Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2020.26450

208 (2020) 196–209
December

The effectiveness of urban water conservation and desalination for water resources management in Jeddah city

Ahmed E.M. Al-Juaidi

Civil and Environmental Engineering Department, King Abdulaziz University, Jeddah 21589, Saudi Arabia, Tel. +966 555 959 725; emails: aealjuaidi@gmail.com/ahmed.aljuaidi@gmail.com (A.E.M. Al-Juaidi)

Received 23 March 2020; Accepted 11 August 2020

ABSTRACT

Jeddah city is anticipated to face water supply shortages due to the expansion of urban development and economic activities. This work aims to investigate the effectiveness of water-demand alternatives with existing desalination on Jeddah's water developments using the Water Evaluation and Planning System (WEAP) model. The analyses of trends in water supply and demand between 2017 and 2030 are considered. Furthermore, vulnerability analysis of the water supply system is examined after identifying the years of unmet demand. Model results show that Jeddah will have a shortage of 504 MCM in 2030 if the existing water supply remains the same. Introducing water conservation and leakage reduction measures to the existing desalination decreased the unmet demands by 66% and 21%, respectively. The implementation of water conservation with the current desalination decreased the unmet demands to 172 MCM which is lower than 504 MCM which occurred in the 2030 baseline. The water conservation measure generates a total vulnerability of 10.27×10^6 MCM which is lower than those happened in the baseline and reduce leakage ones. Moreover, water conservation and desalination are not sufficient to completely eliminate future unmet demand in all demand zones. Therefore, new water supply measures are required to meet future water shortages.

Keywords: Water conservation; Leakage; Desalination; Water resources; Demand; Supply; Jeddah

1. Introduction

The expansion of urban developments with the highest population growth and the economic activities exhaust the existing water supply sources in Jeddah city [1]. Therefore, careful water resources executive arrangements should be utilized to prevent future water scarcity challenges. The population and size of the urban areas in Jeddah city increase dramatically within the last two decades. For example, the urban areas in Jeddah were 174 Km^2 in 1984 and increased up to 218 and 370 Km^2 in 2002 and 2014 respectively (Saudi Geological Survey SGS, 2017). Water supply in Jeddah city is mainly depending on two desalination plants namely Jeddah and Al-Shoaiba desalination plants. These plants provide Jeddah with approximately 33.8 MCM per month which corresponds to 99.31% of the Jeddah's entire water contribution [1,2]. Approximately 0.234 MCM per month of the water supply comes from existing groundwater wells which represent 0.69% of Jeddah water supply. Currently, there is no contribution from recycled sewage as it is only being used in public garden irrigation [2,3].

Jeddah city like many other cities in the Middle East experience water deficit issues that need to be handled and figured out [4–9]. The Municipality of Jeddah currently serves more than 4.69 million capita. The population of Jeddah is expected to increase to seven million capita in 2030. Evaluation of the existing situation should be considered first to recognize the on-going problems and to find out the ramifications. This assessment is implemented by developing water demand alternatives planned by the National

Water Company (NWC) model using the Water Evaluation and Planning System (WEAP) model. Thereafter, the evaluation of the outcome of the planned water development options will be utilized by the WEAP model. WEAP integrates water supply in respect of demand-side issues and serves an easy tool for water resource demand and supply planning and management. WEAP is notable for its integrated approach to simulating water supply systems [10–12].

The research is motivated by the essentials of comprehending the level of the current and future problems in Jeddah's water supply system. The evaluation of the potential solutions for water supply problems is essential for the city as it is expanding vastly. WEAP is a tool that provides immediate answers to any planning inquiries, and therefore, it assists decision-makers in planning and management of water resources supply and demand management.

This paper examines whether the current situation (status-quo), which substantially depends on desalination for water supply, is capable to cope with water needs in Jeddah city from 2017 until 2030. This paper attempts to implement integrated water resources management (IWRM) throughout utilizing urban water conservation and fixing leakage measures in the water distribution system, as planned by the Saudi National Water Company (NWC). These proposed water development alternatives are combined separately with the current situation to observe which alternatives should be given a priority over the other one. Therefore, the WEAP model simulates water demand and shortages throughout demand years from 2017 until 2030. The concept of water sustainability stated that water should be consumed at a certain rate to prevent the decline of groundwater resources and desalinated water for future use [13–19].

Many previous studies have been conducted using the WEAP model as a part of water resources demand and supply management for various areas that experience water shortages around the world. For example, Yates et al. [20] employed WEAP to study the changes in California's Sacramento River basin water supply and found that this approach is beneficial for many California water improvement and management developments. Bharati et al. [21] employed WEAP to conclude that water storage and transport water among catchments in India helps in eliminating future water shortages. Al-Omari et al. [22] used WEAP for Amman-Zarqa catchments to find the best water management alternatives. Höllermann et al. [23] analyzed the impact of various climate change, social and economic alternatives on water development strategies in Benin using WEAP. Hoff et al. [24] utilize WEAP for the Jordan River basin using with more focus on socio-economic and climate change to predict future water scarcity. Vicuña et al. [25] examined the impact of temperature and rainfall on overland runoff and irrigation systems in the Limari catchment. Rheinheimer et al. [26] established a relationship between climate warming on Sierra Nevadas watershed and the production of hydropower by using the WEAP model. Hamlat et al. [27] studied the effect of various management policies on various sources of water in Algerian watersheds. Mourad and Alshihabi [28] employed WEAP to evaluate future water demands and deficits in Syria in 2050. Kou et al. [29] used WEAP to find the combination of best water management alternatives in Xiamen city in China. Al-Juaidi and Attiah [30] used WEAP to evaluate the impact of the existing groundwater and desalination supply on present and future water supply systems in Riyadh city.

The uniqueness of this works is its inclusiveness of influential water demand management alternatives that could have water-saving potentials and reduce future water deficits. The water demand alternatives are leakage reduction from the water supply network and the implementation of household water appliance retrofitting in urban buildings. Water conservation is the first time to be introduced with the exiting water supply (desalination and groundwater) to evaluate the demand and supply of the city five demand zones individually.

This work measures water uses prior to and after the utilization of household appliances based on the recommendation of the Saudi Ministry of Water and Electricity [31]. To facilitate the analyses, at first, a questionnaire has been conducted to measure the willingness and awareness of the public to retrofit the existing old household appliances with a new one. It also provides information about which household water appliances that should be given priority over the other appliances. Water conservation is considered through retrofitting old household appliances as an alternative to be considered along with desalination to meet future demand. Cronbach's alpha coefficient is used to validate the stability of the results of the questionnaire [32]. The one-sample *T*-test is also used to find which household appliance variable is the most water consumer and has to be given a retrofit priority [33,34]. Later, the work evaluates the current situation of the Jeddah city water resources system and to evaluate two proposed water demand management alternatives which are urban water conservation and leakage reduction in the city's water distribution network. It assesses whether the current desalinated water, which provides the city with 99.3% of its water supply, is enough to eliminate future water shortages or not. Then, the other water demand alternatives are considered separately with desalination to measure the impact of these proposed changes on future water demand and shortages.

2. Methodology

The methodology of this research includes three major phases. The first phase includes meetings and surveys with the engineers of the Saudi NWC which includes data collection to on the existing water resources system, and to get a clear picture from the water authority managers on intended management plans to re-run the Jeddah water system. The second phase includes statistical analyses by conducting a questionnaire to test the awareness and willingness of the people of Jeddah to retrofit the old household water appliances by new ones to reduce future water demand. The household water appliances which considered in this work include proposed new technologies of household water appliances according to the Saudi water and electricity manual (2008) [31]. These household water appliances are clothes washers, faucets, dishwaters, toilets, as well as fixing leakages in household plumbing systems. This study includes the water savings quantity as a result of introducing new water conservation into the modeling. The third phase is to create an IWRM tool for Jeddah city. The main steps of the IWRM are as follows: (a) set up the GIS dataset on the current water system as input into the WEAP model; (b) development of the demand management scenarios adapted from the NWC and to be processed using WEAP; (c) evaluation of the demand management planned scenarios and to be compared with the existing conditions. The WEAP model will be executed with the available current conditions data, to investigate its capability to imitate present conditions; (d) a comparison between the existing conditions and the planned water demand alternatives on the simulated future demand and shortages will be carried out using the WEAP model [11]; (e) the actions and implications required according to the best demand management scenario will be elaborated. Last, the performance of the water system will be evaluated by computing the vulnerability indicators on simulated unmet demands. The vulnerability test on the unmet demands for the proposed scenario is intended to choose the least vulnerable one to shortages [35,36].

3. Study area – Jeddah city

Jeddah city is considered one of the central cities in the kingdom situated on the west side of Saudi Arabia between latitude and longitude of 21.54 North and 39.17 East, respectively. Jeddah city is facing many challenges in water shortages due to limited sources of water resources. To reduce the shortage of water, Saudi Arabia's government started to invest in expanding desalination plants. Desalination is the principal water supply source for the city of Jeddah. It receives water from two desalination plants with a quantity of 1,077,285 (MCM/d) [2]. The groundwater is another water supply source. Groundwater wells are located in the Khulais area and supply the Khulais zone with a quantity of 21,000 (m^3/d). The entire current water allocation system is shown in Figs. 1–3. Furthermore, treated wastewater is a potential water source that is currently discharged into the Red Sea [1]. A growth rate of 4.3% is considered from 2018 to 2030 and is considered the most likely one [1]. Jeddah's population in 2017 was 4.69 million capita and is estimated to increase to 7.0 million capita in 2030. Fig. 4 shows an exponential increase in population for each zone from 2017 until 2030 which is projected from the WEAP model. Table 1 shows the water delivered quantity to each demand zone in Jeddah city in 2017. Desalinated water is generated from two desalination plants (Al-Shoaiba and Jeddah desalination plants) and covers 33.8 MCM/month which accounts for 99.3% of Jeddah city supply in 2017 [1,2]. The water delivered to zones is carried out by the water supply network and filling station. The five zones are considered based on the water supply method used to deliver water for these zones according to NWC [1]. For example, the filling station zone only receives water from water trucks and this zone does not have a water pipeline system. Khulais zone received water only from groundwater wells which are stored into tanks before it is delivered to the Khulais zone. The other three zones namely Al-Faysaliah, Briman,

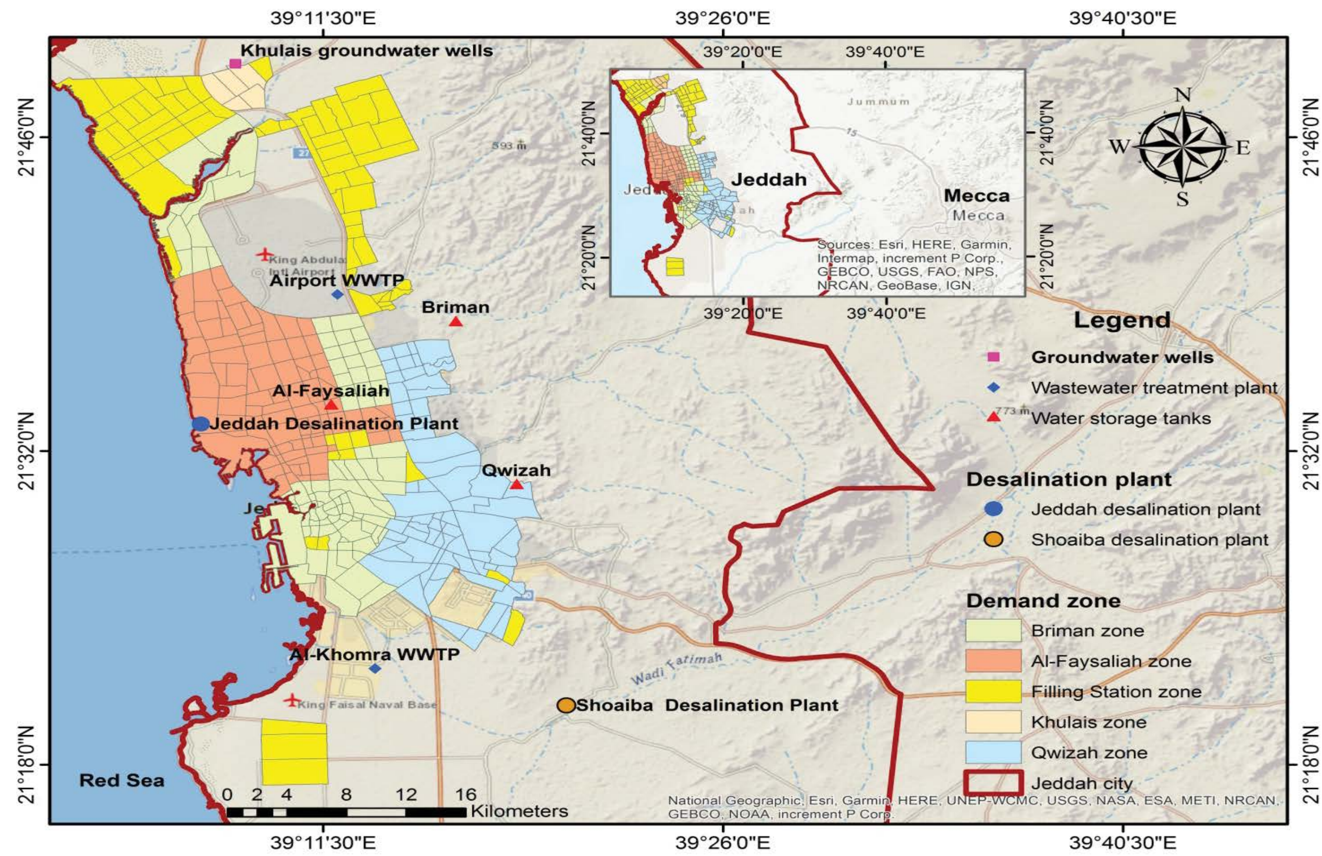

Fig. 1. Study area.

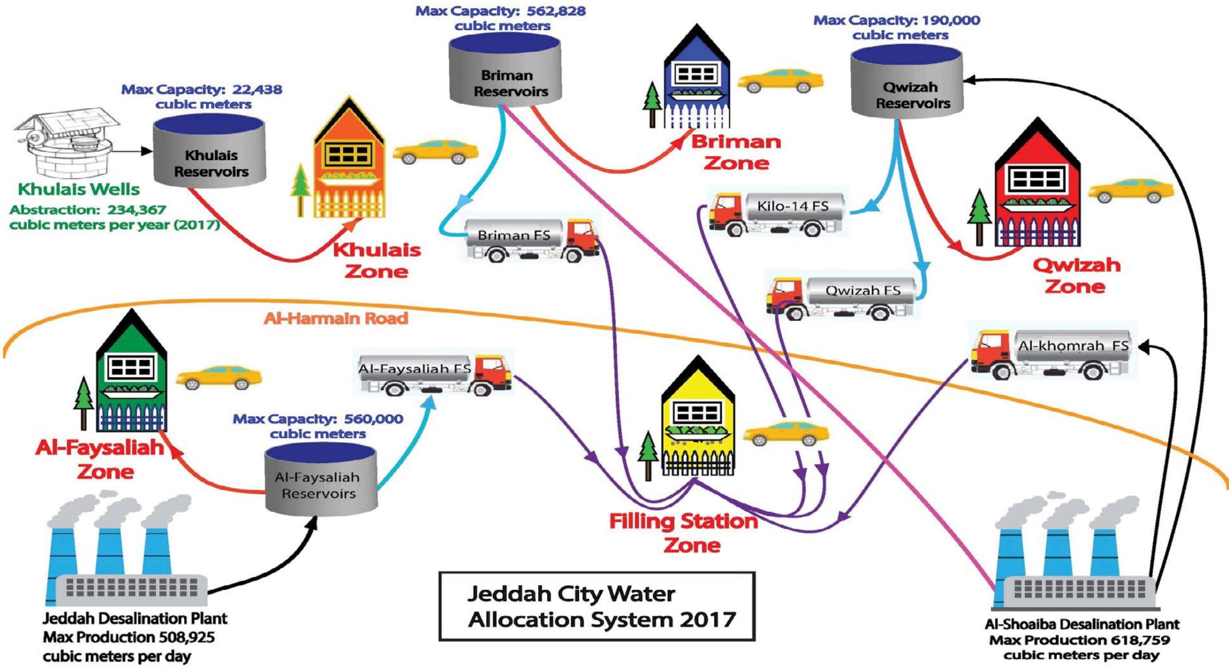

Fig. 2. Water allocation system for Jeddah city in 2017.

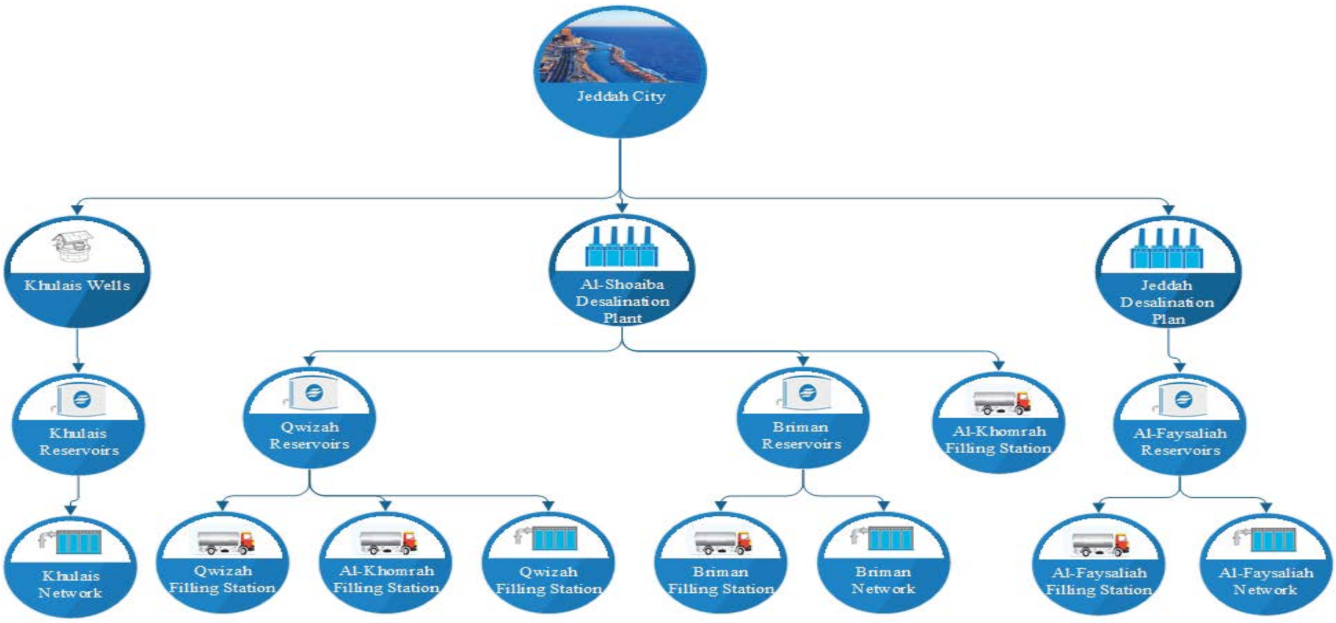

Fig. 3. Current water supply and allocation system for Jeddah city.

and Quizah received water from the desalination plants and stored in water tanks before it was conveyed through water supply networks to these zones [1].

3.1. Current water uses

Existing water in the Jeddah city is separated into five demand zones according to the water use. The average annual water use rate per capita in cubic meter per year for all zones is shown in Fig. 5. The estimated population of the Briman zone is about 1,182,118 capita, and the annual water consumption rate is 73 m^3/person. For the Al-Faysaliah zone, the estimated population is about 1,278,663 capita, and the annual water consumption rate is 91 m^3/person. For the Qwizah zone, the estimated population is about 1,242,208 capita and the annual water consumption rate is 52 m^3/person. The estimated population is about 103,182 capita, and the annual water consumption rate is 48 m^3/person. The fifth

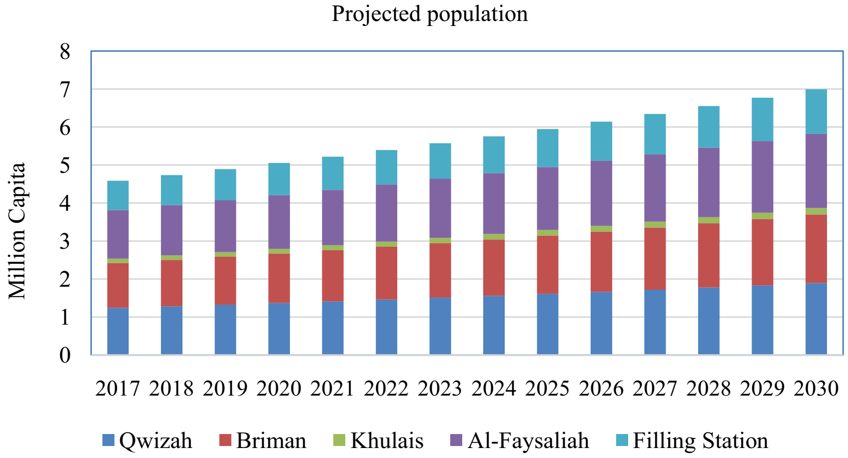

Fig. 4. The projected population for Jeddah city for all demand sites from WEAP.

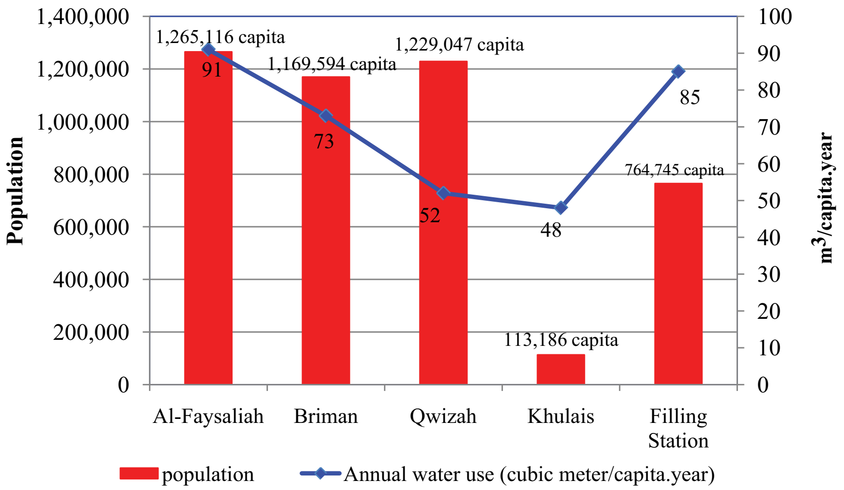

Fig. 5. The average water consumption for Jeddah city.

zone represents zones where the water supply network does not exist. This zone takes water only from filling stations throughout truck vendors. The population of the fifth zone is 467,951 capita. Approximately 10% of the water supply from the filling stations are delivered to the previous demand zones due to the failure of the water supply network in those zones [1,37]. The population served by the filling stations is expected to increase to 885,902 capita [1]. In 2017, the population is approximately 4.69 million capita (Fig. 4). The annual activity level and annual water use rate in the WEAP program is represented by the zones populations and water consumption per capita in the year. Table 1 shows the water supply quantities for Jeddah city from the desalination plant in 2017. The water is delivered to the demand zones via both water distribution networks and filling stations. The existing water supply quantity to Jeddah city from desalination plants is 34,064,895 m^3/month (Table 1).

3.2. Desalination plants

Desalinated water is conveying from the two desalination plants (Al-Shoaiba and Jeddah plants) cover 99.3% of Jeddah city water demand. These desalination plants are the major water source and supply Jeddah city with 34.064 MCM per month [2].

3.3. Leakage in the water distribution system

The leakage in Jeddah water distribution main system accounts for 25% due to illegal connections, unmetered premises, and see page from the network. The water authorities are setting new plans per each district to reduce the leakages from 25% to 10% by subsidizing water meters and repairing leakages. Further, fees will be applied to premises that withdraw water from the network through illegal connections.

4. Water demand management alternatives development

Here, a brief description of the current water system supply and demand practices, as well as the proposed water demand alternatives adapted by NWC, are illustrated. The WEAP model is used to evaluate available current conditions of data, to investigate the capability of the model

Table 1
Water allocation quantities to all demand zones in 2017 [1]

Source	Zone	Water delivery method	Number of water storage tanks	Volume of each storage tank (m^3)	Total storage volume (m^3)	Quantity delivered to zone m^3/month	Total quantity m^3/month	Total quantity delivered m^3/month
Khulais groundwater wells	Khulais	Khulais storage tanks and network	4	5,610	22,438	234,367	234,367	234,367
Jeddah desalination plant	Al-Faysaliah	Khulais storage tanks and network	8	160,000	560,000	11,861,631	27,382,542	34,064,895
			8	400,000				
Al-Shoaiba desalination plant	Briman	Khulais storage tanks and network	4	562,828	562,828	8,773,516		
Al-Shoaiba desalination plant	Qwizah	Khulais storage tanks and network	2	100,000	190,000	6,513,028		
			1	90,000				
Jeddah desalination plant	Al-Faysaliah	Filling station	–	–	–	3,406,122	6,682,353	
Al-Shoaiba desalination plant	Briman	Filling station	–	–	–	625,868		
Al-Shoaiba desalination plant	Qwizah	Filling station	–	–	–	911,790		
Al-Shoaiba desalination plant	Al-Khomrah	Filling station	–	–	–	426,722		

to imitate present conditions and to simulate the proposed water demand alternatives.

4.1. Reference scenario: 99.31% desalination and 0.69% groundwater

The reference scenario represents the current practices of water demand and supply for Jeddah city in 2017. The population growth rate in the reference case is considered to be 3.3% in 2017. The growth rate from 2018 to 2030, based on the most likely scenario for population growth in Jeddah city, is considered to be 4.3% according to [1,37,38]. The simulation of the WEAP model starts from 2017 until 2030. The desalinated water supply Jeddah demand zones with approximately 99.3% of its water demand and 0.69% from the existing groundwater wells in Khulais district. These groundwater wells only provide water to the Khulais demand zone with a quantity of 234,367 m^3/month. In Jeddah, approximately 5,400 m^3/d of the treated sewage is only to irrigate public gardens and not be used for urban water developments [1,39].

4.2. Scenario-1: reference scenario and leak reduction

According to national water authority publication reports, the leakage of the main intra-districts pipeline and inter-districts pipelines is approximately accounted for 25%. The illegal connections, leakages from unrepaired pipes, and un-metered homes are the major cause of these leakages. Here, the WEAP model will simulate a reduction in leakage from 25% to 10% is considered along with the current practices and its effect on future water and unmet demands.

4.3. Scenario-2: reference scenario and water conservation

Water conservation is aiming to reduce the consuming water in urban premises including households and commercial buildings throughout retrofitting the old water appliance with new ones. The Saudi ministry of water and electricity prepared a study plan for retrofitting plans for residential and commercial buildings to reduce the average consumption of water per capita [31]. Based on rough estimates, the Saudi Ministry of Environment Water and Agriculture (MEWA) suggests that the implementation of retrofitting of old water appliances could reduce water consumption from 30% to 40%. The next section of (5.2.1 – Water conservation for each zone) shows the percentage of water use reduction after adopting the water conservation plan.

5. Results and discussions

Here, several statistical analyses on the questionnaire that evaluate the awareness and willingness of people to retrofit their household appliances are presented. The potential water-savings for each demand zone through water conservation each is also investigated. Thereafter, detailed results of the existing situation and the two planned water demand alternatives will be elaborated to measure their effectiveness of future water delivery and shortages.

5.1. Identification of household appliance importance

In this section, a questionnaire has been constructed and analyzed to test the public awareness to identify the household water appliances that consume more and less water and to test the responsiveness and willingness to retrofit the old water appliance by new ones. To investigate the priority of household appliance retrofits, a questionnaire was developed through structured interviews and consultation with 220 respondents from various companies in Jeddah city (Table 2). The chosen experts have diverse educational levels and broad work experience varied from 5 to 20 years. Most of those respondents have a good knowledge and interest in the current and new water appliances performance in public and private sector premises and buildings. The respondents were asked to identify the household efficient appliances which are suitable to conserve water in the following urban buildings: (1) residential buildings, (2) commercial buildings (e.g. office, hotel, shopping mall, and restaurant), and (3) educational buildings (e.g., college, school, library). The study sample was distributed according to the gender variable. The male gender respondents were 208 (95%) while female respondents were 12 respondents (5%). According to the educational level variable, it is shown that 55% of the sample has a bachelor's degree, 25% have a master's degree, while 8 % have a Ph.D. degree (Table 2).

Table 2
Distribution of the sample according to gender and educational level

Demographic data	Type	Number	Percentage (%)
Gender	Male	208	95%
	Female	12	5%
	Sum	220	100%
Education level	B.Sc.	122	55%
	Master	56	25%
	Ph.D.	18	8%
	Other	24	11%
	Sum	220	100%

Table 3
Value of internal consistency for Cronbach's Alpha Method [32,33]

Cronbach's alpha	Internal consistency
$0.9 \le \alpha$	Excellent
$0.8 \le \alpha < 0.9$	Good
$0.7 \le \alpha < 0.8$	Acceptable
$0.6 \le \alpha < 0.7$	Questionable
$0.5 \le \alpha < 0.6$	Poor
$\alpha < 0.5$	Unacceptable

5.1.1. Cronbach alpha test

Cronbach's alpha is an important and pervasive statistics factor that includes test construction and is used for various research disciplines with multiple-item measurements [32,33]. In this questionnaire, the Cronbach's alpha coefficient for the reliability measurement was applying to validate the stability in the results of the questionnaire is conducting more than one time under the same circumstances and conditions [33,34]. It was founded that the value of Cronbach's alpha for this questionnaire is 0.977, which expresses that the questionnaire having a high coefficient of reliability (Table 3).

5.1.2. One sample T-test

The Statistical Package for the Social Sciences (SPSS) model was used to analyze the collected questionnaires and to find the most important household appliance variable that has a high impact on water consumption. The one-sample *T*-test is used to find which household appliance variable is the most water consumer and has to be given a retrofit priority. The one-sample *T*-test includes mean; 95% confidence interval of the difference between inputs, mode, standard deviation; *T*-test (one sample *T*-test) to indicate the significant level of the sample or *p*-value; and the relative importance index as shown in Eq. (1):

$$\text{RII} = \frac{\sum W}{A \times N} \quad (1)$$

where W is the weighting for each account by the respondents from 1 to 5; A is the upper response integer (5), and N is the entire number of respondents. The analysis results of the experts' inputs are shown in Table 4. In this table, six key household retrofits which have high importance in influencing the water conservation decisions: (1) toilet; (2) washer machine; (3) showerhead; (4) faucets; (5) fixing leakage in the household plumbing system; (6) dish-washer. Table 4 summarizes the results of the respondent's input for household water appliance water consumption and retrofits important. For example, the toilet retrofits variable has a mean value of 4.28, a mode of 0.49, a standard deviation of 0.8153, *T*-test value of 35.29, a *p*-value of 0.000, and an importance index of 0.857. On the contrary, the dishwater appliance has a mean value of only 3.467, a less mode of 0.73, a standard deviation of 1.217, a *T*-test value of 19.1, a *p*-value of 0.000, and an importance index of only 0.693. At the same time, all the variables have a *p*-value of 0.000 which means that the sample results are strongly validated. The results show that the significance level value of the *T*-test was statistically significant (less than 0.05) for all household appliance variables (Table 4). It means that there is a consensus from all respondents to the appliances which highly consume water such as toilets and washing machines.

5.2. Household appliance retrofits

Saudi Arabia and Jeddah city have a significant water deficit issue where water abstractions demand to exceed the available desalinated and groundwater supply. This piece of information has encouraged water authorities and the Ministry of Water and Electricity (MOWE) to initiate a substantial urban water conservation responsiveness plan aiming to increase the effectiveness of water use in Saudi Arabia (Fig. 6). The MOWE has established a water use

Table 4
Analysis of the respondents' inputs for household appliance water consumption and retrofits importance

No.	Household conservation	Mean	95% confidence interval of the difference		Mode	Standard deviation	*T*-test	Sig. Level *p*-value	Relative importance index
			Lower	Upper					
1	Toilet	4.289	4.044	4.534	0.49	0.8153	35.29	0.000	0.857
2	Washing machine	4.222	3.959	4.485	0.53	0.8762	32.32	0.000	0.844
3	Shower head	4.0	3.736	4.264	0.53	0.879	30.52	0.000	0.80
4	Faucet	3.956	3.636	4.276	0.64	1.065	24.91	0.000	0.791
5	Leakage repair	3.622	3.27	3.975	0.71	1.173	20.7	0.000	0.724
6	Dish-washer	3.467	3.101	3.832	0.73	1.217	19.1	0.000	0.693

T-test is statistical significant at $\alpha < 0.05$.

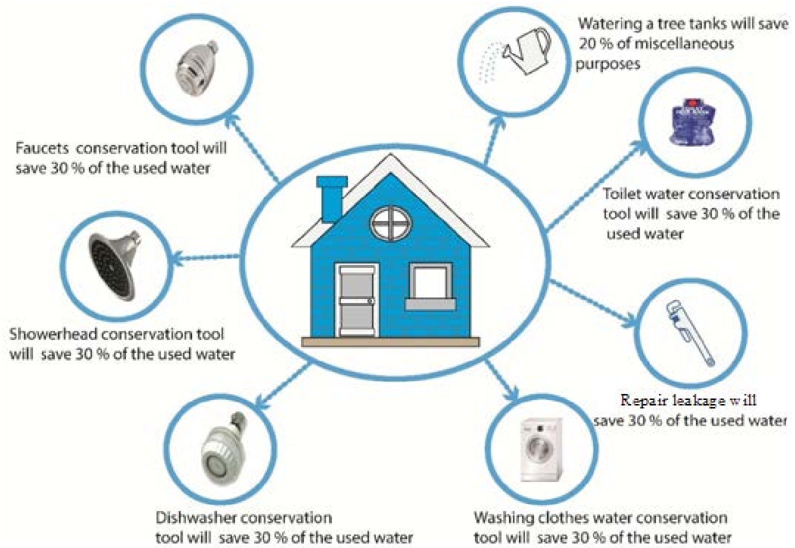

Fig. 6. Water conservation plan [31].

awareness document which includes water conservation retrofits advantages over old household appliances according to the MEWA [31]. It includes water savings potentials when implementing the water appliance retrofits for households, according to the water conservation manual available at (www.mewa.gov.sa). Table 5 shows the proposed water appliances for homes and their potential for saving on water use. According to the questionnaire analyses from the previous section, it is established that toilets and washing machines are the most water-consuming appliances in urban buildings; therefore, retrofitting those appliances should be given higher priority. Also, the public shows that showerheads, faucets, and fixing household plumbing leakages are important appliances that most are considered for water demand reduction. The analyses also established that people have a strong willingness and attitudes to retrofit old household appliances with the new ones.

5.2.1. Water conservation for each zone

Water conservation includes all the policies, strategies, and activities to manage the water used to reduce the water demand. These policies mainly include household appliance retrofitting and fixing leakages within the urban buildings' plumbing system. The Saudi Ministry of Water and Electricity [31] manual provides details about conservation tools in households (Fig. 6). The SMWAE suggested that household appliance retrofits could reduce water consumption from 30%–40%. Table 6 shows the saved water percentage for each demand zone. It also shows the average of water conservation percentages for all demand zone when retrofits of household water appliances.

After applying the water conservation tools suggested by MEWA, water use consumption could be reduced by 32% per capita (Table 6). In Jeddah, the annual water use rate per person is 90.27 m^3/cap y (i.e. 248 L/d). After applying the water conservation plan through appliance retrofitting (e.g., showerhead, toilets, faucet, clothes washer), the water consumption rate was reduced to 60.98 m^3/cap y (i.e., 167 L/cap d). This reduction of water use was calculated for all demand zones after using the Saudi ministry of water and electricity tools. For the Al-Faysaliah zone, the current washing clothes machines are a top-load type and used almost 22% of household total water use according to the MEWA

Table 5
Water conservation measures in urban buildings

Scenario	Main assumption	New Household appliance
Toilet size and expulsion boxes	Toilets are considered the first consumer of water in homes. It consumes around 360 L/d (i.e. 26%) of total household consumption. Installing small toilets with 3–6 L saves 43,800 L/y of water consumption per household. Also installing displacement bags inside an expulsion box of no larger than 6 L saves approximately another 100 L/d.	
Clothes washer	It consumes approximately 22% of the total household water consumption, which makes it the second most available water source. Markets are now having a front-loading washing machine that provides about 40% and 50% of water and electricity efficiency, respectively.	
Showerheads	Bathing consumes about 17% of total water consumption in homes. Consumption can be reduced by installing a provider head that consumes less than 8 L/min, compared to the regular shower head which consumes more than 22 L/min. The Ministry provides them at nominal prices not exceeding the cost price, with an average price of US$ 2.0.	
Sink faucet adaptor	The sink faucet adaptor occupies the fourth place and consumes about 16% of the total domestic water consumption. It consumes more than 15 L/min if the water pressure is high. In regular sinks, these adaptors consume less than 6 L/min. In kitchens, it consumes less than 8 L/min. It has high efficiency in terms of use and in terms of rationalization in water consumption.	
Fixing leakage	Household leaks account for about 14% of consumption, which is comparable to what is consumed in laundries and kitchens. Most household leaks are confined to two locations. The first site of leakage happens through the link between the meter and the household domestic tank. The second site of leakage is in the domestic water tank and this occurs through the failure of the buoyancy system and then leakage of water between the wall and the neck of the tank.	

conservation manual [31]. When new models of a clothes-washer machine-like front-load washer type are utilized, each person can save water by 40% per year. In other words, if the top-load clothes washer consumes 19.86 m^3/person is replaced by the front-load washing machine, the annual water use would be reduced by 11.92 m^3/person/y. Therefore, the annual water saved quantity is 7.94 m^3/cap y (Table 6). For the Briman zone, the annual water use rate per capita is 70.22 m^3/y (198 L/cap d). This annual water use rate was reduced to 48.79 m^3/y (134 L/cap d) after the implementation of water conservation strategies. Similarly, for the Qwizah zone, the annual water use rate per capita is 51.02 m^3/y (140 L/cap d) reduced to 34.49 m^3/y (94 L/cap d) when water conservation is considered (Table 6). In the Khulais zone, the current annual rate per capita before water conservation is 48.37 m^3/y (133 L/cap d). After applying a water conservation plan, water use was reduced to 32.70 m^3/cap y (90 L/cap d). In the filling station zone, the annual rate was reduced from 84.61 m^3/y (232 L/d) to 57.19 m^3/y (157 L/cap d). It is established that the average percentages of water-saving for all demand zones are found to 32%. This reduction was later entered into the WEAP model to simulate the cause of water demand reduction throughout the implementation of water conservation and leakage reduction measures.

5.3. Water development alternative comparisons

In this section, the relationship between the causes and effects of the existing conditions and the proposed two water demand alternatives to be described. The WEAP output parameters are water demand, unmet demand, supply requirement, and supply delivered. These parameters are compared between the three options to assess the long-term impacts of the proposed management alternatives on future water supply and demand.

5.3.1. Reference scenario: 99.31% desalination and 0.69% groundwater

The results demonstrate that water demand reduced from 335 in 2017 to 779 MCM in 2030 (i.e. 56%), as shown in Fig. 7. It indicated that the unmet water demand increased by 100%, from 0.0 MCM in 2017 to 504 MCM in 2030. Fig. 7 also shows the projected supply requirement and delivered

Table 6
The calculated result after apply water conservation plan for the Al-Faysaliah zone

Activity	Water used (%)	Water conservation (%)	Briman			Qwizah			Filling station			Khulais			Al-Faysaliah		
			Water use	Water use after WC	Water saved	Water use	Water use after WC	Water saved	Water use	Water use after WC	Water saved	Water use	Water use after WC	Water saved	Water use	Water use after WC	Water saved
			$m^3/y.cap$			$m^3/y.cap$			$m^3/y.cap$			$m^3/y.cap$			$m^3/y.cap$		
Faucet	16.5	40.0	11.9	7.2	4.8	8.4	5.1	3.4	14	8.4	5.6	8.0	4.8	3.2	14.9	8.9	6.0
Clothes washer	22.0	40.0	15.9	9.5	6.4	11	6.7	4.5	19	11	7.4	11	6.4	4.3	19.9	12	7.9
Showerhead	16.0	30.0	11.6	8.1	3.5	8.2	5.7	2.5	14	9.5	4.1	7.7	5.4	2.3	14.4	10	4.3
Toilet	26.50	30.0	19.1	13	5.7	14	9.5	4.1	22	16	6.7	13	9.0	3.9	23.9	17	7.2
Dish washer	1.50	53.3	1.08	0.5	0.6	0.8	0.4	0.4	1.3	0.6	0.7	0.7	0.3	0.4	1.35	0.6	0.7
Leaks	16.0	20.0	11.2	9.0	2.2	7.9	6.3	1.6	13	10	2.6	7.5	6.0	1.5	14	11	2.8
Other purpose	2.0	20.0	1.44	1.2	0.3	1.0	0.8	0.2	1.7	1.4	0.3	1.0	0.8	0.2	1.81	1.4	0.4
Total	100%	–	72.2	49	23	51	34	17	85	57	27	48	33	16	90.3	61	29
Water-saved %			32.1%			33.3%			32.9%			31.2%			32.4%		

Average of water saved percentage is 32%.

from 2017 until 2030. The result shows that water demand and supply requirements increased over demand years because of an increase in population growth rate with the same water supply quantities. Here, the total amount of supply delivered is found to be 469 MCM and started in 2020 and did not change until 2030. In other words, all demand zones will only receive the existing water tanks maximum storage of 469 MCM/y in 2020. The supply delivered quantities here indicates that Jeddah city has to build new water storage facilities starting from 2020 to be store and deliver water to demand zones. The unmet demand begins in 2018 and exponentially increased until 2030. Therefore, the current water supply sources are not sufficient to eliminate water and unmet demands. In the next two scenarios, water conservation and leakage reduction options are compared with the reference scenario based on the simulated water and unmet demands as well as supply requirements and delivered (Fig. 7).

5.3.2. Scenario-1: reference scenario and leakage reduction

The Saudi water authorities planned to reduce leakage from 25% to 10% [1]. This can be accomplished by maintaining the water pipelines by fixing leakage, enforcing meter for old buildings, and prevent illegal connections. This reduction in water leakage was simulated in the WEAP model and compared against the current situation. After simulating the leakage reduction measures and compared against the reference case, the results suggest that water demands did not change over the demand years. The supply requirements parameters were reduced due to decrease leakage in the water supply system. The WEAP simulated results confirmed that the entire water demand in all demand zones has increased by 57%, from 335 MCM in 2017 to 779 MCM in 2030. The supply delivered quantity reached the maximum storage capacity of water tanks in 2021. In the reference case, the supply delivered value is 469 MCM in 2021 (Fig. 8). After leakage reduction measures are introduced, the supply delivered reached the total water storage facilities in 2024. Therefore, constructing new water storage facilities should be considered starting from 2024 to meet water demands and reduce shortages. The supply requirement in 2030 for all demand zones reduced from 973 in the reference case to 865 MCM after reducing leakages from 25% to 10%. In this case, a 7.0 MCM quantity of unmet demand started in 2018 and reached 781 MCM in 3030. In this case, the unmet demand for all demand zones reduced by 21% in 2030. In other words, the unmet demand in 2030 is found to be 504 MCM in the reference case and decreased to 396 MCM after fixing leakage in the water supply system (Fig. 8). The reduction occurs in the unmet demand due to the difference between water demand and supply requirements. The supply requirements for all demand zones have been reduced by 11%, from 973 to 865 MCM. The leakage reduction measure did not reduce the future water demands from the reference case; therefore, the value of water in the reference case remains the same throughout all demand years.

5.3.3. Scenario-2: reference scenario and water conservation

From the previous section, the execution of water conservation measures as proposed by Saudi water authorities

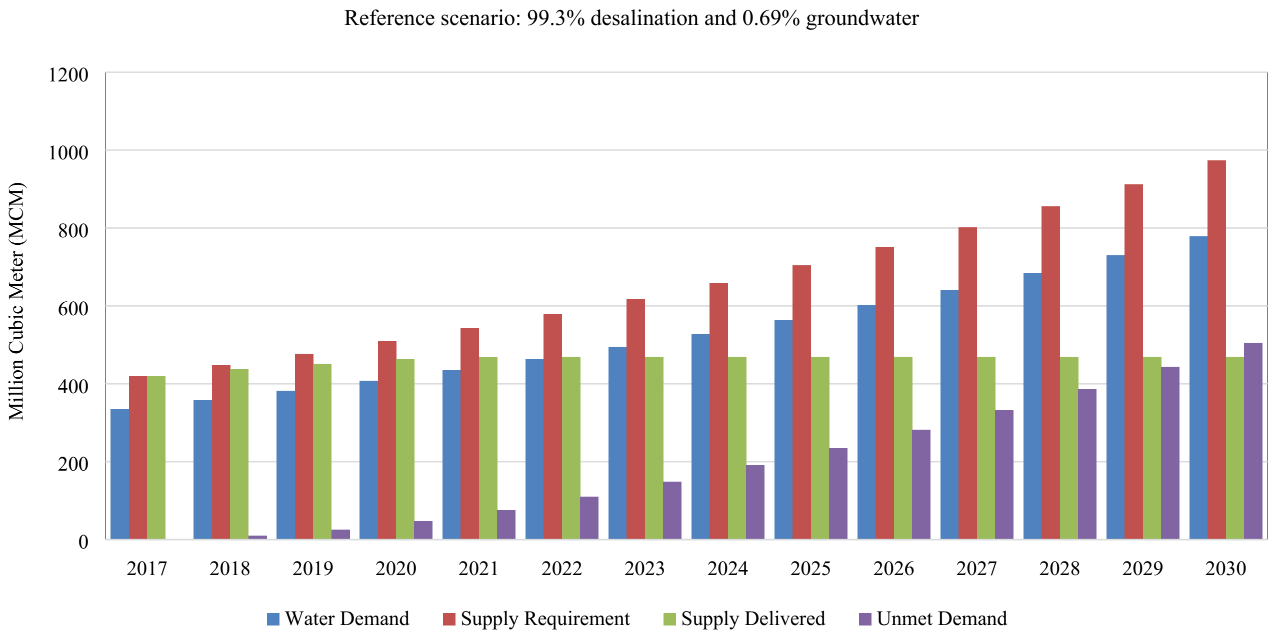

Fig. 7. Projected water and unmet demand and supply delivered and requirement (MCM) for all demand zones for the reference scenario.

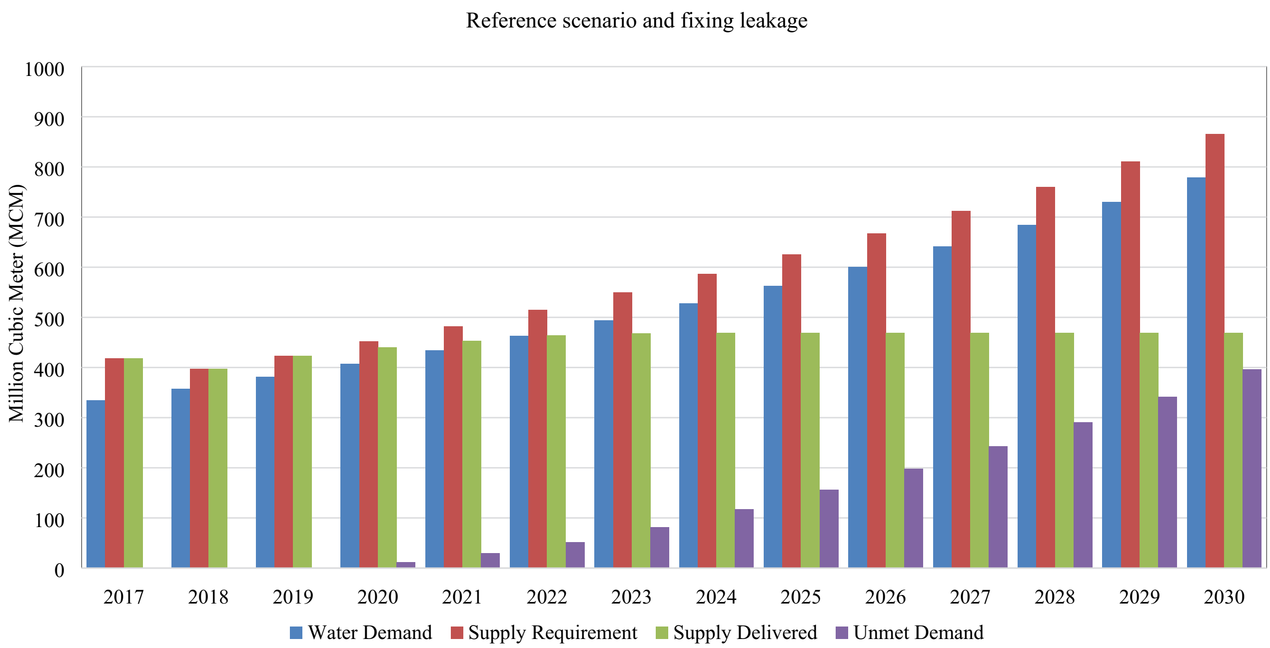

Fig. 8. Projected water and unmet demand and supply delivered and requirement (MCM) for all demand zones for scenario 1.

reduced water consumption by 32%. In other words, after applying water conservation through household retrofits, water demand was reduced by 32% for all Jeddah demand sites (Table 6). Here, the water demands decreased from 779 MCM to 603 MCM in 2030 after adopting urban household's water conservation measures (Fig. 9). Results show that the supply requirements in 2030 decreased by 34% from the reference case (i.e. from 973 to 641 MCM), for all demand sites, after adopting the water conservation measures proposed by the Ministry of water and electricity [31]. The supply delivered maximum value of 469 MCM is found to be in 2026 and stays stable until 2030. As the supply delivered reached the maximum capacity of water storage tanks in 2026, therefore, Saudi water authorities should construct new water storage tanks starting from 2026. Results show that a 3.8 MCM quantity of unmet demand begins

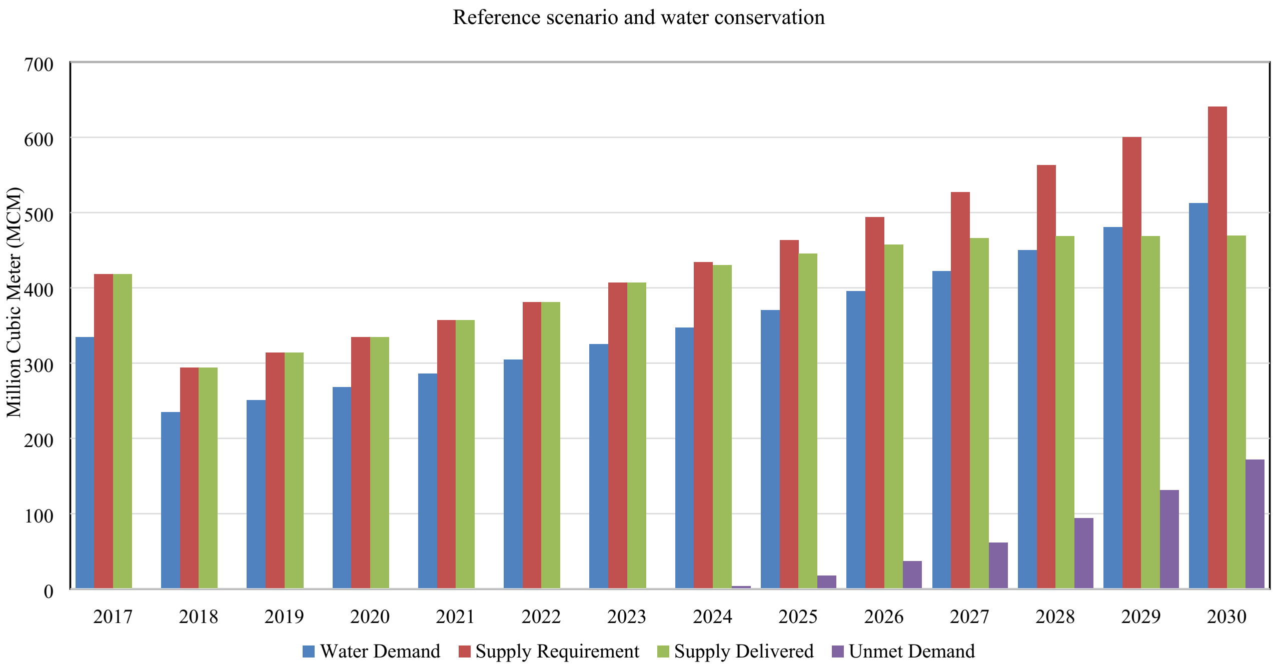

Fig. 9. Projected water and unmet demand and supply delivered and requirement (MCM) for all demand zones for scenario 2.

Table 7
Vulnerability indicator for the reference and two proposed water-demand scenarios

Scenario	Zone	(1) Total number of months	(2) Satisfactory months	(3) Unsatisfactory months	(4) Shortage for unsatisfactory months (MCM)	(5) Vulnerability = (4)/(3)
Reference	Al-Faysaliah	168	49	119	733,460,230	6,163,531
	Briman	168	23	145	734,528,288	5,065,712
	Filling station	168	12	156	639,665,336	4,100,419
	Khulais	168	23	145	49,212,048	339,393
	Qwizah	168	12	156	629,890,640	4,037,761
	Jeddah (Sum)	168	12	156	2,786,756,541	17,863,824
Leak reduction	Al-Faysaliah	168	70	98	470,052,125	4,796,450
	Briman	168	46	122	507,877,090	4,162,927
	Filling station	168	33	135	455,304,150	3,372,623
	Khulais	168	42	126	34,409,152	273,089
	Qwizah	168	33	135	449,374,217	3,328,698
	Jeddah (Sum)	168	30	138	1,917,016,733	13,891,426
Water conservation	Al-Faysaliah	168	96	72	244,972,321	3,402,393
	Briman	168	70	98	304,309,506	3,105,199
	Filling station	168	59	109	286,678,871	2,630,081
	Khulais	168	68	100	21,030,457	210,305
	Qwizah	168	60	108	283,817,310	2,627,938
	Jeddah (Sum)	168	57	111	1,140,808,464	10,277,554

in 2024 and arrived at 172 MCM in 3030 (Fig. 9). It can be noticed that implementing water conservation reduced the total unmet demand for all demand zone drastically in 2030 by 66%, from 504 to 172 MCM. Additionally, the unmet demand started in 2018 in the reference case with 9.3 MCM and became 504 MCM in 2030. On the other hand, after utilizing the water conservation measures, the unmet demand starts in 2024 by 4.0 MCM and arrived at 172 MCM in 2030. Therefore, conservation measures in urban buildings along desalinated water are a necessary water combination that reduced unmet demand by 66% of the current practices.

6. Vulnerability analyses

Vulnerability is defined as the probability of failure to occur [35,36,40]. Attention should be carefully considered to the potential consequences of failure even when the occurrence of failure is small. In this work, vulnerability is calculated by the sum of shortages in months that experience water shortages over the number of these unsatisfactory months (events). The unsatisfactory month or event means that supply did not meet the demand for a given month. The vulnerability analyses were conducted on the unmet demands simulations from the WEAP model that occurs from 2017 until 2030 for the three considered scenarios (i.e. Reference, leakage reduction, and water conservation). The results show that the highest vulnerability is found to be 17,863,824 MCM for the reference scenario. Table 6 shows that the sum of all shortages is found to be 2,786,765,541 MCM occurred in 156 months for all demand zones. It indicated that the sum of all shortages for the Jeddah city could reach 106,322 MCM per month if the current situation goes on without water supply or demand enhancements. After reducing the leakage reduction from 25 to 10%, the vulnerability decreased from the reference scenario by 22.2%, therefore, the sum of water shortages for Jeddah city reached 82,687 per month (Table 7). Results show that consideration of water conservation achieved the highest reduction of the vulnerability index for Jeddah city. In other words, the vulnerability was reduced from the reference scenario by 42.4%, accordingly the water shortages for Jeddah city reduced to 61,175 MCM per month.

7. Conclusion

The expansion of urban development and economic activities put extreme pressure on Jeddah's available water resources. This paper includes the evaluation of the water resources supply system in Jeddah city to examine whether the current water resources desalination and groundwater are capable to meet future water demand and eliminate shortages. It proposed two proposed water demand alternatives including water conservation and leak reductions for sustainable water resources development. Further, this work conducted a questionnaire aimed to identify the community priorities and attitudes towards household water conservation options. Moreover, this work is aiming the water authorities with a clear insight into the future impacts of water conservation or leakage reduction on meeting future water demands and eliminating water shortages. To achieve this goal, WEAP software is used to build an IWRM model taking Jeddah service area, examine the proposed water development strategies by the national water authorities, and produce quantitative results regarding future water demand and shortages. WEAP is known for its special capabilities and abilities to realize management goals and allows a comparison between various water management strategies.

- The results of the current situation confirmed that the unmet demand increases over the demand years (2017–2030). Therefore, considering water demand measures such as water conservation is essential to improve the Jeddah water supply system. An additional quantity of 504 MCM is essential in 2030 to eliminate future water shortages if the existing practices continue without any water supply enhancements.
- The development of water conservation measures along with desalinated water is extremely important in reducing water and unmet demand throughout the demand years 2018 to 2030. The unmet demand reduced from the reference case by 66% (from 504 to 172 MCM) in 2030 indicating significant recovery of water supply system due to utilizing water conservation measures.
- Improving the water-related infrastructure of the city to fixing leakages and reducing water losses is less important than utilizing water conservation in mitigating future water shortage problems throughout demand years. The unmet demand reduced by 21% (from 504 MCM in the reference case to 396 MCM) in 2030. Here, the water demand was not affected because fixing leakage reduced the supply requirements by 11%. In other words, water demand reduced from 973 MCM in the reference case to 865 MCM in 2030.
- The development of water conservation measures along with desalinated water is an important water alternative measure in reducing water and unmet demand throughout the demand years 2018 to 2030. The unmet demand reduced from the reference case by 66%, from 504 to 172 MCM in 2030. Therefore, the development of urban conservation measures should be given supremacy over fixing leakage measures in the water supply system.
- The vulnerability analysis confirmed that water conservation produced the least vulnerability index of (10.27×10^6 MCM); therefore, the water conservation option along with desalination is preferred over the leakage reduction measures.

In conclusion, it is established that implementing household water conservation is more beneficial than fixing leakage for reducing future water demands and shortages. That is, water conservation and leakage reduction measures reduced future demands in 2030 by 66% and 21% respectively. Therefore, water conservation measures are preferred over the leakage reduction ones. In both cases, future water shortages in 2030 were not entirely eliminated. Therefore, additional water supply enhancements such as new desalination plants may be required for meeting future water demands.

Acknowledgment

This project was funded by the Deanship of Scientific Research (DSR) at King Abdulaziz University, Jeddah, under grant no. (G:270-135-1441). The authors, therefore, acknowledge with thanks DSR for technical and financial support.

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