GIS based hydrological model and climate change projections. It is a function of the crop water requirements and the naturally available water. The FAO has developed projections for the development of irrigated areas based on the irrigation potential, projections for international trade and food demand. In combination with the modelled increase in crop water demand, these were used to estimate future irrigation water demand. Domestic demand and industrial water demand are based on statistics taken from the current situation. Future demand is a function of population, GDP and the current demand. Data from the FAO's AQUASTAT database were used as a reference, and water demand growth projections were based on GDP per capita (GDPP) and population projections. It was assumed that per capita domestic water use increases in step with GDPP but that it increases at a decreasing rate with increasing GDPP, i.e. it is a concave curve, because increasing wealth will result in increased investment in water saving technologies.

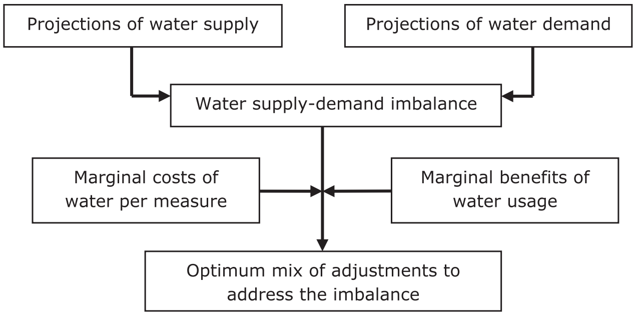

Fig. 1. Conceptual MENA Water Outlook Framework (MENA-WOF).

Projected water supply is also determined by the hydrological model. There are two sources that can be used to satisfy demand: renewable groundwater and surface water. The discrepancy between the total demand and these two combined supplies is defined as the water supply–demand imbalance. This discrepancy is addressed by implementing measures that increase the quantity of water supplied or reduce the quantity of water demanded in the event that such measures become too expensive. Water supply and demand curves will be used to determine the optimum mix of adjustments in the quantity supplied and demanded to address imbalances.

The Water Evaluation and Planning System (WEAP) (SEI, 2005) forms the basis of the MENA-WOF framework. The aim is to integrate human interventions into the hydrological cycle. MENA-WOF is forced by results from a distributed hydrological model. The current and future water supply is assessed using the PCRaster Global Water Balance hydrological model (PCRGLOB-WB). This model was developed with the explicit aim of simulating terrestrial hydrology at macro scales under various land use and climate conditions and with a temporal resolution of between one and several days. The model has been used to analyse groundwater depletion, climate change impacts and to forecast seasonal river discharge (Bierkens and Van Beek, 2009; Sperna Weiland et al., 2010; Wada et al., 2010). The PCRGLOB-WB model was set up at a resolution of 10 km for the entire MENA region and forced by downscaled climate change scenarios from 2010 to 2050 as discussed later. The results of these analyses were used as input for the MENA-WOF. Details of the methodology can be found elsewhere (Immerzeel et al., 2011).

The hydrology is modelled in a fully distributed manner at a 10 km spatial resolution using the PCRGLOB-WB model, as was the recharge to the groundwater system. The output of the hydrological model feeds into the WEAP model which is used to model trade-off between water supply and demand and consequently quantify water supply–demand imbalances in the future using transient time series from an ensemble of climate change scenarios. The WEAP approach is by definition aggregated into a total for the whole region. However, the PCRGLOB-WB model cannot be replaced by an Excel spreadsheet approach as this will ignore all spatial hydrological processes related to evapotranspiration, runoff generation and groundwater recharge, which are all location-specific and cannot be combined without introducing large uncertainties.

It is assumed that the following aspects are present within a single country: streams, reservoirs, groundwater, irrigation demand, urban demand and industrial demand. These are all interconnected and a combined approach is assumed for each country. All types of water uses can obtain water from both surface and groundwater sources. Details for each aspect are provided in Droogers et al. (2012). These aspects have been proven to be effective in overall scenario analysis in the evaluation of the impact of climate change and measures (Droogers and Perry, 2008; Immerzeel and Droogers, 2009; Droogers, 2009; Sandoval-Solis and McKinney, 2010; Yates et al., 2009).

2.1. Climate change scenarios

Monthly precipitation and temperature data from nine general circulation models (GCMs) were downloaded from the IPCC Data Distribution Centre. From the various emission scenarios, this study uses the A1B greenhouse gas (GHG) emission scenario. This scenario is chosen because it is widely used and adopted by the IPCC. The A1B scenario is considered as 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 GCMs were statistically downscaled to a spatial resolution of 10 km with a daily time step using a number of ancillary datasets for the current climate (e.g. TRMM for precipitation and NCEP/NCAR reanalysis data for temperature). Further details on the downscaling procedure can be found in Immerzeel et al. (2011). The PCRBLOB-WB model was forced by the downscaled data from the nine GCMs and the average, driest (dry) and wettest (wet) were selected and used as input for MENA-WOF (Droogers et al., 2012).

2.2. Groundwater

One important aspect of MENA-WOF is the use of groundwater as a resource. However, very little reliable information on groundwater storage capacity at country level is available. For specific countries, extensive surveys could have been used, but no systematic and universal approach is followed. The objective of the International Groundwater Resources Assessment Centre (IGRAC) is to share groundwater information on a global scale. However, this information is much more qualitative and fragmented and therefore also not suitable for use in this study.

Due to this lack of reliable information, it was for this study impossible to determine the optimum rate of extraction nor the time by which fossil water mining must stop on the basis of economic theory. The absolute value of the total groundwater resource is therefore not used; instead, only renewable groundwater supplies are considered. The regional recharge is estimated by means of MENA-WOF. This means that non-renewable groundwater is not considered as a source of water supply in this study, whereas it can be substantial and that water supply–demand imbalances are consequently overestimated.

2.3. Economic concepts

Had groundwater storage capacity at country level been known, it would have been possible to demonstrate on the basis of economic theory (by means of a dynamic model of groundwater use) that the mining of fossil water could be efficient until a steady state is reached. From a standard economic perspective, optimum groundwater management is defined by the rate of extraction over space and time that maximises the present value of benefits minus costs subject to the physical hydrology of the aquifer and related water resources. A descriptive solution of this dynamic optimisation problem states that the marginal benefits or value of extracting an additional unit of groundwater at all times and locations must equal the full marginal opportunity cost of extracting that unit of groundwater. The marginal benefits of groundwater consist of the direct use value, indirect use value and non-use value of in situ services. Non-use values include buffering value, subsidence avoidance, water quality protection and prevention of seawater intrusion. The full marginal opportunity cost consists of the actual marginal cost of extracting a unit of water plus the present value of the increase in future marginal costs caused by the absence of that unit of water. The increase in future marginal costs falls into two general categories: the future increase in marginal costs of all extractors and the marginal reduction of future non-extractive benefits that depend on water stock or flows from that water stock (Qureshi et al., 2012). Lower stock increases the depth of the groundwater and consequently the future pumping costs of all affected users and decreases future water supply and hence extraction alternatives for all users. This means that fossil water pumping has to stop at some point. The long-term steady state solution depends on the value of water for potential users and on the costs of measures to increase the quantity of water supplied.

Water supply and demand curves can be used to explore in conceptual terms how water imbalances can be addressed (Fig. 2). The ordering of these adjustments is, however, robust, The demand curve for water, representing the marginal value of water, slopes downwards indicating that users allocate water to the highest value uses first and subsequently to lower value uses. In other words, that the marginal value decreases as more water is used. The supply curve for water, representing the full marginal cost, slopes upwards indicating that the marginal costs of water provision increase with the quantity supplied. The equilibrium price of water P^* is the price at which marginal benefits are equal to marginal cost.

Suppose that quantity Q_1 is supplied and consumed in the reference period. The demand curve shifts outwards over time as more will be demanded at the same price, due to increased water demand and climate change. With the same price and allocation mechanisms, the water imbalance will be Q_2–Q_1 (see Fig. 2). However, it is not economically efficient to supply Q_2, since the marginal costs exceed the marginal benefits. A gradual increase in quantity supplied and a gradual reduction in quantity demanded are required until the marginal costs are equal to the marginal benefits which is the case at Q^*. This economic concept is used in this paper to explain the optimum mix of supply-side and demand-side adjustments required to address the imbalance.

The 2030 Water Resources Group (2009) uses water availability cost curves to estimate the cumulative costs of reducing water supply–demand imbalances. They rank both supply-side and demand-side measures from low marginal costs of supply and low marginal opportunity costs of sacrificing the marginal value. Such a simplified analysis, does not distinguish gradual supply-side and demand-side adjustments to achieve the equilibrium quantity, as shown in Fig. 2. Understanding demand-side management is, however, just as important as supply-side management.

3. Results

In Table 1 the annual water supply–demand imbalances, i.e. difference between future water demand and renewable water supply, in Iran, Morocco and Saudi Arabia are shown for the average climate projection. It is important to note that these results are based on monthly calculations to ensure that variations within a year are properly taken into account. Since this year-to-year variation of these climate projections is only meant to be used as an indication of changes, rather than specifying this to a particular year, all results are presented as running averages.

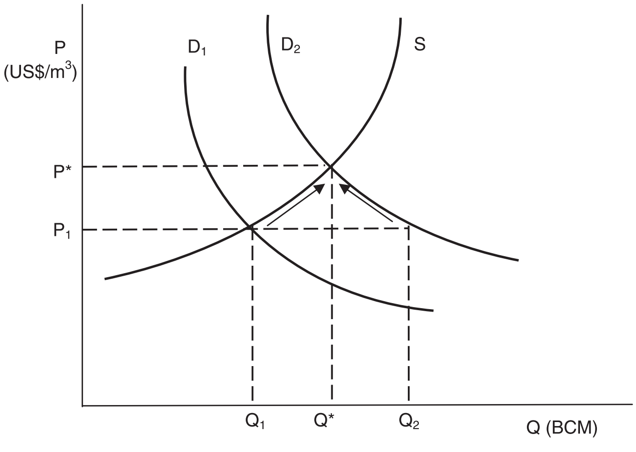

Fig. 2. Water demand curves in the reference period (D_1) and in the future (D_2) and water supply curve (S).

Table 1
Annual supply–demand imbalance in Iran, Morocco and Saudi-Arabia in BCM for the average climate projection.

BCM	Iran 2000–2009	Iran 2040–2050	Morocco 2000–2009	Morocco 2040–2050	Saudi-Arabia 2000–2009	Saudi-Arabia 2040–2050
Demand	74.537	97.107	15.739	24.223	20.439	26.633
Irrigation	67.153	80.828	13.942	18.173	17.788	15.062
Urban	6.275	14.627	1.403	5.386	1.972	10.098
Industry	1.109	1.652	0.395	0.665	0.678	1.474
Imbalance	10.419	41.959	2.778	15.688	12.008	20.841
Supply	64.118	55.148	12.961	8.535	8.431	5.792
Surface water	44.135	38.740	10.440	6.899	7.285	5.025
Renewable groundwater	19.982	16.408	2.521	1.636	1.146	0.767

For the average climate projection, the water supply–demand imbalance in the reference period in Iran, Morocco and Saudi Arabia are respectively 10.4, 2.8 and 12.0 billion cubic metres (BCM) per annum (Table 1). Demand exceeds supply due to the fact that the full marginal opportunity costs of extraction are not included in the supply curve that water users face, which means that this curve is below the full marginal cost curve (curve *S*, Fig. 2). As a result, the price is lower than the equilibrium price.

For the average climate projection, future water supply–demand imbalances will be respectively 42.0, 15.7 and 20.8 BCM per annum which is approximately 43%, 65% and 78% of total future demand (Table 1).

For the dry climate projection, future water supply–demand imbalances will be respectively 67.0, 19.7 and 23.4 BCM per annum in Iran, Morocco and Saudi Arabia, which is 65%, 75% and 83% of total future demand (Table 2). For the wet climate projection, future water supply–demand imbalances will be respectively 9.1, 8.8 and 17.7 BCM per annum. This indicates that Morocco and Saudi Arabia are less sensitive to climate change than Iran, which can be explained on the basis of the high share of irrigation water demand – which is expected to increase under climate change – in total water demand in Iran.

For the average climate projection 18%, 36% and 37% less renewable groundwater will be available in respectively Iran, Morocco and Saudi Arabia by the year 2040–2050 compared to the reference period, due to climate change which reduces rainfall and increases evaporation (Table 1). Under the dry climate projection it will be reduced even further and about 45%, 55% and 55% less renewable groundwater will be available in the future in Iran, Morocco and Saudi Arabia compared to the reference period (Table 2).

4. Water supply and water demand curves

The cost-effectiveness of seven measures, i.e. ways of increasing the quantity of water supplied, are compared in this section. Measure *A* increases supply through the improved efficiency of water use. Measures *B* and *C* increase supply through the increased reuse of water. Measures *D*, *E*, *F* and *G* increase the supply itself through expanding the reservoir capacity and desalination. This explorative study assumed that each of the seven different measures does not affect another measure, i.e. they are evaluated independently. Although this is true for non-hydrologically connected sources (e.g. desalination and reuse), other measures are interdependent. A more detailed study could reveal how this interdependency works and for which combinations positively or negatively feedback can be expected.

As each measure can be achieved in various ways and there is a great deal of uncertainty about future costs, crude assumptions have been made regarding the marginal cost of each measure (Table 3). These include the annualised capital cost plus the net operating cost per cubic metre of water compared to business as usual. The assumptions made are described in more detail in Immerzeel et al. (2011).

MENA-WOF is used to evaluate the effectiveness, from a water resources perspective, of the seven measures in terms of their potential contribution to reducing water imbalances. The results are shown in Table 3 for the average climate projection.

It is interesting to note that the effectiveness of the same measure differs from country to country from a water resources perspective. Expanding the reservoir capacity (*D* and *E*) could be an effective measure in a country like Iran, for example, but not in Morocco. Water supply in Iran is relatively high and reservoirs are a good option for capturing this water, whereas in Morocco precipitation is projected to be lower in 2040–2050 so additional storage is unlikely to be needed.

Combining the marginal costs of these seven measures (Table 3) with the reductions in water supply–demand imbalances brought about by the seven measures (Table 4) results in water supply curves. Each of the seven measures is represented as a block on the curve. The width of the block (m^3) represents the amount of incremental water that becomes available as a result of the measure, taking into account return flows. The height of the block represents its marginal cost (US\$/m^3). The order of the marginal costs of the measures (respectively *A*, *D*, *C*, *E*, *B*, *F*, *G*) reflects their cost-effectiveness. Figs. 3–5 show the net impact of each measure on water supply (reduction in water imbalance) in Iran, Morocco and Saudi Arabia respectively.

In estimating the demand curve, MENA-WOF has been used to evaluate the extent of future urban, industrial and irrigated water imbalances and assumptions have been made about associated marginal values of water. Of the evaluated future imbalance of 42 BCM in Iran, about 3.9 BCM is urban water, 0.4 BCM is industrial water and 37.7 BCM is irrigation water. The total future imbalance of 15.7 BCM in Morocco consists of 2.9 BCM urban water, 0.4 BCM

Table 2
Annual supply–demand imbalance in 2040–2050 for Iran, Morocco and Saudi Arabia in BCM for the wet climate projection and dry climate projection.

BCM	Iran Wet	Iran Dry	Morocco Wet	Morocco Dry	Saudi-Arabia Wet	Saudi-Arabia Dry
Demand	90.949	103.461	22.443	25.939	25.857	27.424
Imbalance	9.099	66.969	8.847	19.749	17.722	23.371
Supply	81.850	36.492	13.596	6.190	8.135	4.053
Surface water	57.571	25.418	11.062	5.059	7.089	3.534
Renewable groundwater	24.279	11.074	2.534	1.131	1.046	0.519

Table 3
Assumed marginal costs (US\$/m^3) of seven supply-side measures. *Source*: Immerzeel et al. (2011).

Measure	Marginal cost (US\$/m^3)
A: Improved agricultural practices	0.02
D: Expanding reservoir capacity (small scale)	0.03
C: Increased reuse of water from irrigated agriculture	0.04
E: Expanding reservoir capacity (large scale)	0.05
B: Increased reuse of water from domestic and industry sources	0.30
F: Desalination by means of using concentrated solar power	0.90
G: Desalination by means of reverse osmosis	1.20

industrial water and 12.5 BCM irrigation water. The total future imbalance of 20.8 BCM in Saudi-Arabia consists of 7.4 BCM urban water, 1.3 BCM industrial water and 12.1 BCM agricultural water. It is assumed that the marginal value of domestic water usage varies between US\$3/m^3 and US\$1/m^3 and that the marginal value of industrial water usage varies between US\$1/m^3 and US\$0.7/m^3. The marginal value of irrigation water usage is maximum US\$0.7/m^3 for crops such as fruits and vegetables (Hellegers et al., 2011) and mainly varies between US\$0.15/m^3 and US\$0.05/m^3 (Hellegers and Perry, 2006). An ordering of these uses from the highest marginal value to the lowest and by cumulatively summing the associated water imbalances according to the order of descending value yields a number of observations. On the basis of these observations demand curves have been estimated and plotted in Figs. 3–5, which should be considered as guide for understanding demand-side management. See for more details on the methodology used Hellegers and Davidson (2010).

Figs. 3–5 indicate that for the average climate projection the marginal costs are equal to the marginal benefits at 27.4, 4.3 and 6.5 BCM in Iran, Morocco and Saudi Arabia. These increases in quantity supplied are insufficient to address the water imbalances of 42.0, 15.7 and 20.8 BCM per annum and the quantity of water demanded has to be reduced by 14.6, 11.4 and 14.3 BCM per annum. The optimum mix of adjustments required in order to avoid imbalance in Iran therefore mainly consists of adjustments in water supply (65%); in Morocco and Saudi Arabia this mix consists mainly of adjustments in water demand (73% and 69% respectively). This means that supply enhancement in Morocco becomes too costly to irrigate the majority of the current crops, while in Saudi Arabia supply enhancement is even too costly for a proportion of industrial water demand. Only in Iran under the wet climate projection can water imbalances of 9.1 BCM per annum be avoided entirely through supply enhancement.

To test the sensitivity of the results to the assumed marginal values of water, the impact of 50% higher and 50% lower marginal values of water on the optimum mix of adjustments has been assessed for the average climate projection. The results of Iran will not be affected. In Morocco, a 50% lower value will also not affect the optimum mix, while a 50% higher value of water will make additional supply (of about 0.5 BCM per annum) of desalinised water for irrigation of high value crops feasible. In Saudi Arabia, 50% lower and 50% higher values will both affect the optimum

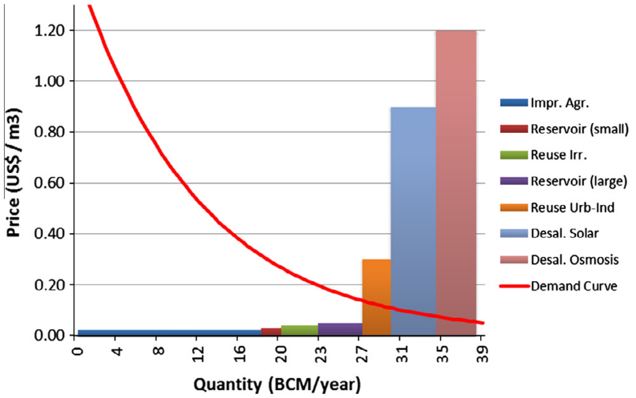

Fig. 3. Water supply and demand curves in 2040–2050 for Iran for the average climate projection.

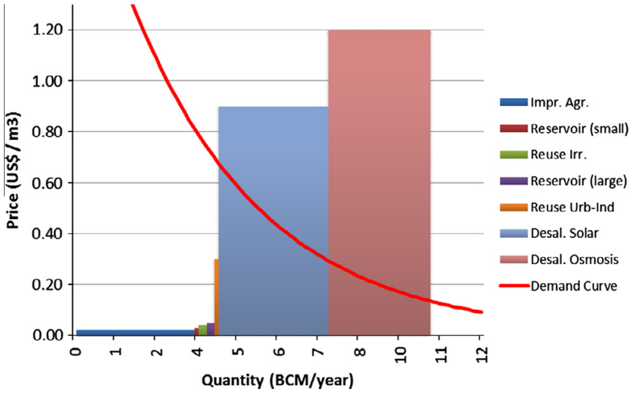

Fig. 4. Water supply and demand curves in 2040–2050 for Morocco for the average climate projection.

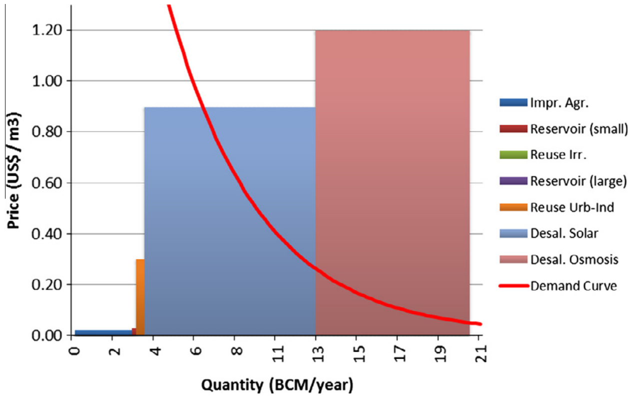

Fig. 5. Water supply and demand curves in 2040–2050 for Saudi Arabia for the average climate projection.

Table 4
Annual water supply–demand imbalance and the potential reduction in water imbalance resulting from each of the seven measures (*A*–*G*) for the average climate projection in 2040–2050. *Source*: Immerzeel et al. (2011).

(BCM/year)	Water imbalance	*A*	*B*	*C*	*D*	*E*	*F*	*G*	Total *A*–*G*
Iran	41.959	−17.582	−2.573	−3.733	−3.558	−2.643	−4.289	−4.073	−38.451
Morocco	15.688	−3.563	−0.166	−0.122	−0.157	−0.294	−3.214	−3.037	−10.553
Saudi Arabia	20.841	−3.143	−0.384	−0.126	−0.010	−0.066	−8.689	−8.042	−20.460

mix (by about 1.5 BCM per annum). In the latter case, desalination would become feasible for all future industrial water demand. The future feasibility of measures will also depend on changes in the marginal costs of measures, for instance as a result of cheaper energy or technological breakthroughs.

5. Conclusions and discussion

The main aim of this paper was to evaluate future water supply–demand imbalances in Iran, Morocco and Saudi Arabia under dry, average and wet climate change projections and to show the optimum mix of adjustments on the supply-side and demand-side to address imbalances. The modelling results indicate that all three countries will face water imbalances from renewable sources in 2040–2050 under each climate change projection. It also indicates that water imbalances in Morocco and Saudi Arabia are less sensitive to climate change than water imbalances in Iran, as a result of the high share of irrigated agriculture in total water demand in Iran.

It is important to note that the water supply–demand imbalance, which was defined in this paper as unconstrained projections of water demand exceeding renewable water supply under a static policy regime, is a conceptual notion. It is also important to note that the evaluated imbalance is overestimated as fossil groundwater sources are not considered in the analysis, whereas they can be substantial.

The modelling results indicate that only in Iran, under the wet climate projection, the water imbalance can be entirely addressed through supply enhancement. In all other cases, supply enhancement becomes too expensive and demand has to be reduced, which is indeed what is currently happening already. Saudi Arabia is relocating part of its wheat production to South Sudan. In 2008, the government of Saudi Arabia, which was one of the Middle' East's largest wheat growers, announced the country was to reduce its domestic cereal production by 12% a year to conserve water (Cotula et al., 2009).

The use of water supply and water demand curves is limited in this paper to comparing financial costs and benefits. It is important to note that these may be different from the socio-economic costs and benefits for society as a whole, which also include externality costs, opportunity costs, subsidies, etc. By not taking such costs into consideration, measures with low financial costs but high socio-economic costs – like measures that make use of highly subsidised energy – might seem to be cost-effective whereas in reality they are not attractive for society as a whole. However, the supply and demand curves are not prescriptive but should be considered as a guide for understanding supply-side and demand-side management. Of course, financial cost is not the only basis on which choices are made. As the three countries, even in the same region, face different socio-economic costs and benefits; results of this general assessment should be interpreted with care.

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