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ORIGINAL PAPER

Assessment of future urban water resources supply and demand for Jeddah City based on the WEAP model

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Abstract

Jeddah City is expected to experience water supply stress due to rapid population growth and expansion of urban developments. This paper aims to assess the impact of possible water demand on Jeddah water resources in 2030 and to examine the effectiveness of desalinated water on future water demand. To facilitate the analyses, a scenario-based modeling is used in conjunction with Water Evaluation and Planning (WEAP) software to find the best combination of scenarios that meet future water demands. For each scenario, the water resource implications were compared to a 2017 baseline. The model enabled analyses of unmet water demands, water demand, supply delivered, and supply requirement for each scenario. The study identifies the year of unmet demand and calculates the reliability, resiliency, and vulnerability of the supply system. Results show that the gap between demand and supply will grow dramatically if current desalinated supply condition continues. An additional quantity of more than 504 MCM is needed in 2030 to satisfy water needs and development. The implementation of the leakage reduction measures proposed by the National Water Company (NWC) with the current desalinated water, in conjunction with the application of reuse of treated wastewater and water conservation practices, can decrease the unmet demands and deficits to levels lower than, or similar to, those occurred in the 2017 baseline. However, in all cases, these involvements will be insufficient to completely meet the demands of all demand zones. The results confirmed that the WEAP model can be applied to various operating policies towards decision support system for water resources management in Jeddah City.

Keywords Demand management · Desalination · Water conservation · Leakage · WEAP model · Jeddah

Introduction

Water shortage is a major challenge facing Jeddah City. Rapid population growth, urbanization, expansion of development, and the economic activities in Jeddah City exert pressure on available water resources (NWC 2017). Therefore, water demand management plan should be considered to avoid future water scarcity. Jeddah City depends mainly on desalinated water from two existing desalination plants. Desalinated water provides Jeddah City about 34 MCM per month, which represents 95% of the total water supply. Groundwater is another minor water supply source and represents 4% of the total water supply. Only 1% of treated wastewater (TWW) is used for irrigation of public green areas and Jeddah's industrial city (NWC 2017), while 99% of the TWW is discharged into the Red Sea.

Water managers need to combine a series of complex subjects to allocate limited water resources efficiently and to reduce the water demand deficit (Al-Juaidi et al. 2009; Al-Juaidi 2017a, b; Al-Juaidi and Hegazy 2017a, b). This study provide analysis towards an integrated water resource management (IWRM) for Jeddah City using Water Evaluation and Planning (WEAP) software. This will be performed through assessing the current water system conditions and planned future demand and supply scenarios by Saudi National Water Company (NWC) taking into consideration diverse operating policies and factors that affect demand.

Integrated water resources management (IWRM) as considered by the Dublin principles is defined by Global Water Partnership as part of sustainable development (World Bank

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2010; Al-Juaidi et al. 2014). It is recognized by meeting present water demand without compromising the ability to meet water demands of future generation (Al-Juaidi et al. 2010, 2011a, b; 2018, Al-Juaidi 2018; 2019a, b).

The WEAP is a water allocation model and can be used at spatial and temporal levels. The WEAP enables users to have interactive control on data input, model operation, and output display. It is capable of building and comparing different scenarios (SEI 2001). The scenarios can be addressed on a wide range of "what if" questions. What if leakage reduction in the distribution system is reduced? What if water conservation in household is implemented? What if various combinations of different water supply/demand options are implemented?

Previous related work in Saudi Arabia

Many early applications of water demand and supply management were established in Saudi Arabia to evaluate the current system and to predict the demand in the future. For example, Abu Raziza et al. (1994) evaluated the present and future (1985–2010) water demands and the water resources of the Jeddah-Makkah-Taif (JMT). World Bank (2004) assessed current water resources in Saudi Arabia. Al-Zahrani and Baig (2011) proposed various strategies for managing household Water in Saudi Arabia. Kamis (2012) presented water demand/supply for the city of Jeddah and predicted future domestic water demand and water source from 2012 to 2038. Chowdhury and Al-Zahrani (2012) investigated the effects of climate change on water resources in Saudi Arabia. Albalwai (2015) explored ways to respond to growing water demand in Saudi Arabia through water demand management approach. DeNicola et al. (2015) studied the effect of climate change on water resources in Saudi Arabia due to increases in average global temperatures. Chowdhury and Al-Zahrani (2015) defined the characteristic of water resource trends in Saudi Arabia by identifying all type of water resources in the kingdom (groundwater, desalinated water, and TWW). Almazroui et al. (2017) evaluated Landsat data to monitor urban growth in Jeddah.

The objective of this paper is to evaluate the existing condition related to the water supply system in the city of Jeddah and to evaluate the long-term impact of the proposed water management system using WEAP (SEI 2001). It includes water supply/demand analysis for the city of Jeddah to analyze the current situation of water demand and propose water supply alternatives to improve the performance of water supply system considering different factors like population growth, water conservation, leak reduction, and reuse of treated wastewater in agriculture. This is accomplished through evaluating the existing water demand and supply conditions and expected future demand and supply scenarios considering the different operating policies and factors that affect demand. The study identifies the year of unmet demand and calculates the reliability, resiliency, and vulnerability of the supply system. Moreover, the study is looking at the demand management approach as opposed to the traditionally practiced supply management approach and considered the first of its kind to be developed for Jeddah City.

Methodology

The study consists of four stages. At first, all required data are collected from different water authorities (e.g., NWC, Jeddah municipality) and further processed using Geographical Information System (GIS). Then, the GIS was employed to specify spatial location of various water utilities to be incorporated in the WEAP model. In other words, the spatial coordination of the water utilities (i.e., reservoirs, filling stations, groundwater wells, desalination, and wastewater plants) are taken from the GIS and inserted into the WEAP. Second, the current water system (supply/demand) for the city of Jeddah and future water management options are established. Third, assessment of various water demand management options is considered for the year 2030. Finally, the study also recognizes the year of unmet demand and estimates the reliability, resiliency, and vulnerability of the supply system.

Jeddah City case study

Jeddah City is located on the west side of Saudi Arabia in the middle of the Red Sea with a total area of 5460 km^2. The urbanized area of Jeddah City is about 1765 km^2. The average temperature is about 28.69 °C over the period 1981–2010 (DeNicola et al. 2015; Jeddah Municipality 2017). In 2017, the population of Jeddah City was 4.69 million capita with a growth rate of 3.3% (General Authority for Statistics 2017). The population of Al-Faysaliah, Briman, Qwizah, Khulais, and filling station zones are 1.65, 1.17, 1.23, 0.113, and 0.764 million capita in 2017. Trends show that the population is expected to increase, and it is projected that the population will reach 7.0 million in 2030 (NWC 2017). The water consumption in Al-Faysaliah, Briman, Qwizah, Khulais, and filling station zones are 91, 73, 52, 48, and 85 m3/person/year in 2017.

Current water use

In this study, Jeddah City is divided into five zones (i.e., five demand zones) according to their geographical location and the existing water supply practices (see Figs. 1 and 2). For each demand zone, the percentage of all allocated water in each demand zone is equal to 100%. The average quantity delivered to Briman zone in 2017 is 8,773,516 m^3/month (see Table 1). Table 1 shows detailed summary for the quantity of water

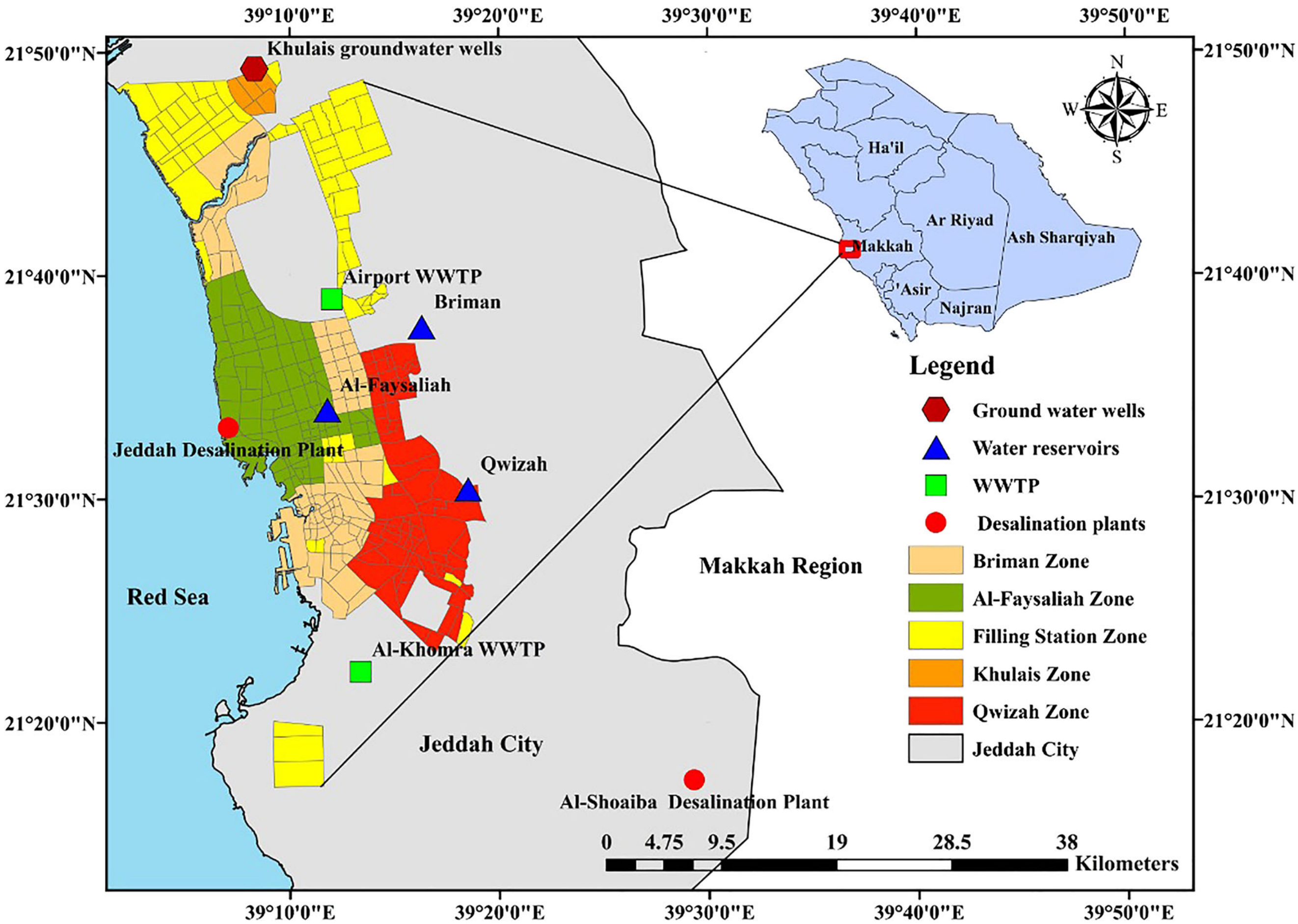

Fig. 1 Study area

allocated from various sources across Jeddah City in 2017. Al-Faysaliah zone received an average water quantity of 11,861,631 m^3/month in 2017. Qwizah zone received an average water quantity of 6,513,028 m^3/month in 2017. Khulais zone represents districts that are not connected to the water distribution network. This zone received water only from filling stations and water delivery tanks, with an average water quantity of 6,682,353 m^3/month in 2017. According to the NWC, 10% of the Jeddah population in the first four zones will receive water from filling stations when the network failed to deliver water. Khulais reservoir takes its water from groundwater wells and finally distributes it to Khulais zone with an average quantity of 234,367 m^3/month in 2017. Groundwater is being delivered to Khulais zone by water distribution system network. All zones obtain water from an existing 16 small reservoirs. Figure 3 shows the monthly variation (MV) of the allocated water for all demand zones.

Desalination plants

Jeddah city has two major desalination plants, namely, Jeddah and Al-Shoiaba. Jeddah desalination plant contains three reverse osmosis (RO) desalination units, and water evaporation and condensation unit. Jeddah desalination plant has a maximum capacity of 508,925 m^3/day. Al-Shoaiba desalination plant has a capacity of 618,759 m^3/day and is located about 110 km south of Jeddah City (see Fig. 4). Both desalination plants are owned and operated by the Saline Water Conservation Corporation (SWCC 2005).

Wastewater treatment plant

The total capacity of the existing two wastewater treatment plant (WWTP) is approximately 247 MCM/year (NWC 2017). The treated effluent from both plants is primarily discharged to the Red Sea. Currently, less than 161,100 m^3/month of TWW is being reused for irrigation of public gardens.

Water reservoirs

Jeddah City has 23 reservoirs with a total capacity of 1,312,828 m^3 day. Al-Faysaliah zone has 16 reservoirs,

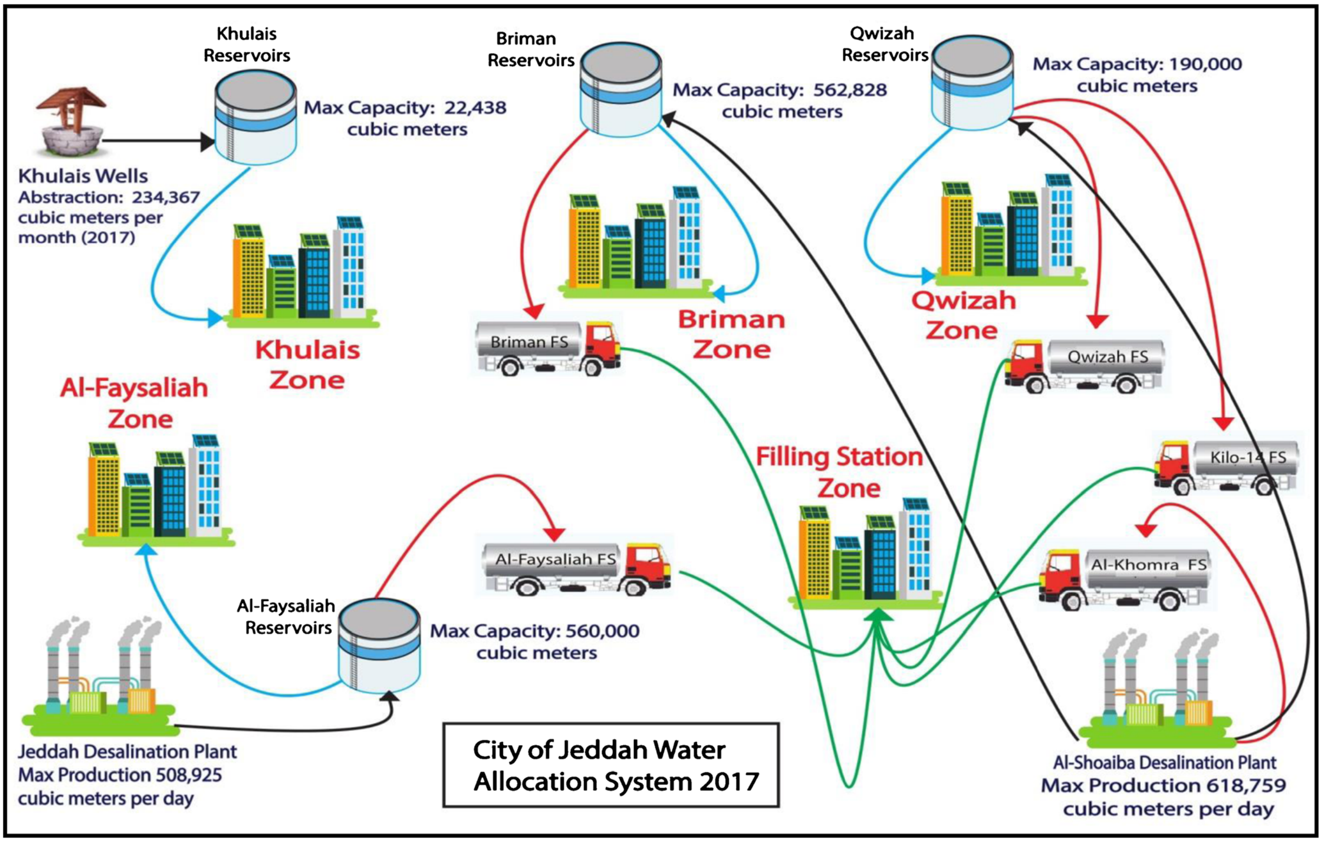

Fig. 2 Current water allocation system for all demand zones

with a total volume of 560,000 m^3. Eight reservoirs have a capacity of 160,000 m^3 (i.e., 20,000 m^3 per reservoir), while the other 8 reservoirs have a capacity of 400,000 m^3 (50,000 m^3 per reservoir). In the Briman zone, there are 4 reservoirs with a total storage capacity of 562,828 m^3 (i.e., 140,000 m^3 per reservoir). The Qwizah zone has 3 reservoirs with a total storage volume of 190,000 m^3. Two reservoirs have a storage volume of 100,000 m^3 (50,000 for each one), while the third one has a storage volume of 90,000 m^3. The Khulais zone has 4 reservoirs with a total storage volume of 22,438 m^3.

Water management scenario development

In this paper, six scenarios were set up based on developing a process of Saudi National Water Company (NWC) and Saudi Ministry of Environment, Water and Agriculture (MEWA). For each scenario, the water resource implications were compared to a 2017 base-case. The model allowed us to analyze unmet water demands, water demand, water delivered, and supply requirement for each scenario. The supply requirements include water demand and losses. Table 2 shows brief details for the six water management scenarios.

Table 1 Average water allocation in 2017 for Jeddah City (NWC 2017)

Source	Supply	Type	Quantity (m^3/month)	Total quantity (m^3/month)	Total (m^3/month)
Jeddah desalination plant	Al-Faysaliah	Network	11,861,631	27,382,542	34,064,895
Al-Shoaiba desalination plant	Briman		8,773,516		
Al-Shoaiba desalination plant	Qwizah		6,513,028		
Groundwater wells	Khulais		234,367		
Jeddah desalination plant	Al-Faysaliah	Filling station	3,406,122	6,682,353	
Al-Shoaiba desalination plant	Briman		625,868		
Al-Shoaiba desalination plant	Qwizah		911,790		
Al-Shoaiba desalination plant	Al-Khomrah		426,722		

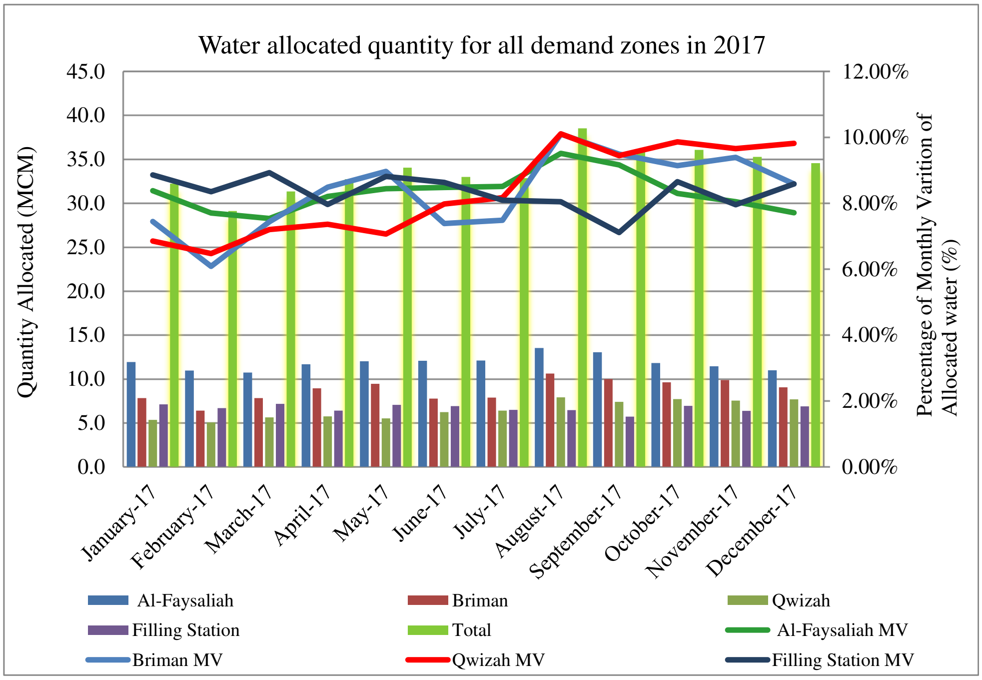

Fig. 3 Monthly variations (MV) of water allocated quantity for Jeddah zones in 2017

Basic assumptions for base-case situation

The basic assumption in the Jeddah WEAP model included population, daily consumption (l/day), annual water consumption (m^3/capita/year), growth rate (%), losses in network (%), and treated wastewater reuse (%). The total population for all the Jeddah zones in 2017 is 4.69 million capita. The daily consumption of water is 309.0, 247.0, 175.0, 166.0, and 290.0 l/day for Al-Faysaliah, Briman, Qwizah, Khulais, and filling station zones, respectively. According to the NWC, population growth rate is considered to be 3.3%. The current water losses in the network are assumed 20% due to leakage and illegal connections. The quantity of treated wastewater used for agriculture is 296,000 m^3/month. It represents 1.0% of the total treated wastewater quantity of 247 MCM/year. The other scenario assumptions are listed in Table 2.

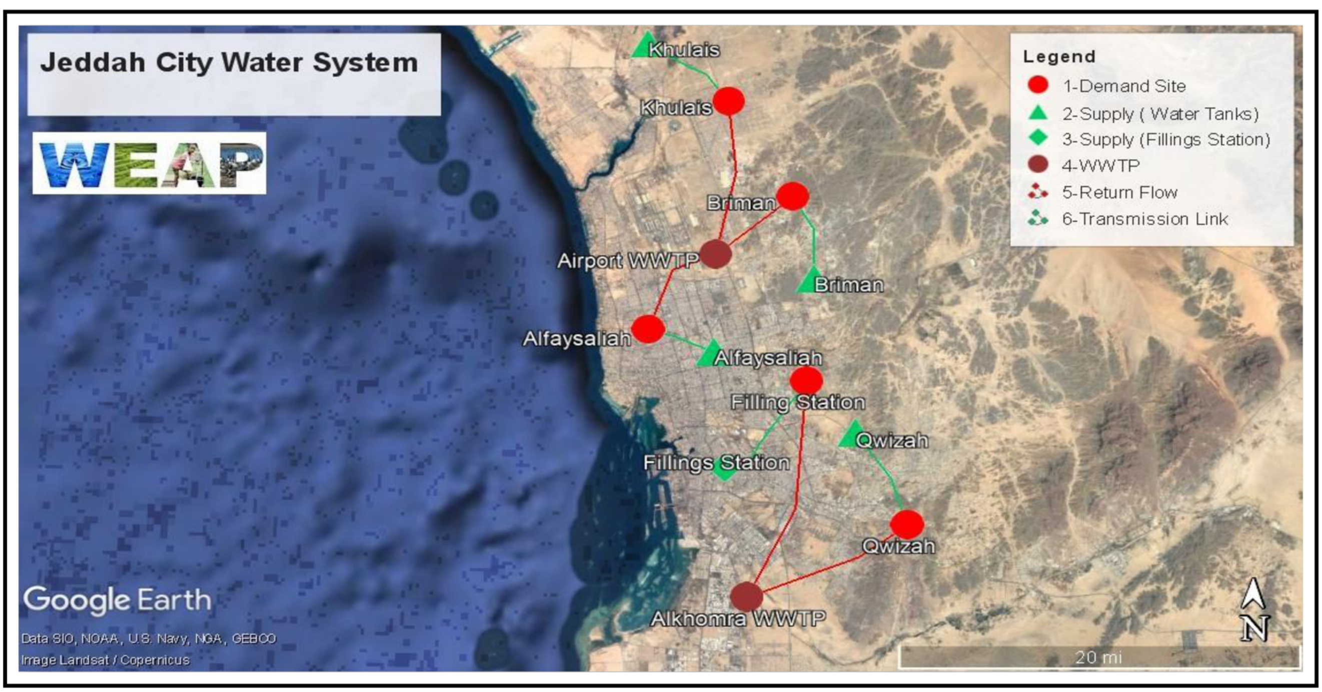

Fig. 4 Conceptual WEAP model of Jeddah City for the base-case scenario

Table 2 Scenarios and assumption of Jeddah City WEAP model

Scenario	Main assumption
Base-case	The base-case scenario represents the current account that was initially set up for the year 2017. It represents the current system conditions including demand zone and water supply. Base-case represents population growth rate of 3.3% with existing water allocation and policies and existing irrigation practices. In this case, the WEAP is executed for the next 13 years (starting from 2017 until 2030).
Scenario 1	It is expected that Jeddah City will expand due to local migration from the countryside. This scenario considers an increase in population growth from 3.3 to 4.3%, according to the NWC. A growth rate of 3.3% is assigned for year 2017, while years from 2018 to 2030 take a growth rate of 4.3%. The NWC has three population growth scenarios which are optimistic 3.3%, most likely 4.3%, and pessimistic 5.0%. According to interviews with NWC managers, it was recommended to use the most likely one.
Scenario 2	The current leakage in Jeddah's distribution system is more than 25% (NWC 2017). This leakage is due to various reasons including unaccounted water, illegal connections, and leaks in the distribution system. In this case, the only change from the base-case scenario is to reduce the leakage in the water distribution network from 25 to 10%. The NWC plans to establish new projects and to hire domestic and foreign companies to reduce leakage to 10%.
Scenario 3	At present, the concept of water conservation is not applied in Jeddah City due to lack of awareness about the economic benefit of water conservation, and absence of a comprehensive plan to conserve water (MEWA 2008). However, the NWC is planning to implement water conservation to all existing and new building. Household retrofits aim to minimize the average consumption of water use per capita from 30 to 40% (NWC 2017; MEWA 2008).
Scenario 4	Jeddah City has two major wastewater treatment plants (WWTPs). The NWC is planning to increase the level of treatment for Jeddah wastewater treatment plant through constructing new lines of treatment in parallel to the existing ones (NWC 2017; Al-Juaidi 2017a, b). The NWC is planning to increase the reuse of treated wastewater quantity in agriculture to 20%. This scenario differs from the base-case scenario only by increasing reuse of wastewater from 1% (5370 m^3/day) to 20% (107,400 m^3/day). Therefore, 20% of wastewater reuse for irrigation will be considered from 2018 to 2030.
Scenario 5	The NWC is planning to reduce leakage and implement water conservation plan according to the Saudi Ministry of Environment Water and Agriculture (MEWA 2008) guidelines. According to the NWC, the water conservation plan with leakage reduction should be implemented from 2018.
Scenario 6	This scenario represents the increase in the reuse of TWW from 1 to 20%, reduces leakage in the water distribution system from 20 to 10%, and introduces conservation management plan. The water conservation plan is considered through the implementation of water saving appliances in a household to reduce the demand from 30 to 40% (NWC 2017).

Results and discussions

Base-case scenario

The WEAP result of water demand indicates that the water demand will increase from 335 MCM in 2017 to 779 MCM for the year 2030, as shown in Fig. 5a. Figure 4 and Table 3 shows the WEAP output parameters for the base-case scenario. The WEAP result of supply requirement indicates that it will increase (if no change in water supply) from 418 MCM in 2017 to 973 MCM in 2030 as shown in Table 3. The unmet demand is 504 MCM for all demand zones to be found in 2030. The increase in water demand is due to the increase in future population, while the supply of water remains constant. The supply requirement increased exponentially over demand years due to the increase in demand on water. In this case, the maximum water delivered occurred in 2020 and remain constant until 2030 (see Fig. 6). It indicates that demand zones will not receive more water in 2021 due to the maximum storage capacity of the water reservoirs (469 MCM). The unmet demand starts from the year 2018 and continues to increase exponentially until of 2030 (Fig. 7a). Therefore, there is a need to consider a new water demand/supply option to reduce the increase of unmet demands.

Scenario-1: (high population growth—HPG)

This scenario represents the change in population growth from 3.3 to 4.3%. Results show an increase in population from 4,585,684 to 7,926,841 capita from 2017 to 2030, respectively. The WEAP result of water demand showed that the demand increased from 335 MCM in 2017 to 1000 MCM in 2030. This demand quantity is increased from the base-case scenario by 221 MCM. Increased water demand affected the supply requirements. For instance, the supply requirement of water for all

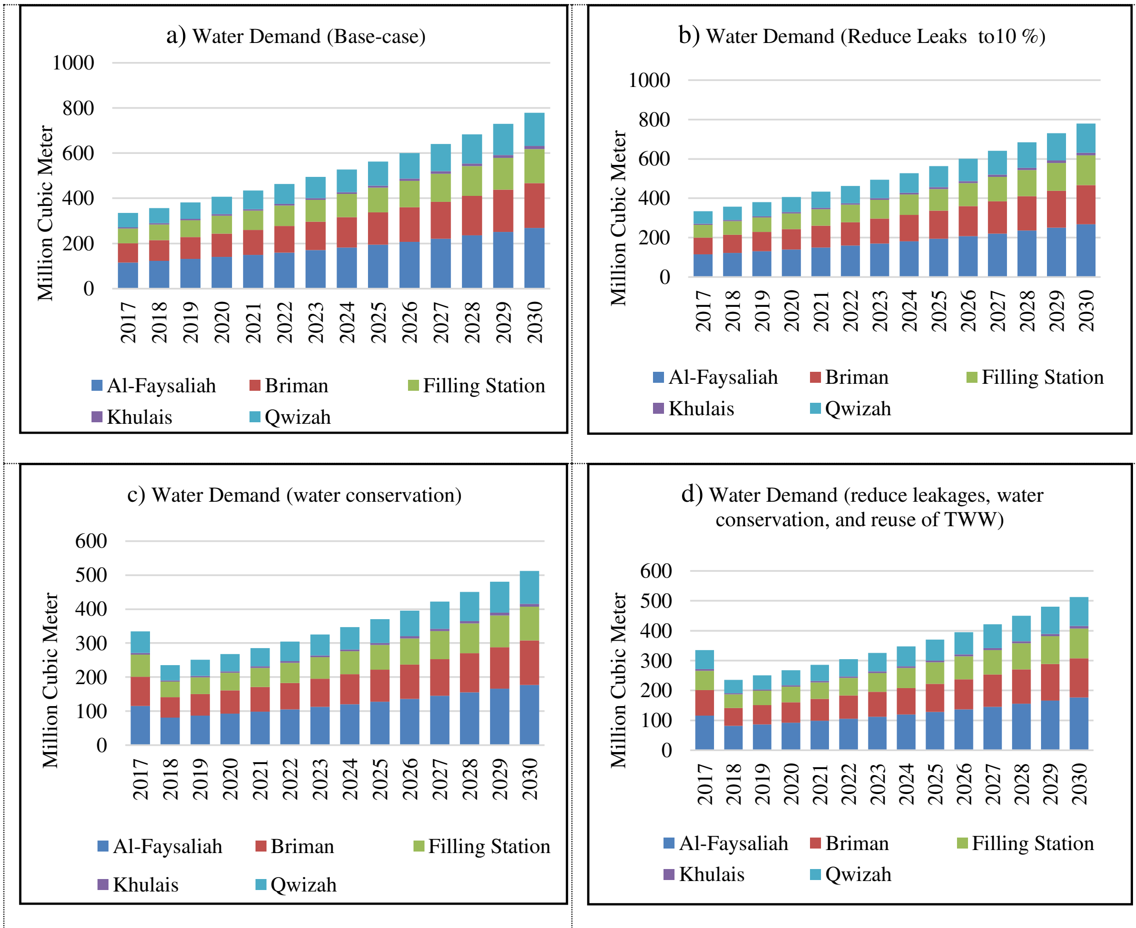

Fig. 5 Computed water demand for base-case scenarios and scenarios 2, 3, and 6

demand zones in 2030 is found to be 1250 MCM. It has increased from 973 MCM to 1250 MCM. Water delivered reached the maximum capacity of reservoirs in the year 2022 (469 MCM/year) and remained constant until 2030. This indicates that water cannot reach demand zone starting from the year 2021 due to the limited capacity of water reservoirs. The supply requirements (demand plus losses) is found to be 579 MCM in 2021, while the unmet demand in 2022 is 110 MCM. The unmet demand in 2030 reached 781 MCM. The unmet demand for this scenario will be the highest when we comparing it with other unmet demand scenarios.

Scenario-2: (reduce leaks to 10%)

This scenario suggests leakage reduction from 25 to 10% according to the NWC. Results show that the total required water demand in all demand zones has increased from 2017 to 2030 from 335 MCM to 779 MCM, respectively. When compared with the

Table 3 Computed demand and supply requirements from the WEAP for all scenarios

Scenario	Water demand (MCM)		Supply requirement (MCM)		Supply delivered (MCM)		Unmet demand (MCM)	
	2017	2030	2017	2030	2017	2030	2017	2030
Base-case scenario	335	779	418	973	418	469	0	504
Scenario 1	335	1000	418	1250	418	469	0	781
Scenario 2	335	779	418	865	418	469	0	396
Scenario 3	335	513	418	641	418	469	0	172
Scenario 4	335	779	418	779	418	469	0	310
Scenario 5	335	513	418	570	418	469	0	101
Scenario 6	335	513	418	456	418	442	0	14

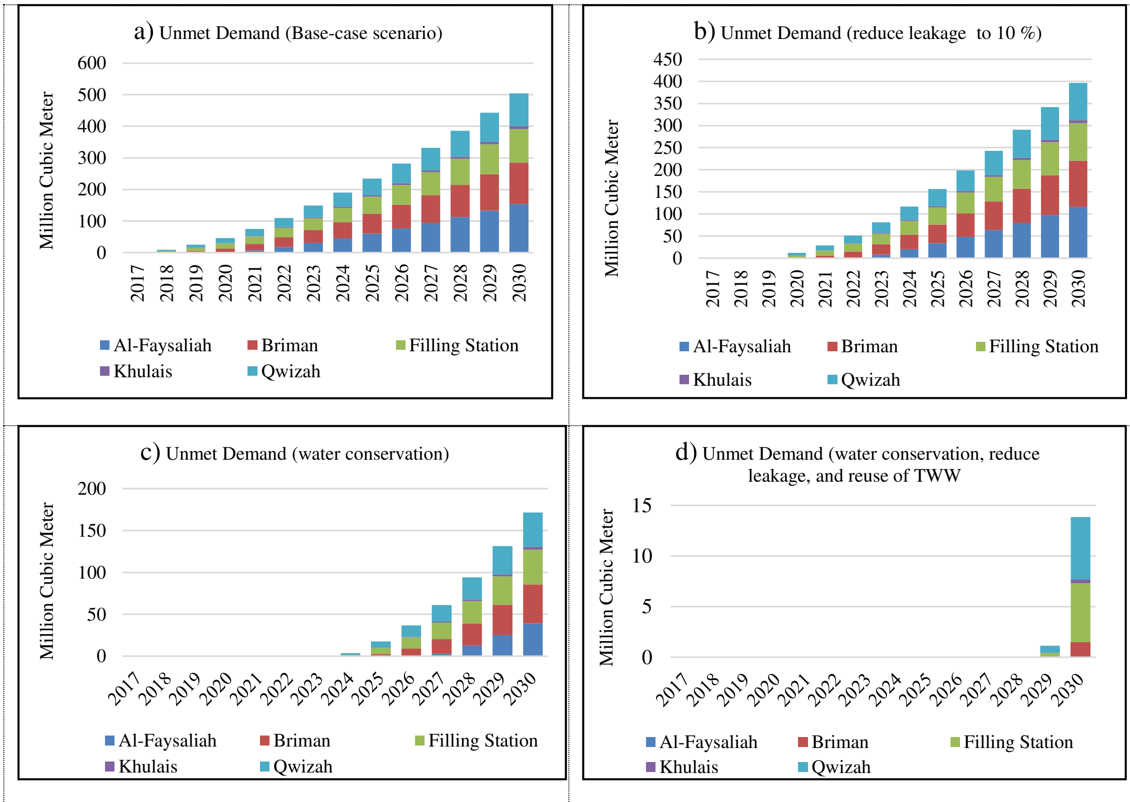

Fig. 6 Computed unmet demand for base-case scenarios and scenarios 2, 3, and 6

base-case scenario, there is no change in water demands over demand years (see Fig. 5b). However, the change occurs in supply requirements because leakage primarily increases losses in the water distribution. Supply requirements decreased due to reduction in network leakages and losses. Here, water delivered reached its maximum capacity in 2024 and remained constant until 2030. In the base-case scenario, water delivered reached its maximum in 2021. In other words, when leakage is reduced, reservoirs reached their maximum capacity in 2024. It means that the NWC would require establishing new reservoirs to meet future demand after 2024. In other words, the supply requirements for all demand zones are 865 MCM in 2030, while the supply requirement is 937 MCM in the base-case scenario. The unmet demand started in 2019 with a quantity of 0.4 MCM and reached 396 MCM in 2030 (see Fig. 7b, Table 3). Leak reduction has a significant impact on reducing unmet demand in 2030 by 108 MCM when compared with the base-case scenario (see Table 3).

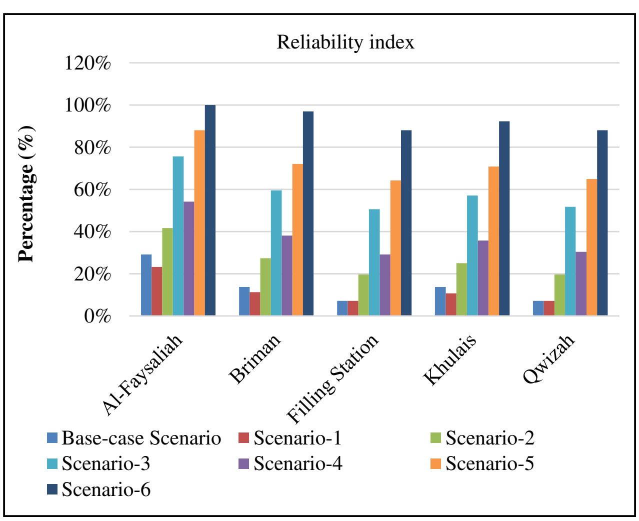

Fig. 7 Reliability index for all demand zones

Scenario-3: (apply water conservation)

Results show that implementation of water conservation in households as suggested by the NWC has a major impact on future water demand. Water demands reduced for all demand years and all demand zones. It is reduced to 513 MCM in the year 2030 after introducing water conservation. The supply requirements (e.g., demand plus losses) decreased due to a reduction in water demand from 973 MCM in the base-case to 641 MCM in this case for all demand zones in 2030. In this case, water delivered reached its maximum capacity in 2028 and remained constant until 2030 (see Fig. 6). When water conservation is introduced, reservoirs reached their maximum capacity in the year of 2028. It means that the NWC would require to consider new reservoirs to meet future demand starting from 2028 (see Table 3). Here, the unmet demand started in 2024 with a quantity of 3.8 MCM and reached 172 MCM in 3030 (Fig. 7c). Results suggest that conservation is an important water management option to reduce unmet demand. The WEAP result of unmet demand is reduced to 172 MCM in 2030 after conservation implementation for household.

Scenario-4: (reuse of TWW)

This scenario suggests increasing the reuse of TWW for agriculture from 1% (5370 m^3/day) to 20% (107,400 m^3/day), according to the NWC and MWAE. Under this scenario, 20% (107,400 m^3/day) of the treated wastewater reuse was divided among the five demand zones and allocated for agriculture sector. This will reduce the use of freshwater for agriculture in all demand zones (Al Farawati et al. 2008). In this case, the water demands remain constant for all demand years for all demand zones. The WEAP result of supply requirements decreased from 973 MCM in the base-case scenario to 779 MCM after reusing TWW. This reduction refers to use the TWW for agriculture. Water delivered reached its maximum capacity in 2025 and remained constant until 2030. When TWW is introduced, reservoirs reached their maximum capacity in the year 2026. This means that the NWC would require establishing new reservoirs to meet future demand after 2026. Here, the unmet demand started from the year of 2021 with a quantity of 3.8 MCM and reached 310 MCM in 3030. Results suggest that TWW is an important water management option in reducing unmet demand for 2030 by 194 MCM when compared with the base-case scenario.

Scenario-5: (reduce leakage and apply water conservation)

This scenario combined two scenarios (2 and 3), water conservation and leakages reduction of 10%. Result shows that the water demands have the most significant reduction throughout all demand years for all demand zones. The demand decreased from 779 MCM in the base-case to 513 MCM in this case for 2030 for all demand zones. The supply requirements decreased significantly from 973 MCM in the base-case scenario to 570 MCM after considering both conservation and leak reduction. Water delivery reached its maximum capacity of reservoirs in 2028 and remains constant until 2030. This means that the NWC would require establishing new reservoirs in the year of 2028 to meet future water demand. Furthermore, the unmet demand started in the year of 2023 with a quantity of 0.7 MCM and reached 101 MCM in the year 2030. Result suggests that this scenario is a very effective one to reduce unmet demand and supply requirements.

Scenario-6: (reduce leakage, apply water conservation, and reuse TWW)

This scenario represents the most effective solution for the city of Jeddah when considering water conservation through household retrofits, in conjunction with leakage reduction of 10% with reuse of TWW in agriculture. Water demands have the most significant reduction throughout all demand years for all demand zones, when compared with the base-case scenario. When comparing water demand in this scenario with previous ones, it is concluded that water demand is only influenced by water conservation in household (see Table 3). The demand decreased from 779 MCM in the base-case to 513 MCM in this case for 2030 (see Fig. 5d). However, the supply requirements decreased significantly from 973 MCM in the base-case scenario to 456 MCM after implementing these options. In this case, water delivered (442 MCM) did not reach the maximum capacity of existing reservoirs (469 MCM) (see Table 4). This means that NWC would not require establishing new reservoirs to meet future demand. The unmet demand starts from the year of 2029 and 2030 with a quantity of 1.1 and 13.4 MCM, respectively. Result suggests that this scenario is the most effective water management option to reduce unmet demand, supply delivered, water demand, and supply requirements when compared with the base-case scenario (see Table 3). In this scenario, water delivered did not reach the maximum capacity and there is unmet demand. This is due to the fact that some of water tanks and filling stations have more water and cannot provide water to zones that have water shortages. These zones which have unmet demand are not connected to water tanks and/or filling stations. For instance, the Qwizah reservoirs and filling station have a maximum capacity of 74 MCM and cannot connect to other reservoirs and filling station to meet

Table 4 Supply delivered for all scenarios in MCM

Supply delivered	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Base-case scenario	418	437	451	462	469	469	469	469	469	469	469	469	469	469
Scenario 1	418	442	458	467	469	469	469	469	469	469	469	469	469	469
Scenario 2	418	442	458	467	469	469	469	469	469	469	469	469	469	469
Scenario 3	418	294	314	335	357	381	407	430	445	458	466	469	469	469
Scenario 4	418	357	381	407	430	445	458	466	469	469	469	469	469	469
Scenario 5	418	261	279	298	317	339	361	386	412	443	448	459	467	469
Scenario 6	418	209	223	238	254	271	289	309	329	351	375	400	426	442

water demand of 81 MCM. Therefore, it is suggested that the Qwizah zone be connected with the Al-Faysaliah zone to cover the unmet demand.

Table 3 shows that water conservation in scenario 3, scenario 5, and scenario 6 produced the same water demand in 2030 due to the implementation of water conservation strategies. The least water demand found to be 513 MCM in 2030 when compared with other scenarios. The unmet demand increased from 504 MCM in the base-case scenario to 781 MCM in scenario 1. It has decreased to 396 MCM in scenario 2, to 310 MCM in scenario 4, to 172 MCM in scenario 3, to 101 MCM in scenario 5, and to 14 MCM in scenario 6. Further, water delivered reduced from 469 MCM in the base-case scenario to 442 MCM in scenario 6 for 2030. When scenario 6 is considered, then, the NWC is not required to construct new water supply reservoirs. This is because the maximum water delivered in 2030 for scenario 6 is 442 MCM (see Table 4), which is less than the maximum storage of all reservoirs (469 MCM) in 2030. The lowest unmet demand is 14 MCM in 2030 when implementing scenario 6. This is due collectively to several water demand management including water conservation, reduce leakage, and reuse of TWW. All of these water management practices reduced unmet demand from 504 MCM in base-case scenario to 14 MCM in this case for 2030. Water demand reduced from 779 MCM in the base-case scenario to 513 MCM in scenario 6 for 2030. Further, the supply requirements reduced from 973 MCM in the base-case scenario to 456 in scenario 6 for 2030.

Water system performance evaluation

In order to better assess Jeddah water supply system's performance and further show the system improvement from introducing the maximum supply available, the unmet demand analysis was analyzed over 13 years of supply and demand between 2017 and 2030. Reliability, resiliency, and vulnerability indicators are used to evaluate the current water delivery system's performance for Jeddah City (Hashimoto et al. 1982; Loucks and Van Beek 2017). These indicators will be used to assess the selection of the best management water management scenario.

Reliability

The reliability of water system is defined as the number of months in which supply meets the demand over the total months from 2017 to 2030 (Hashimoto et al. 1982; Loucks and Van Beek 2017).

$$\text{Reliability} = \frac{S}{N} \quad (1)$$

where S is the set of all satisfactory demand instances and N is the number of total measurements. The highest reliability index percentage represents the best reliable water demand scenario for the next 13 years.

Resiliency

Resiliency can be expressed as a measure of how fast a system is likely to return to recover after a failure has occurred. This case is represented by finding the month that did not have water shortage (e.g., unmet demand) after a month of having a water shortage (Hashimoto et al. 1982; Loucks and Van Beek 2017):

$$\text{Resiliency} = \frac{\text{TS}}{\text{US}} \quad (2)$$

where TS is the number of times a satisfactory value (i.e., meeting water demand) go after an unsatisfactory value and the US is the number of times an unsatisfactory value occurred. Here, resiliency means that system returns to recovery very quickly with a satisfactory state (e.g., supply meets demand) after a month of experiencing water shortage (i.e., unsatisfactory state, supply did not meet demand).

Vulnerability

Vulnerability is the likely magnitude of failure if one occurs (Loucks and Van Beek 2017). Even when the probability of failure is small, possible consequences of failure should be carefully considered. Here, the sum of shortages in all months was divided by the number of unsatisfactory months:

$$\text{Vulnerability} = \frac{\text{SH}}{\text{US}} \quad (3)$$

where SH is the sum of shortages and US is the number of times an unsatisfactory value occurred.

Result shows when implementing scenario 6, the reliability index (i.e., water supply which meets water demand) achieved the highest reliability performance of 60% for Briman zone (see Fig. 7, Table 5). It means that 40% of the water is not delivered and considered unmet demand for this zone. Interestingly, this scenario has achieved the highest reliability for each zone when compared with other scenarios (see Table 4, Fig. 7).

In scenario 6, results show that the system is resilient by achieving highest resiliency values for each zone when compared with other scenarios. It means that the system returns to recovery very quickly when implementing leak reduction in conjunction with water conservation and reuse of treated wastewater (scenario 6) (see Table 5 and Fig. 8). The highest vulnerability is found to be in scenario 2 when the population growth increased by 4.3%. For instance, the total shortage is 909,460,522 MCM which occurred in 156 months in the Qwizah zone. It indicates that the shortages in the Qwizah zone could reach 5,829,875 MCM per month. On the other hand, scenario 6 was found to be the least vulnerable one for each zone. In the Qwizah zone, the

Table 5 Detailed selected results for the reliability, resiliency, and vulnerability analysis for (base-case, scenario 1, scenario 6)

Scenario	Zone	(1) Total number of months	(2) Satisfactory state (months)	(3) Unsatisfactory (months)	(4) No. of successes	(5) Shortage for unsatisfactory months (MCM)	(6) Reliability (Eq. 1) = (2/1) (%)	(7) Resilience (Eq. 2) = (4/3) (%)	(8) Vulnerability (Eq. 1) = (5/3)
Base-case	Al-Faysaliah	168	49	119	5	733,460,230	29	4.20	6,163,531
	Briman	168	23	145	4	734,528,288	14	2.76	5,065,712
	Filling station	168	12	156	0	639,665,336	7	0.00	4,100,419
	Khulais	168	23	145	4	49,212,048	14	2.76	339,393
	Qwizah	168	12	156	0	629,890,640	7	0.00	4,037,761
Scenario 1—HPG	Al-Faysaliah	168	39	129	3	1,226,373,202	23	2.33	9,506,769
	Briman	168	19	149	3	1,109,190,162	11	2.01	7,444,229
	Filling station	168	12	156	0	926,541,379	7	0.00	5,939,368
	Khulais	168	18	150	3	73,211,582	11	2.00	488,077
	Qwizah	168	12	156	0	909,460,522	7	0.00	5,829,875
Scenario 6 (LR, WC, and TWW)	Al-Faysaliah	168	168	0	0	0.0	100	100	0.0
	Briman	168	163	5	3	1,496,510	97	60.00	299,302
	Filling station	168	148	20	2	6,234,131	88	10.00	311,707
	Khulais	168	155	13	4	362,872	92	30.77	27,913
	Qwizah	168	148	20	1	6,875,551	88	5.00	343,778

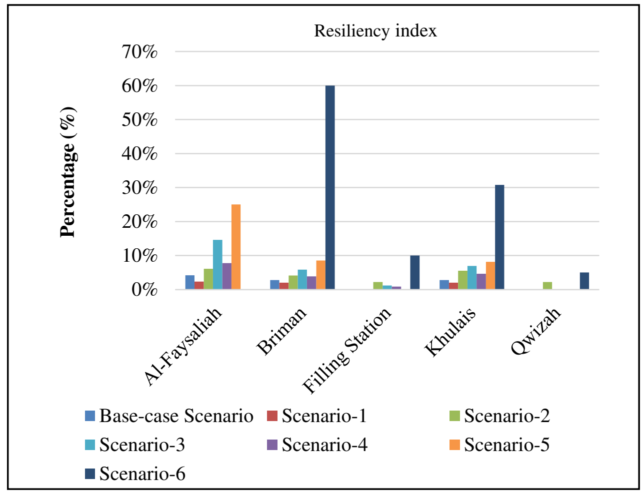

Fig. 8 Resiliency index for all demand zones

total shortages of 6,875,551 MCM occurred in 24 months, which produced a vulnerability of 343,778 MCM (see Table 5 and Fig. 9). Scenario 6 was the least vulnerable option due to implementing several water demand and supply practices simultaneously considering reduce leakage, reuse of treated wastewater in agriculture, and water conservation. Furthermore, in scenario 6, results show that the Al-Faysaliah zone has the lowest vulnerability and highest resiliency values. This could be referred to the fact that the Al-Faysaliah reservoir receives 11,861,631 m^3/month, which is considered the highest quantity of water to be delivered to this zone from Jeddah desalination plant.

Summary and concluding remarks

In this paper, a WEAP-based water resource simulation model is developed for Jeddah City water supply system and

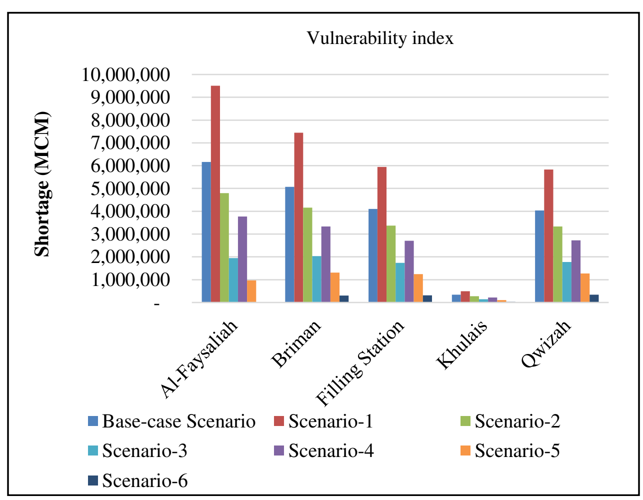

Fig. 9 Vulnerability of water system for all demand zones

included six water demand subsystems and their water supply—demand relationship for different water demand sectors. The allocation of water resources among Jeddah City's zones was also considered a finer-scale assessment. Furthermore, the water resource supply and demand, as well as water saving potentials, were projected from 2017 to 2030 under different water resources development scenarios. The key findings of this study can be summarized as follow:

1- The model gives a fair assessment of future water demand for Jeddah City based on existing information. The results revealed that an additional amount of more than 504 MCM would be required in 2030 to satisfy water needs and development if the current desalinated water supply continues.
2- The results show that water demand would reach about 1000 MCM in 2030 when the population increased by 4.3%. This necessitates establishing other water supply/demand management options to meet future water demand.
3- Fixing leakage of the water distribution system is an important factor that reduced supply requirement. When leakage reduced by 10%, the supply requirements in 2030 reduced by 11% from 973 MCM in the base-case to 865 MCM.
4- The total water demand in 2030 reduced from 779 MCM in the base-case to 513 MCM when water conservation is applied (i.e., 32%). Further, water requirements also reduced from 973 MCM in the base-case to 641 MCM.
5- Increasing the reuse of wastewater to 20% for agriculture is important in reducing supply requirements. Water requirements reduced from 973 MCM in the base-case scenario to 779 MCM.
6- The water demand could be reduced from 779 MCM in the base-case to 513 MCM by water conservation and leak management. The supply requirement would be reduced by 42%, from 973 MCM in the base-case to 570 MCM under these measures.
7- The lowest unmet demand is found when introducing leakage management in conjunction with water conservation and reuse of TWW (i.e., scenario 6). The unmet demand reduced from 504 to 14 MCM. It is also worth to mention that unmet demand is only found in the years of 2029 and 2030 in scenario 6.
8- Results revealed that the NWC should consider constructing new water supply reservoirs if scenario 6 was not executed. When considering leak reduction in conjunction with reuse of TWW and conservation practices (i.e., scenario 6), supply delivered is 442 MCM, which is below maximum capacity of reservoirs storage (469 MCM) in 2030.
9- It is established that using various water demand tools simultaneously with current supply (e.g., desalination) as described in scenario 6 produced the most reliable and less vulnerable option to satisfy demand for each zone.

Based on the findings of this paper, many management insights have to be considered to achieve an efficient re-operating Jeddah water system. At first, it is necessary to apply water management plan to conserve water in households through utilizing water educational program and subsidized retrofits. Since the weak infrastructure is responsible for water leakage, it is necessary to plan for annual maintenance to the water distribution system network to minimize the leakage to reduce the supply requirements. Jeddah City requires additional water reservoirs to increase the quantity of water delivered and to reduce the unmet demand. This paper is a good example to create similar research for all cities in the Kingdom of Saudi Arabia to build management plan for water demand and supply. Last, this work needs a strong institutional framework between water planners and decision makers to better implementation of water conservation and reuse of treated wastewater for agriculture.

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