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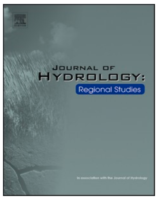

Evaluation of policy scenarios for water resources planning and management in an arid region

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ABSTRACT

Study region: Abu Dhabi, United Arab Emirates (UAE)
Study focus: Water demand in the Emirate of Abu Dhabi (EAD) has increased significantly over the last few decades. Hence, a main challenge for the EAD water policy makers is to develop long-term resilient water resources strategies. This study evaluates future water supply-demand condition in the EAD and identifies water management strategies that support a sustainable future. A dynamic water budget modelling framework is used to evaluate future water demand as affected by population growth, economic growth, proposed water related policies, consumption patterns, and climate change. The Abu Dhabi Dynamic Water Budget Model (ADWBM) is used to construct future water scenarios and assess the status of the EAD water system until 2050 in terms of water supply-demand balance. This study presents four suites of water scenarios, namely: Business as Usual (BAU), Policy First (PF), Sustainability by Conservation (SC), and Rainfall Enhanced Sustainability (RES) scenarios.
New hydrological insights: Simulation results indicate that both SC and RES scenarios achieved balanced water budget without any shortage throughout the entire period until 2050. The RES scenario is recommended for adoption because of the reasonable and achievable proposed consumption reductions needed in the different demand sectors. The obtained results should be valuable for devising appropriate strategies to prevent potential future water shortages in the Emirate.

1. Introduction

One of the major problems for policy makers in water management is the need to deal with uncertainties about the future. This is because water policies guide actions for decades, and therefore, one should be able to forecast the future and provide solutions accordingly. Water infrastructure planning is a long-term activity, and the lifetime of the infrastructures exceed 50–100 years. Future

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water conditions are dependent on a number of factors like environmental, economic, social, and political drivers that include demographic changes, water resources availability, water consumption patterns, land use patterns, governmental policies, and so forth (Proskuryakova et al., 2018). Hence, one of the main challenges for water managers is to foresee the future accurately, and design appropriate infrastructure plans and policies based on the future requirements. In such instances, scenarios can be useful for evaluating the future conditions of water resources for management and infrastructure planning purposes.

Many countries already face the problem of maintaining reliable water supplies to meet the growing demands, and this will continue to worsen due to urbanization and industrialization. The United Arab Emirates is not different with remarkably rapid changes in the population, lifestyle, and economy (Mohamed and Almualla, 2010a,b). Several public policies may influence water demand. For example, policies supporting the expansion of agriculture with the aim of protecting the national heritage and decreas dependency on imported food could increase the demand for irrigation water. Likewise, desert greening policies aiming to provide habitat for wild animals and stabilize sand around roads could also increase the demand for irrigation water. Other relevant policies include the development of public parks; residential and commercial megaprojects implemented to support local population and tourism; and industrialization driven by the government's diversification into non-petroleum related industries. Furthermore, climate change could be an important factorfor sustainable development as it may cause rising of sea levels, drying up of surface water and groundwater, and intense droughts (National Center of Meteorology, 2020). Due to its arid climatic condition, the EAD has very limited renewable resources of groundwater and negligible surface water, the key conventional sources of water (Environment Agency - Abu Dhabi, 2009a). Water deficit in UAE is generally managed by providing desalinated water and reusing treated wastewater (Statistics Centre - Abu Dhabi, 2015, 2018). The environmental impacts of desalination plants on the Arabian gulf is well acknowledged in several studies (Al-Zubari, 2009; Ministry of water and environment, 2010; Alghafli, 2016). Thus, integration of both supply and demand side management is essential for a sustainable water resources development in the region. It is crucial to determine how the current and proposed policies will impact the long-term objectives of water resources management and sustainability in the EAD.

Mathematical simulation models could enhance our understanding of the socio-economic, political, and environmental factors; and help us to evaluate the current and future water supply-demand systems. Scenarios represent expositions of possible futures and are advantageous for examining the changing factors in shaping the future, judging possible diversions from the current trends, and preparing strategically for uncertainties and complexities in the long term. Scenarios can be used to assess future uncertainties and aid development of water management strategies (Carter et al., 2007). Thus, scenarios analysis (SA) can help in choosing a reliable water policy for a state or nation by highlighting the best options among those predicted. The development of scenarios has become popular topic ever since scenarios were first used by the U.S. in military planning (Van Der Heijden, 2005). Scenario development as a strategic planning tool became popular in different applications like social forecasting, public policy analysis and decision making, environmental management, business development and water resources management (Hulse and Gregory, 2001).

Many studies of scenario analysis for water resource management exist. For example, (Zhuo et al., 2016) deployed SA with a focus on crop production by assessing the water footprints and virtual water trades for time horizons between 2030 and 2050. (Proskuryakova et al., 2018) developed water scenarios for Russia by using SA data mining for a time horizon of 2030. These scenarios focused on sustainability, water demands of households and industry, and other basic needs. In India, (Amarasinghe et al., 2007) developed scenarios for food and water futures for 2025–2050 and addressed various issues related to the business as usual scenario.(Saraswat et al., 2017) conducted a study in Nepal that focused on urban water management and used SA to develop strategies for achieving sustainable water management practices for 2030. (Cetinkaya and Gunacti, 2018) developed scenarios for Turkey and used a multi criteria analysis to measure the performance of these scenarios. (Dong et al., 2013) carried out a detailed review on the status of scenarios methodology in water resources management and indicated that the scenario approach was widely popular in exploring future water resource conditions and developing strategic plans. (Amer et al., 2013) reviewed the strengths and weaknesses of approaches typically applied in scenario planning. This work also considered scenario selection, the appropriate number of scenarios required, and ways to conduct scenario validation. (Stewart et al., 2007) proposed a five-step, iterative scenarion constructing approach. (Mahmoud, 2008) proposed a formal scenario development method for water resources management in the south-western US. (Henriques et al., 2015) used SA for addressing water management challenges in England and Wales for the years up to 2050, and four future scenarios were constructed based on stakeholder discussions and expert advices. (Ercin and Hoekstra, 2014) developed scenarios for 2050 to understand changes in water footprints at both global and regional scales. In a review study in the Netherlands, (Haasnoot and Middelkoop, 2012) concluded that scenario approaches are useful to deal with the uncertainties faced by water managers in decision making. In the Middle East, (Al-Zubari, 2009) developed four water scenarios for the Gulf Cooperation Council (GCC) countries considering the different patterns of economic developments that can be implemented in the region. Al-Zubari identified four drivers that represent future scenarios as the market, sustainability, policies, and security. The literature confirms scenario development and analysis as a key tool to promote sustainable water management by planning in advance for a plausible future.

In this paper, a dynamic simulation model developed for EAD is applied to evaluate the water supply and demand for sustainable water resource management of Abu Dhabi. The detailed description of the model development is available in (Mohamed et al., 2016). The components and framework of the model are described here under methodology. The model works on the basic time step of evaluating water balance every year. Each scenario is evaluated with regard to consumption reductions needed in water demand drivers as well as in water resources utilization. The overall purpose of this study is to explore scenarios for water supply and demand of EAD to 2050. Outcomes of this study can be used by water decision makers, water policymakers and stakeholders to develop long-term plans and strategies for the EAD water sector until 2050. This study explores four sets of plausible future scenarios along with the associated strategic steps required to achieve a sustainable future in water resources. In the design process of these scenarios, a number of drivers including population growth, economic growth, water consumption pattern and climatic change were incorporated. The four future scenarios examined in this study are Business as Usual (BAU), Policy First (PF), Sustainability by Conservation (SC), and Rainfall Enhanced Sustainability (RES). This study could serve as the basis for future refinement in water resources planning and management using scenarios development, in arid or semi-arid regions.

The main innovative aspects of this paper are: (1) conducting a detailed evaluation of Abu Dhabi's unique, highly-stressed, water system (with negligible surface water resources and man-made water systems); (2) considering several governmental policies relevant to water in developing plausible water scenarios for Abu Dhabi; and (3) demonstrating scenarios development for a data scarce system.

This paper is organized as follows. This section is followed by description of the study area in Section 2. The methodology in Section 3 describes the Abu Dhabi water system, scenarios development and evaluation. In Section 4, the obtained results obtained of the four scenarios are presented. Section 5 discusses the results and their implications with respect to achieving a balanced water budget. Finally, the conclusions drawn are given in Section 6.

2. Study area

Abu Dhabi is the largest emirate of the United Arab Emirates. It is divided into three regions, namely, Abu Dhabi region, Al-Ain region and Western region, as shown in Fig. 1. The EAD is bordered by Oman in the east, Saudi Arabia to south and west, and the Arabian (Persian) Gulf in the north. It is characterized by an arid climate with scanty rainfall, high temperatures, high humidity, and high evapotranspiration rates. The land cover is mostly desert. Abu Dhabi has a long coastline of more than 600 kms that is responsible for the humid climatic conditions. The maximum temperature average above 40 °C (104 °F) during the April-September summer period. The October-March period is comparatively cool. As rainfall is rare, the natural recharge into groundwater is very low; about 40 million cubic meters (MCM)/yr (Environment Agency - Abu Dhabi, 2009a; Mahmoud et al., 2019) which adds to the water concerns of the emirate. The EAD has limited groundwater resources, and as the abstraction rates are higher than the natural and artificial recharge rates, major decline in groundwater levles, and quality, has been observed in many locations of the emirate (Elmahdy and Mohamed, 2013 and 2015; Mohamed et al., 2010a;b).

Water supply comes from different sources including groundwater, seawater desalination, treated sewage and surface-runoff from rainfall. These can be categorized into potable or non-potable sources based on the type of demands they can satisfy. Of the seven demand sectors identified in EAD, four are considered potable, namely, residential, commercial, municipal, and industrial. These sectors require high quality fresh water. Desalinated water is the only source to meet potable demands of these four sectors. Desalination plants situated at different strategic locations within or outside the EAD. On the other hand, groundwater is the main source for the other three non-potable sectors; agricultural, forestry and amenities. Treated sewage and surface-runoff provides minor support for non-potable demand. Treated sewage (TS) is supplied to complement the needs in the forestry and amenities sectors only. TS is a non-conventional source of water produced by treating wastewater to reusable quality. In EAD, there are wastewater treatment plants at all key population centers to produce and distribute TS.

The EAD receives very low rainfall; usually less than 100 mm per year (Environment Agency - Abu Dhabi, 2009a). Consequently, rainfall and runoff are not abundant water resources in the region. Very little data is available on Abu Dhabi's surface runoff. Most of the terrain is flat, consisting of sandy soil with scattered dunes and some low elevation sabkhas (flat area with salt deposits). Therefore, little runoff is generated. However, in the East of the EAD, rainfall produces runoff that drains into the wadis (creeks) and flows westward, crossing into Abu Dhabi providing about 7.6 MCM annually (Environment Agency - Abu Dhabi, 2014). Rainfall is estimated from data recorded at 24 stations across the EAD.

Water demand has increased significantly in the EAD, and the total water demand in 2011 was about 3416 MCM (Statistics Centre

Fig. 1. Location map of the EAD (Regions- Abu Dhabi, Al Ain and Western).

-Abu Dhabi, 2012). The main driving forces of this increase are population growth and economic development. Population increase has driven much of the water consumption increase in Abu Dhabi Emirate; especially, the residential, commercial, and municipal consumptions. In 1975, the total population was 211,812, and increased to 1,399,484 by 2005, a 6 fold increase in 30 years (Statistics Centre - Abu Dhabi, 2015). Abu Dhabi population has doubled in following nine years reaching 2,656,448 in mid-2014 (Statistics Centre - Abu Dhabi, 2018). The average annual population growth rate (2005–2014) is 7.6 %. Of the total population, 507,479 people (19.1 %) are Emirati citizens and the rest, 80.9 %, are non-citizens. More than 66.5 % of the population are males which is due to an influx of male migrant workers (Statistics Centre - Abu Dhabi, 2018). The fertility rate in Abu Dhabi Emirate is higher than most developed regions of the world, and the mortality rate remains low. In 2014, the crude birth and death rates were estimated to be 14.3 and 1.2 per 1000 population, respectively (Statistics Centre - Abu Dhabi, 2018), reflected in the high net growth rates of the population. The population density of Abu Dhabi Emirate in 2014 was 44.7 persons per square kilometer. The population density in the three regions of the Abu Dhabi Emirate (Abu Dhabi region, Al Ain region, and Western region) are 148.9, 52.6, and 8.9 persons per square kilometer, respectively; reflecting the varying urbanization levels (Statistics Centre - Abu Dhabi, 2018).

Moreover, changes in lifestyle have increased water demand for irrigation, human consumption, and industrial activities. Several public practices intensified the increase in water demand. For example, expansion of agriculture to protect rural heritage and reduce dependency on imported food. Also the expansion of desert greening to provide a habitat for wild animals, stabilize the sand around roads, and develope public parks to enhance outdoor activities.

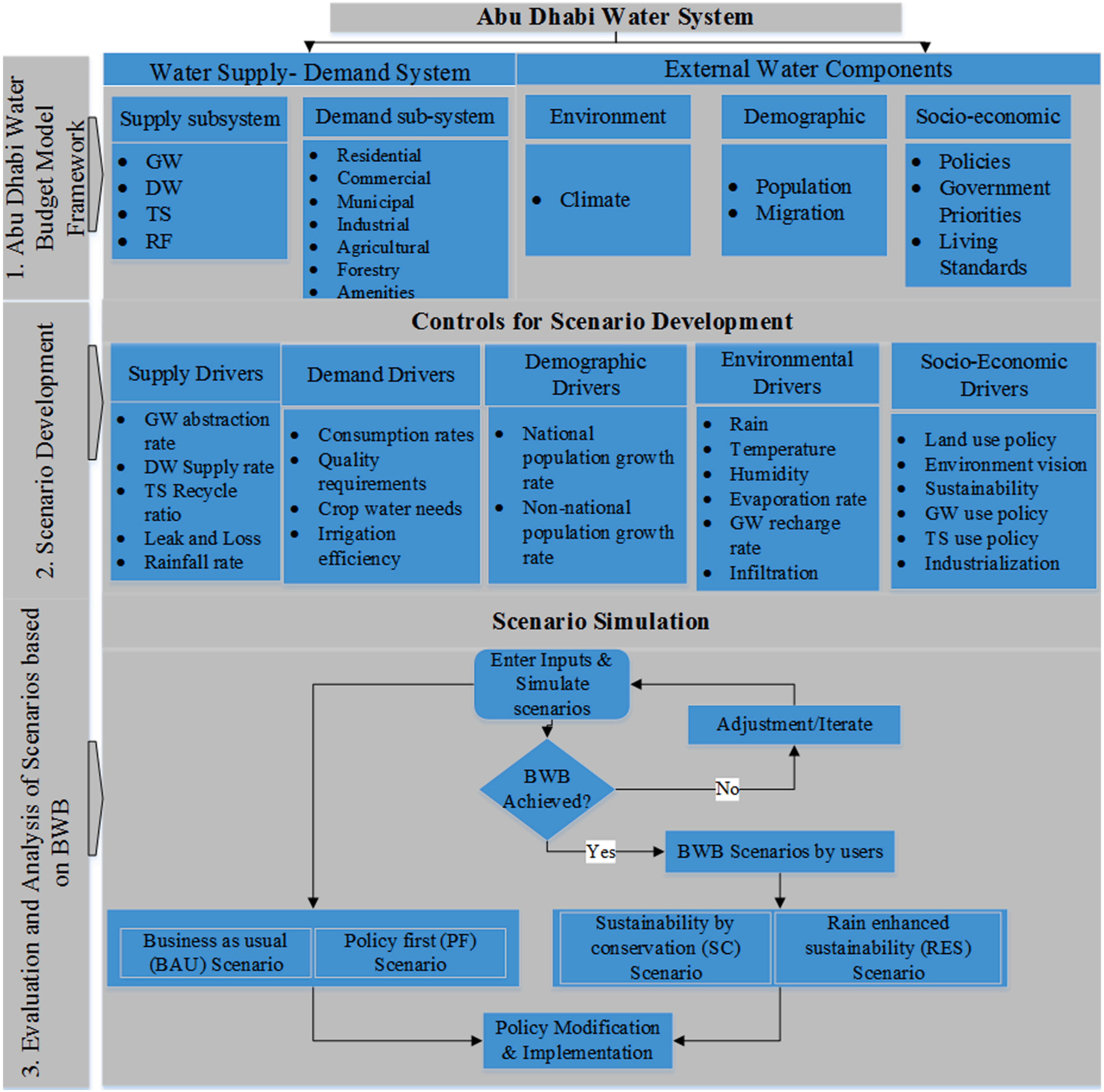

Fig. 2. The overview of stepwise framework of the study.

3. Methodology

The overall framework of the study is divided into three parts and is illustrated in Fig. 2. First, the conceptual and dynamic structure of the Abu Dhabi water system was developed as shown in the upper part of Fig. 2. Then, the future scenario were designed and developed using control parameters and drivers to forecast future situation, as shown in the middle part of Fig. 2. Finally, the developed scenarios were simulated using the Abu Dhabi Dynamic Water Budget Model (ADWBM) (Mohamed et al., 2016) to evaluate the future water balance, and to identify needed interventions in the future consumption and supply patterns to achieve water balance, as shown in the lower part three of Fig. 2.

3.1. The Abu Dhabi water system

The framework of Abu Dhabi water system is composed of the water supply-demand elements and the external components that drive demand and supply. The four supply sources (groundwater (GW), desalinated water (DW), treated sewage (TS) and rainfall (RF)) and seven demand sectors (agriculture (A), forestry (F), amenities (AM), residential (R), municipal (M), commercial (C) and industrial (I)) conceptualize the structure of water system in Abu Dhabi. The external drivers are categorized as environmental, demographic, and socioeconomic factors. The ADWBM was developed by establishing a holistic mass balance for the entire system. During the process, all the required data were collected and analyzed to identify key parameters that are essential for establishing the water balance. These key parameters formed the basis for forecasting future water conditions.

ADWBM is designed to evaluate the annual water balance. The model also comprises external parameters that drive the water consumption and supply in the study area. Environmental and climatic components include rainfall, humidity, evaporation, temperature, and other climatic parameters that affect water demand and supply in Abu Dhabi. Additionally, the different policies, visions, and strategies could impose impacts on the water resources. Therefore, ADWBM incorporates all these drivers to develop future water scenarios.

3.2. Scenario development

Scenarios refer to a series of assumptions or storylines depicting how the future of Abu Dhabi water system might unfold. They can also be treated as a form of sensitivity analysis of the relationship between the changing forces and their outcomes, the possible futures (Parsons et al., 2007). The future water demand of the EAD is dependent on many factors such as population growth, urbanization, environmental factors, and policies. The weights of these factors are diverse according to the scenario configuration and different assumptions are needed to test the effects of these factors. Hence, scenario analysis is used to explore the balance of water supply and demand to achieve the goal of a sustainable Abu Dhabi as proposed in the EAD Environment Vision 2030 (Environment Agency - Abu Dhabi, 2012). In order to identify the key driving forces that determine the future of water system in Abu Dhabi, stakeholders' workshops were organized to discuss the current situation and to explore the focal objectives relevant to achieving sustainability in Abu Dhabi.

Population growth and water demand data as well as other ADWBM parameters serve as the foundation of this scenario development. Tables 1–3 represent the baseline values of all model input parameters.

Water demand, especially the potable water demand sectors, is directly linked to population. Therefore, population is incorporated as one of the key demand drivers for all potable sectors. Four population growth rates are considered in this study. They are very high (P1), high (P2), medium (P3), and low (P4) growth rates (Table 1). These growth rates P1, P2, P3 and P4 are aligned with population trends described in the Abu Dhabi Environment Vision 2030″ (Environment Agency - Abu Dhabi, 2012) and (Lutz et al., 2014). The high growth rates, P1 and P2, represent the "worst case" and the "market first (MF)" growths, respectively, as described in (Environment Agency - Abu Dhabi, 2012). The MF growth represents high immigration rates into the UAE reflecting the rapid economic

Table 1
Projected average annual population growth rates used for developing scenarios.

Population growth rate	Population Category	Average Annual Growth Rate (%)		
		2015–2020[a]	2021–2030[a]	2031–2050[b]
P1 (Very high rate)	Nationals	3.2	2.8	2.5
	Expatriates	8.6	7.7	4.7
	Total	7.6	7.0	4.4
P2 (High rate)	Nationals	3.2	2.8	2.5
	Expatriates	5.7	5.2	2.7
	Total	5.2	4.8	2.7
P3 (Medium rate)	Nationals	3.2	2.8	2.5
	Expatriates	5.7	4.7	3.0
	Total	5.2	4.4	2.9
P4 (low rate)	Nationals	3.2	2.8	2.5
	Expatriates	5.0	3.9	2.0
	Total	4.6	3.7	2.1

Note: a Estimated based on (Environment Agency - Abu Dhabi, 2012); b Estimated based on (Lutz et al., 2014).

Table 2
ADWBM parameters and their sample values.

Model Components	Sample Values*	Unit	Sources
GW reserve	220 (2010)	BCM	(RTI International, 2015)
GW extraction rate	2217 (2012)	MCM/yr	(Environment Agency - Abu Dhabi, 2014)
GW inflow from external aquifers	140	MCM/yr	(Environment Agency - Abu Dhabi, 2014).
GW recharge from rainfall	24–40	MCM/yr	(Environment Agency - Abu Dhabi, 2009a)
Surface Run-off	7.6	MCM/yr	(Environment Agency - Abu Dhabi, 2009a)
Leaching rate	5–20	%	(Environment Agency - Abu Dhabi, 2009b)
DW Plant Capacities	1280 (2014)	MCM/yr	(Abu Dhabi Water and Electricity Company, 2018)
DW transmission and distribution loss and leakage	8–10	%	(Environment Agency - Abu Dhabi, 2009a)
Evaporation rate	5.3- 5.5	mm/day	(Terrestrial Environment Research Centre, 2015), (Environment Agency - Abu Dhabi, 2009a)
Evapotranspiration rate	6.85–8.2	mm/day	(Abubaker et al., 2015)
WTP Capacity	408 (2012)	MCM/yr	(Statistics Centre - Abu Dhabi, 2015)
TS use data	284 (2012)	MCM/yr	(Statistics Centre - Abu Dhabi, 2015)

* Values in the parenthesis refer to respective years.

Table 3
Baseline water consumption (as of 2015) for different sectors (BAU scenario).

Demand sector	Drivers	Value (unit)
Residential	Overall Consumption rate	610 lpcd
	Shabiyats Indoor	320 lpcd
	Shabiyats Outdoor	1280 lpcd
	Villas Indoor	240 lpcd
	Villas Outdoor	960 lpcd
	Flats	400 lpcd
Commercial	Overall Consumption rate	170 lpcd
	Office Employees	56 L/emp./day
	Retail Employees	47 L/emp./day
	Restaurants	30 L/m^2/day
	Hotel Rooms	330 L/room/day
	Carwash	284 L /vehicle
Municipal	Overall Consumption rate	250 lpcd
	Government offices	2.2 L/m^2/day
	Mosques	12,774 L/mosque/day
	Schools	34 L/student/day
	Hospitals	259 L/bed/day
Agricultural	Water requirement for fruit crop	2040.7 L/m^2/yr
	Water requirement for field crop	603.7 L/m^2/yr
	Water requirement for vegetable crop	605.6 L /m^2/yr
	Irrigation efficiency for agriculture field	54 %
Forestry	Water requirement for forest-Western Region	156 L/m^2/yr
	Water requirement for forest-Al Ain Region	221 L/m^2/yr
	Irrigation efficiency for forest land	56 %
Amenities	Per capita amenities water consumption	410 lpcd
Treated Sewage	Potable water return ratio (PWR)	0.286
	Infiltration rate to sewer line	10 %

growth in the region. The medium population growth (P3) represents a balanced environment and gradual economic growth in Abu Dhabi; whereas, the low population growth (P4) represents a green economy. The later could be also used during extreme cases (such as the current COVID-19 pandemic) reflecting low immigration rates into UAE.

The availability of renewable water resources depends on climate factors like rainfall and temperature, and may adversely be affected by future climate change in the region. The EAD is vulnerable to the impacts of climate change due to its extreme arid climate and low-lying coastal areas. The EAD has developed a climate change strategy that was incorporated into Abu Dhabi Plan (Environment Agency - Abu Dhabi, 2012). The change in climate is determined by past greenhouse gas emissions and, for Abu Dhabi, the impact of climate change is unlikely to make a severe change on water resources by 2050 (Dougherty et al., 2009; Environment Agency - Abu Dhabi, 2014).

This study designed four suites of water scenarios, namely Business as Usual, Policy First, Sustainability by Conservation, and

Rainfall Enhanced Sustainability. The first two scenarios focus on predicting the future of Abu Dhabi water under a continuing pattern of economic growth. Whereas the latter two are designed to achieve a balanced water budget until 2050. Each scenario, with a different set of assumptions and constraints for water use and supply, was tested using several population growth models.

3.2.1. Business As Usual (BAU) scenarios

The BAU is a base scenario, which represents a continuation of current trends of water demand and supply. All the key parameter values are assumed to remain unchanged as in the baseline year 2015 except the population. Two population growth models, medium (P3) and very high (P1), were used to develop two sub-scenarios of the BAU scenario. The BAU scenario with P3 (medium) population growth represents a balanced and gradual economic growth. this is termed here as BAU Status Quo sub-scenario (BAU-SQ). The BAU worst case (BAU-WC) sub-scenario considers a very high population growth rate, P1, without a balanced environmental and economic growth rates.

These two reference sub-scenarios illustrate a situation where there is no improvement in water supply and demand infrastructures with respect to the baseline year (2015). Furthermore, the BAU sub-scenarios assume no restriction on groundwater extraction. Therefore, under these BAU sub-scenarios, water consumption will continuously increase in the population dependent sectors (e.g. residential) while other sectors (e.g. agricultural and forestry) would maintain the baseline consumption throughout. The BAU water consumption values for the baseline year 2015 are summarized in Table 3.

3.2.2. Policy First (PF) scenarios

The PF scenario considers the currently approved policies to reduce water consumption in different demand sectors. The Abu Dhabi Water Strategy (Environment Agency - Abu Dhabi, 2014) specifies these policies as follows: (i) desalination water demand is set to increase by 20 % from the 2020 level in commercial/municipal megaprojects, (ii) annual groundwater extraction limit to 1980 MCM (10 % reduction) and 1430 MCM (35 % reduction) for 2020 and 2030, respectively, (iii) 20 % reduction of water use in public parks and gardens (amenities) by 2020 relative to 2010 consumption, (iv) 10 % and 20 % reduction of water use in forestry sector by 2020 and 2030, respectively, relative to 2010 water consumption, and (v) 20 % reduction of indoor and outdoor water consumption in residential sector by 2020, relative to 2010 water consumption.

Based on population growth models, the PF scenario is divided into three sub-scenarios. The first is called policy first-market first (PF-MF) assuming future high economic growth rates, which will result in higher immigration rates of workers into the EAD. Therefore, this sub-scenario uses the high population growth model (P2) as discussed earlier. The second sub-scenario promotes environmental sustainability using low population growth model (P4) and is called policy first-environment first (PF-EF). In this sub-scenario, lower immigration rates of expatriates into the EAD are expected. The Environment First (EF) sub-scenario used in this study represents a green economy (Environment Agency - Abu Dhabi, 2012). A balance between these two sub-scenarios is assumed in a third one, called policy first-balanced growth (PF-BG) sub-scenario, which uses medium population growth model (P3).

3.2.3. Sustainability by Conservation (SC) scenarios

This scenario represents a sustainable future as explained in the Abu Dhabi Environment Vision 2030. Under such future, there is a growing interest on sustainability across economic, social, and environmental sectors. The current water consumptions rates in the EAD are not considered to be sustainable. Over-exploitation of scarce groundwater resources for agriculture should be constrained Therefore, this scenario is a target-based scenario in which reductions in water consumption rates (demand management) in different sectors are sought through an iterative process to achieve a balanced water budget (BWB) until 2050. The SC sub-scenarios are developed considering three population growth models, sustainability by conservation-balanced growth (SC-BG) using P3, sustainability by conservation-market first (SC-MF) using P2, and sustainability by conservation-environment first (SC-EF) using P4.

3.2.4. Rainfall Enhanced Sustainability (RES) scenarios

The RES scenario is another target-based scenario, which is developed to achieve a balanced water budget until 2050 taking into account key assumptions on rainfall and other water resources utilization factors. Rain enhancement technologies through cloud seeding is a promising solution offering a cost-effective tool towards supplementing water supplies in the UAE. In this technology, harmless natural salts such as potassium chloride and sodium chloride are used for cloud seeding. Therefore, in this suite of sub-scenarios, it is assumed that Abu Dhabi will have an increased rainfall by 20 %. In addition, strict sustainable use of available water sources (desalination water, groundwater and treated sewage), is also assumed. The desalination capacity can only be increased by 20 % while remaining sustainable. Sustainable use of GW requires recharge rates to exceed abstraction rates. For TS, the sustainability condition is achieved by maximum utilization of generated TS in non-potable demand sectors. Accordingly, 95 % utilization of generated TS is assumed in this scenario. Therefore, an iterative simulation process was followed to find the optimized reductions needed for major potable and non-potable sectors. The main objective of this scenario is to determine an optimal solution for achieving water security in the EAD. Like previous scenarios, three sub-scenarios are developed for three population growth rates, which are RES-Balanced Growth (RES-BG) using P3, RES-Market First (RES-MF) using P2, and RES-Environment First (RES-EF) using P4.

3.3. Evaluation and analysis of scenarios

All scenarios should be analyzed using a suitable mathematical simulation model, to assess the consistency and coherence of the resulting data (Gallopin and Rijsberman, 2000). In this study, the ADWBM was used to evaluate the impacts of the developed scenarios. All scenarios are evaluated with regard to water balance (surplus or deficit), compatibility with environmental and sustainability targets, and sensitivity to key variables. A schematic representation of the steps involved in scenarios simulations using ADWBM is given in part three of Fig. 2. Detailed description of the simulated results obtained from ADWBM for all scenarios is presented in the next section.

4. Results

4.1. BAU scenarios

Two sub-scenarios were simulated under this scenario. In the first one, BAU-SQ, water demand is assumed to be driven by moderate population growth (P3). Total annual water demand of Abu Dhabi will increase from 3518 MCM in 2015 to 6107 MCM in 2050, with a 74 % increase. The key simulation results of BAU-SQ scenario are given in Fig. 3. The bar graphs show the annual sector-wise demands. The trend of GW decline and annual supply by each source are represented by trend lines.

The results showed that the EAD will face a deficit in both potable and non-potable water requirements unless interventions are implemented. The water deficit forecast under this sub-scenario for the years 2020, 2030, 2040 and 2050 are presented in the Table 4. For BAU-SQ, the model predicts a shortage of 1675 MCM and 555 MCM in potable and non-potable water supply, respectively. By the year 2050; the overall shortage will reach 2230 MCM. The GW reserves under this scenario continue to decline steadily and will be reduced to half of the current GW reserve by 2050 (Fig. 3). These increases in water demand and water shortages along with the steady decline in GW in the EAD are alarming. This, therefore, calls for achievable strategies to prevent water crisis in the future if the current consumption trends are continued. It is evident that BAU-SQ is not a balanced water budget scenario and thus cannot be adopted.

In the suite of BAU scenarios, a worst-case future, “Business as Usual-Worst case” (BAU-WC) is simulated as the second sub-scenario. It reflects potentially large increases in population identified by P1 in Table 1. Generally, BAU takes current trends forward. In the case of Abu Dhabi, however, population and economic growths have been increasing dramaticaly, and it is this continuation of this dramatic growth that provides one extreme of the BAU envelope. Although this worst case is unlikely to happen, it was included to show the huge impacts of such high population growth rates on water demands in the future. In BAU-WC, total water demand will reach 8389 MCM in 2050, nearly double that of the BAU-SQ scenario. Fig. 4 shows the sectoral demand over time. The most consuming sectors, if a BAU-WC scenario is adopted, are those driven directly by population, namely, residential, municipal, commercial, and amenities. The huge annual demand increase in the residential sector approaches 3000 MCM in 2050.

Although the results show that there are significant differences in water deficit between BAU-SQ and BAU-WC, both show an alarming increase of water deficit requiring practical strategies and policies to avoid water crisis in the future.

4.2. Policy First scenarios

The key results; sector-wise water demands, water supply and decline of GW reserves for the PF-BG scenario are shown in Fig. 5. The results demonstrate the positive impacts of approved policies against the BAU scenarios. The impacts on reducing water demands in all sectors are clear, especially for the potable sectors. Based on PF-BG results, these polices, if implemented, will be effective in achieving a water balance until 2027. This is as expected as these policies were originally designed to help address water demands through 2030. However, the results predict that some shortages will appear in 2028 and 2029 (Fig. 6), for both non-potable and potable demands, which might require another set of policies such as an additional increase in the desalination capacity. The model presented estimates of these shortages in both the potable and non-potable sectors, and these data could help to shape these new

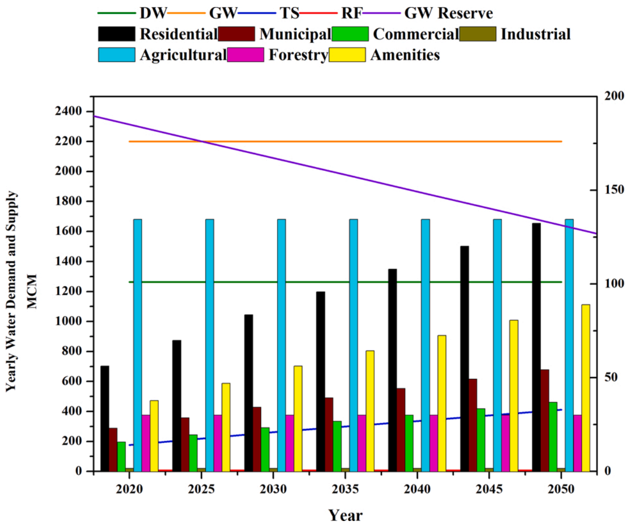

Fig. 3. Simulation results from ADWBM for BAU-SQ scenario.

Table 4
Increasing trend of water deficit over years for BAU-SQ and BAU-WC.

Year	BAU-SQ			BAU-WC		
	Potable	Non-Potable	Total	Potable	Non-Potable	Total
2020	70	150	220	179	178	357
2030	647	295	942	1236	444	1680
2040	1161	425	1586	2272	705	2977
2050	1675	555	2230	3308	966	4274

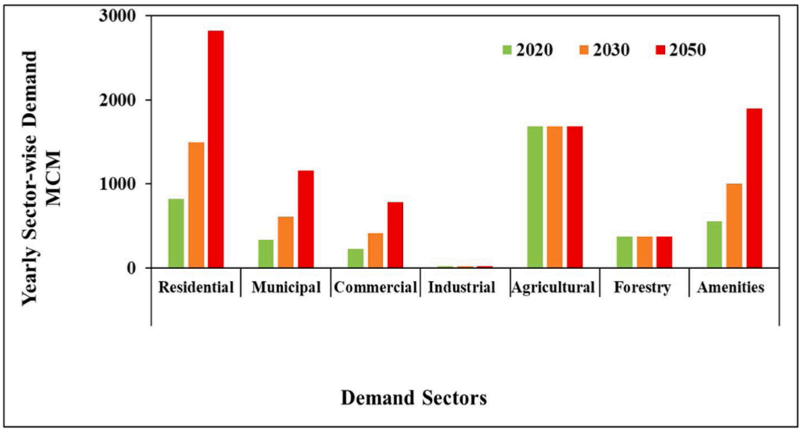

Fig. 4. Water demand in all sectors under the BAU-WC scenarios for 2020 (first bars), 2030 (second bars), and 2050 (third bars).

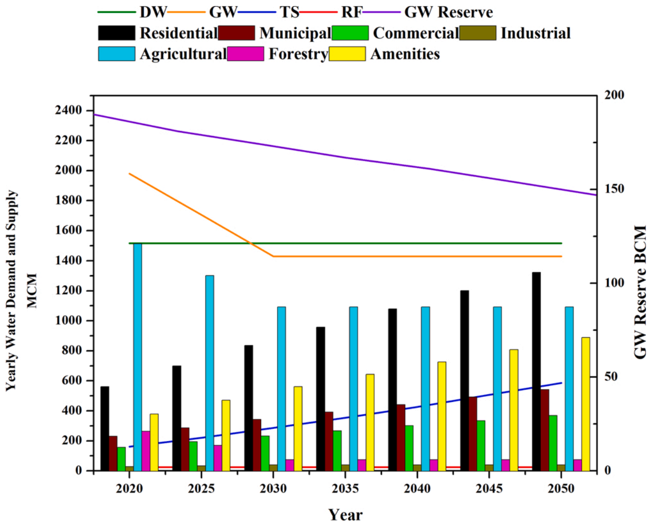

Fig. 5. Simulation results from ADWBM for PF-BG scenario.

polices, if needed.

Within the PF scenarios, another two cases simulated the impact of high (MF) and low (EF) population growth rates on the policies. From the results, PF-MF scenario with high population growth showed a water deficit as early as 2026 (Fig. 6), earlier than PF-BG scenario and will require an earlier change in policies. However, in the case of PF-EF scenario, the low population growth would maintain a positive water balance until 2033 (Fig. 6). Thereafter, deficiencies appear in the potable supply-demand balance which

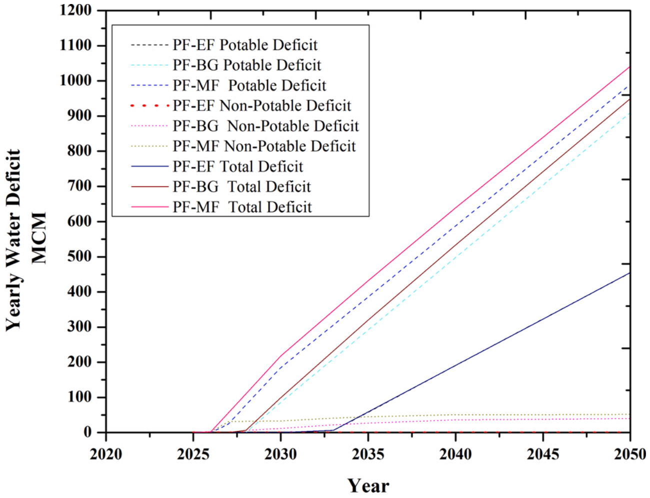

Fig. 6. Growth of potable, non-potable and total deficit for PF-EF, PF-BG and PF-MF scenarios.

must be addressed. There is no non-potable deficit forecast in this case.

4.3. Sustainability by Conservation scenarios

SC scenarios are target-based iterative simulations carried out to achieve no water deficit until 2050. The corresponding conservations to be implemented in each demand sector are estmated during this iterative process. The demand and supply details for the SC-BG scenario are shown in Fig. 7. This figure shows that less than 15 % of the strategic groundwater reserves are utilized until 2050 (Fig. 7). It is clear that huge induced reductions in all sectors are needed to achieve the goals of this scenario. The most notable are in the residential, commercial, agricultural, and amenities sectors. Two additional cases associated with different population levels, namely, SC-MF and SC-EF, were also simulated.

In order to achieve a BWB, a second level of simulations were carried out to identify the demand drivers (or demand sub-sectors) responsible for controlling majority of the water consumptions. It is important to identify these drivers to implement the required demand reductions. Breakdown of these reductions at drivers' level to achieve a BWB in the four major demand sectors is presented in Table 5.

Residential sector uses eight drivers which control residential demand. Table 5 summarizes the values of these drivers required to achieve the sought BWB, for all three SC sub-scenarios. It is worth noting that extreme reductions are needed in outdoor consumption, especially by the year 2050.

Commercial sector consumption is driven by five main drivers: (1) office employees, (2) retail employees, (3) restaurants, (4) hotel rooms, and (5) carwashes. The target consumption rates to be achieved for these drivers are also shown in Table 5.

Reducing the water consumptions in agriculture without affecting the production could be feasible by increasing irrigation

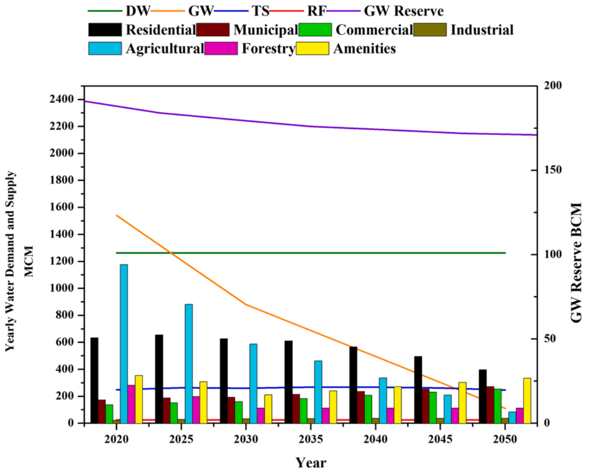

Fig. 7. Simulation results from ADWBM for SC-BG scenario.

Table 5
Target consumption rates to be achieved in sectors/subsectors by 2030 and 2050, under RES and SC scenarios.

Sectors / sector wise demand drivers	2030						2050					
	RES-BG	REF-MF	RES-EF	SC-BG	SC-MF	SC-EF	RES-BG	REF-MF	RES-EF	SC-BG	SC-MF	SC-EF
Residential												
Shabiyats Indoor (lpcd)	256	256	272	256	256	256	224	224	240	208	208	208
Shabiyats Outdoor (lpcd)	705	705	960	640	640	640	448	448	768	665	665	665
Villas Indoor (lpcd)	192	192	204	192	192	192	168	168	180	156	156	156
Villas Outdoor (lpcd)	528	528	720	480	480	480	336	336	576	240	240	240
Flats (lpcd)	240	240	300	180	180	180	180	160	260	110	100	124
Commercial												
Office Employees (liters/emp./day)	33	30	32	30	31	32	31	29	32	29	29	32
Retail Employees (liters/emp./day)	25	26	27	25	25	26	24	24	25	25	25	26
Restaurants (l/m^2/day)	16	15	17	15	15	15	15	15	15	15	15	15
Hotel Rooms (liters/room/day)	185	152	139	148	172	191	172	172	182	172	172	172
Car wash (liters/vehicle)	159	153	160	156	148	159	142	148	154	142	148	148
Agriculture												
Irrigation efficiency (%)	60	60	60	60	60	60	60	60	60	60	60	60
Cultivated area of crops (% reduction)	50	50	50	50	50	50	86	86	86	86	86	86
Forestry												
Irrigation efficiency (%)	60	60	60	60	60	60	60	60	60	60	60	60
Forestry area - Al Ain and Western Region (% reduction)	30)	30	30	30	30	30	30	30	30	30	30	30

efficiency. So, this efficiency was iteratively increased to reach the sought reductions in consumptions at different years to achieve a BWB scenario. For the year 2020 and afterward, it was not feasible to achieve BWB by just improving the irrigation efficiency because of the large required reductions in consumptions. The only solution to achieve this was to reduce crop area. After assigning a 60 % increase in efficiency at these years, the minimum reduction in crop area to achieve BWB was found to be 50 % in 2030 and 86 % in 2050 for all the SC scenario cases (Table 5). The selected 60 % irrigation efficiency is perceived to be practical and feasible. However, irrigation efficiency improvements for vegetable crops and field crops are expected to be more achievable because of the likely increase in the use of drones for optimizing irrigation though assessments of crop health and soil moisture as this is more applicable for low lying field crops rather than orchards.

For forestry, similar to the agricultural sector, the first option considered was to increase irrigation efficiency without changing the current forestry area. Increasing efficiency alone will not be sufficient to achieve a BWB from 2020 and beyond, which implies that reductions in the forest area will be needed. Reductions required are 30 % in 2030 and 2050 if the irrigation efficiency can be increased to 60 % (Table 5).

Although, SC scenarios showed the target values needed to achieve BWB for Abu Dhabi until 2050, some of the conservation

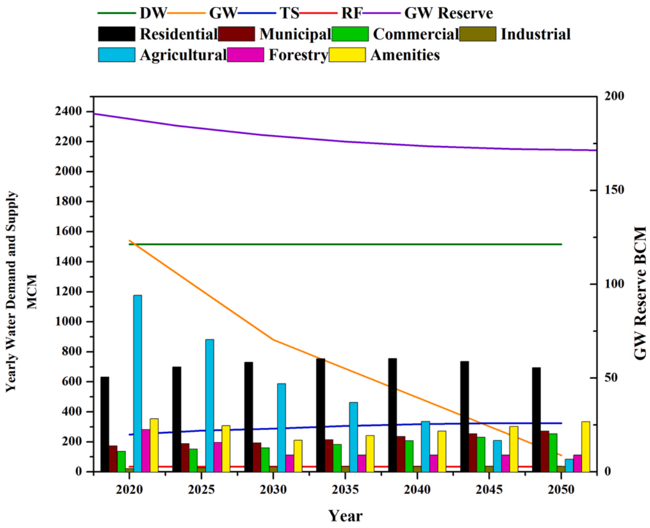

Fig. 8. Simulation results from ADWBM for RES-BG scenario.

requirements are very challenging and need a complete change in consumption patterns in Abu Dhabi. Hence, this scenario calls on policy makers to have long term strategy implementing stringent water conservation policies.

4.4. Rainfall Enhanced Sustainability scenarios

The demand, supply, and GW conditions for the RES-BG scenario are shown in Fig. 8. Two sub-scenarios for the high and low population growth rates were simulated. Analysis of all SC scenarios indicate that with the effective implementation of different demand conservation strategies it will be possible to achieve a BWB. This triggered proposing this set of RES scenarios. Maximum utilization of TS (95 %) and minimum use of GW (abstraction equal to recharge) are assumed in this scenario.

Similar to SC scenarios, iterative simulations were conducted to find the optimized reductions needed for various demand sectors, particularly, residential, commercial, agricultural and forestry sectors. Table 5 summarizes the reductions needed (by 2030 and 2050) for the different drivers (relative to their current values) to achieve a BWB in all three RES sub-scenarios (RES-BG, RES-MF, RES-EF). Such reductions for residential and commercial drivers are expectedly lower in the RES scenarios when compared to SC scenarios. For agriculture and forestry sectors results were similar to the SC scenarios.

In this scenario, the supply increase from RF and DW will not relax the expected future shortage in water. One of the reasons is that this additions in rainfall along with the sustainable increase in DW, will not be in par with the growing population. However, the increased rainfall can enhance the natural recharge of groundwater thus improving the sustainability of GW aquifers. Thus, for a sustainable future, large scale and sustainable increased rates of RF and DW are needed to avoid adopting strict conservation measures at the user level.

Thus, from the analyzed scenarios, only strict conservation strategies can support the management of the existing water supply and demand system of the emirate, and in turn can contribute to the realization of sustainable Abu Dhabi. However, RES scenario may be preferred over SC scenario because comparatively lenient conservation measures may prevent water shortages in future.

5. Discussion

5.1. Conservation-based management for sustainable future

The reductions in water demand that are to be achieved for each scenario require interventions to implement specific programs. Regulations and market interventions will be insufficient to attain such goals unless there is an acceptance of the need for change, and this requires engagement programs. Here, six interlinked categories of interventions and programs are discussed which can be applied to achieve a balanced water budget for Abu Dhabi.

5.1.1. Long-term adjustment of attitude

Long-term interventions are required to adjust the context and expectations; without this, interventions are likely to be unused, discontinued or result in criticism. Two long-term interventions are important, namely, (i) education and (ii) value promotion. Education concerning the importance of saving water needs to be part of the core curriculum in schools.

If a part of the infrastructure is to be recognized as important and valuable, then some modest value has to be placed on its provision to the individual. Abu Dhabi has already taken the important, indeed vital, first step in this by pricing and billing for domestic water use. This needs to be expanded across all the water using sectors, with the prices raised to a meaningful level. The idea is not to use tariffs to control demand but to ensure that water is having a value. For a long period, water was free of charge to the customers, but given the extreme water use per capita seen in many segments of the economy, there is clearly a case for driving, more forcefully, recognition of its value. Water value enhancements and recognition through pricing and education are mutually supportive and underpin the long-term success of the direct water saving interventions.

5.1.2. Short-term technological/legislative interventions

External water use (outdoor consumption) is the major component of overall residential water use and needs to be tackled immediately both in terms of frequency and volume. There are several technical and legislative options that can be adopted such as: (1) allow external hose to use only on a permit and/or rotational basis, (2) fit all external taps with pressure reduction valves, (3) fit all external taps with a period of use cut-off (simple or delayed restart), (4) legislate to ensure that all external demands use only recycled water, and (5) legislate to provide external water use permits only if full recycling is in place.

External use in a residential sector is for gardens primarily. Thus, to mitigate the reduction in garden irrigation water, information on the targeted irrigation of plants and the use of smart soil moisture sensors must be provided, and adoption could be supported perhaps by some modest financial encouragement. Table 5 presents a series of reduction percentages in the residential sector needed to achieve the BWB for the SC and RES scenarios. This table depicts the rather elevated reduction levels needed in outdoor consumption (in villas and shabiyats) where reduction percentages from baseline values in some cases reached above 75 % by 2050. Introducing bylaws, such as plumbing regulations, to mandate greywater and toilet plumbing separation in construction for example will yield additional flexibility for the introduction of reuse requirements (RTI International, 2009) and eventually lower the outdoor gardening demands.

Many interventions to reduce indoor residential consumption exist. Several studies have demonstrated that high-efficiency and low-flow appliances can be effective regulators of residential demand (Ahmad and Prashar, 2010; Grafton et al., 2011; Qaiser et al., 2011; Rockaway et al., 2011). Low-cost devices, with the highest potential savings, are likely to be favored by residential consumers.

Tap atomizers for instance are extremely low-cost with high potential savings. They can be installed easily and can reduce the consumption by as much as 90 %. This installation/adaptation has specific relevance to Abu Dhabi since a residential end-use study identified high tap use as a significant contributor to overall residential water use.

Replacing the entirety of large appliances in existing homes may be seen as a less favorable option by the consumers because of the higher price and the installation time (and thus inconvenience and disruption) associated with it. In a USA study, showerhead and toilet replacements proved successful at producing significant water savings (RTI International, 2009), and so prioritizing installation of efficient toilets and showers to new buildings exclusively is deemed appropriate. Replacement of standard efficiency toilets and showerheads with high-efficiency equivalents when a property is sold could be required. This equates to the requirement in the many UK areas that meters be installed on the sale of a house. Importantly, these recommendations are supported by the Environment Vision 2030, which seeks to increase indoor water-use efficiency of new and existing buildings by modifying current building codes (Environment Agency - Abu Dhabi, 2014).

Modification of taps and showers to reduce flow is of high priority because of the low cost and immediate savings associated with these options, as well as their success in existing studies (Ahmad and Prashar, 2010; Rockaway et al., 2011). Such mandatory retrofitting could be expanded to xeriscaping in new and existing homes in the Abu Dhabi Emirate and is likely to produce greater savings due to the high ratio of outdoor: indoor usage. Xeriscaping is key to achieving the SC and RES scenarios in particular. Other devices that should be considered but at a lower priority include dual-flush toilets and sub-metering. Dual-flush toilets have been seen to have a statistically significant negative effect on water consumption (Grafton et al., 2011). Sub-metering has been successful in some studies, although voluntary installation produces bias since it is usually adopted by self-selected low water users (Mitchell and McDonald, 2015).

Use of behavioral apps in promoting water conservation has been successful in the USA and Europe over recent years. These apps could potentially be successful in the Emirate because of the relative youthfulness of the population and the experience and acceptance of rapid change and modernization. Behavioral campaigns have been tried over a longer time period with variable success (Fielding et al., 2013). Sustained programs are needed to assess the impact on water use, but remain few in number (Ozkaynak et al., 2012). In the EAD, appealing to the conscience of the people through their underlying Islamic tradition and beliefs could help to achieve greater benefits from these campaigns (Ozkaynak et al., 2012). The Chartered Institute of Water and Environmental Management in the UK promotes behavioral change through faith leaders with conservation messages supported by scripture (Nawaz and Sadek, 2010).

5.1.3. Legislative changes in the market place

In the same way as white goods are sold with a water and energy efficiency grading, all housing can be subject to standards of water efficiency. In the UK this has been attempted for social (state) housing and voluntarily for other developments. Clearly, the same absolute target volume of water per house per day would not be realistic or indeed sensible, and so requirements need to be set for each house type and incorporated into building codes. There are a variety of international water standards for housing that are either based on whole-house water use or set limits for each individual appliance. Since the most likely future for the EAD is one of significant housing expansion, such legal water standards will, over the years, significantly reduce water demand. To achieve improved water standards, the purchase of water inefficient goods from the Abu Dhabi market must be made impossible, e.g., by implementing water market transformations. This is a successful action adopted throughout Europe to control parts of the energy market, specifically the removal of incandescent light bulbs.

5.1.4. Fiscal and information interventions

The use of pricing mechanisms to control water demand has many drawbacks, and there are very few instances of successful examples. Water is not readily substituted if it becomes more expensive, unlike for example, potatoes, which can be substituted by wheat, rice etc. As water is not substitutable and is vital for life, it is inelastic; that is, when the price changes, the rate of consumption shows little movement. Examples of price influencing demand in Denmark and Bulgaria required a five-fold increase in price to the point where it became punitive. In addition, if the price of water is broadly the same for all customers, the modest reduction in demand as price per unit of water is increased found among the poorer customers is not likely to be found among in more affluent customer reactions. However, if a rising tariff is applied, it will serve three functions; (i) first, it will exercise a very modest control on water demand, (ii) second, it will provide income to the water company to fund supply and demand side initiatives thus reducing pressure on the national government, and (iii) third, it will reinforce the message that water is a precious resource. Further, the use of smarter meters informing customers of the volume used and the direct and indirect price (an estimate of the energy used to heat the water) will influence conservation behavior.

Some studies have suggested an elasticity for outdoor water use of about 0.35, double that of indoor use. Most literature suggests indoor water demand is relatively insensitive to price, decreasing at best by 10 % against a 100 % increase in price. A possible additional intervention therefore is to price and meter indoor and outdoor water use separately. This implies that there will have to be some means of regulating between these two uses. The most obvious system would be through differently threaded/connected outdoor taps and water systems, i.e., through building codes and appliances regulations discussed earlier. That further implies that the building regulations and the specifications for water using systems available on the market would also have to be controlled. This is congruent with limiting the availability of low water efficiency goods in the market. Clearly, such regulatory and market interventions would only be used under particular policy climates, and thus, applications would only occur in some scenarios.

Although in its infancy, a water cap and trade system applied to all consumers could potentially reduce residential water consumption in the long term by levering in the technical and behavioral innovations discussed here. Such a system addresses issues with the inefficiency of water pricing as a measure to curtail demand, and its potential is reflected in the success of cap and trade systems for other common pool resources (Mitchell and McDonald, 2015).

5.1.5. Market interventions

The various approaches discussed earlier will reduce water demand but are relatively inflexible tools unlikely to be able, alone, to reach the targets needed and unable to respond to changing conditions in a progressive and controlled manner. Cap and trade offers, in the longer term, a means by which control can be exercised in the water market. Cap and trade at its simplest establish a ceiling on the amount of water to be used and requires customers to trade water use certificates that control the amount of water they are permitted to use. It has been explained in detail in (Mitchell and McDonald, 2015), who effectively demonstrated that the cap and trade system, typically used in the energy and pollution control sectors, can be applied to water. Cap and trade need not cover all water sectors at first; it could be implemented on a trial basis on industry. The limitation perhaps for Abu Dhabi is the modest size of the various water sectors, but this is offset by the sustainability commitment and the ready acceptance of cutting-edge approaches. (Mitchell and McDonald, pers com) have completed a global analysis of which countries have the sophistication to run such a system and also have the water resource deficit needed to make such a system necessary. Abu Dhabi scores very highly on both counts in terms of having a serious water imbalance and very highly sophisticated infrastructure capable of driving a cap and trade system. It also has the regulatory sophistication to control such a system.

5.1.6. System interventions

Currently, there appears to be an information deficit, particularly in agriculture, which lacks accurate or precise measures of the water used, nor an estimation process. Thus, it is impossible in some sectors to target interventions correctly. Consequently, it is suggested that the water balance model be used to identify the most important information deficits and to set underway actions to reduce that deficit, which could include simple modelling to estimate usage in unmetered activities. Several projects and initiatives have been implemented in recent years to cover this information gap.

Also, there are major opportunities to further integrate water and renewable energy management to enhance sustainability as outlined by (Teschner et al., 2012).

5.2. Supply-driven management for sustainable future

There are opportunities to further integrate water supply and renewable energy to enhance sustainability in Abu Dhabi as discussed under this section.

5.2.1. Desalination

There is debate over the best way forward for GCC countries to ensure sustainable water supplies through the desalination process. (Al-Damkhi et al., 2009) argues that the government should focus on existing resource use and non-nuclear renewable energy technologies. This follows recommendations from the Masdar City project in Abu Dhabi, and thoughts from (Fencl et al., 2009). Masdar City obtains its primary water supply from solar-powered desalination (Owen, 2011). However, (Al-Mutaz, 2001) advocates the use of nuclear energy for desalination, despite its negative implications (McDonnell, 2014). Therefore, there is a case to focus on existing and renewable energy resources, which are likely to drive desalination costs down (Ghaffour et al., 2013), in combination with consumer resource conservation. However, the validity of this recommendation will depend on the long-term success of the UAE’s first nuclear plant (McDonnell, 2014) once fully operational, and future advances in desalination technology.

5.2.2. Wastewater reuse

Wastewater reuse has great potential to contribute to supply and minimize the supply–demand gap (Chowdhury et al., 2015). Wastewater recycling is likely to significantly augment future water resources of the GCC countries (Al-Damkhi et al., 2009). Wastewater reuse is currently limited to municipal landscape irrigation (El Din et al., 1994). Further research into the feasibility of harnessing wastewater for reuse in all sectors is required. Commercial car washing facilities recycle their effluent for instance (Al-Damkhi et al., 2009). Combining reuse with a total outdoor conservation scenario in an arid region reduced demand by an additional 0.11 MCM/day (Qaiser et al., 2013). Therefore, for a sustainable future optimized recycle wastewater usage is recommended.

5.2.3. Leakage and irrigation

To achieve the modeled sustainability scenarios, leakage and irrigation should both be targeted (Qaiser et al., 2011, 2013; Environment Agency - Abu Dhabi, 2014; Saif et al., 2014). Households lose an average of 124 L/day to leaks, and outdoor use is in excess of 1,200 L/household/day. Total outdoor conservation was identified as the best option among different conservation scenario options in a Las Vegas study (Qaiser et al., 2013). There have been a number of successful programs in the USA, for example, which have resulted in water savings following an irrigation landscaping review (RTI International, 2009). Improving irrigation efficiencies and crop choices should be prioritized, by changing the cropping calendar, shifting to smart or drip irrigation systems, reducing the area planted, and altering the timing of watering gardens (Fencl et al., 2009; Qaiser et al., 2011; Saif et al., 2014). Over irrigation causes water losses through evapotranspiration and seepage to groundwater (Qaiser et al., 2011). Replacement of Rhodes grass with Buffelgrass, a more water efficient crop, should continue, (Fencl et al., 2009).

5.3. *Strengths and limitations of the study*

In this study, the use of scenarios revealed water management challenges for the EAD up to the year 2050. A set of existing scenarios relevant to water management were elaborated through stakeholder workshops, interviews, and expert knowledge to identify drivers of water supply-demand, their interdependencies, and influence on Abu Dhabi water system. Thus, this study provided insights to the real context and challenges of Abu Dhabi in the realm of water management.

Some values used in model are based on historical data, projections, and estimations. Some projections are based on assumptions supported by the available data.

6. Conclusions

This study produced a forecast of the water balance in the Emirate of Abu Dhabi to the year 2050 from which it was possible to identify actions needed to eliminate potential water shortages. A series of future water scenarios were constructed to represent different future water conditions. Demographic conditions related to present and future water consumptions in the Emirate of Abu Dhabi were central to the analyses. The study presented a review of recommended actions to achieve a BWB. All of the proposed actions were tailored to accommodate tangible conservation in water consumption. The main and most important actions that should have long-term and comprehensive impacts on all types of water use include public awareness programs that have already started in recent years. Other specific technologies and legislations targeting reductions in water consumptions for different demand sectors were also discussed. While both the SC and RES scenarios achieved a BWB throughout the entire period (with no shortage), the RES scenario is recommended because the proposed interventions are expected to be more achievable and flexible given future uncertainties. The study showed that new resources will be needed, e.g., desalinated water, to support the major increase in potable demands in later years if the Business As Usual and Policy First scenarios are followed. The business as usual path is not sustainable and the EAD must make major changes in order to pursue the alternative sustainable pathways modelled. However, efforts need to be maximized at all levels, from household to nationwide, in order to make sustainability a reality.

Data availability

Some of the data presented could be requested from the corresponding author upon approval from the Environment Agency of Abu Dhabi.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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