Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2020.25538

جمعية علوم وتقنية المياه
Water Sciences and Technology Association

Evaluation of municipal water supply system options using water evaluation and planning system (WEAP): Jeddah case study

Ahmed E. M. Al-Juaidi*, Ahmed S. Al-Shotairy

Civil Engineering Department, King Abdulaziz University, Jeddah, Kingdom of Saudi Arabia, emails: aaljuaidi@kau.edu.sa/aealjuaidi@gmail.com (A.E.M. Al-Juaidi)

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. To facilitate the analyses, a scenario-based modeling is used in conjunction with WEAP to find the best combination of scenarios that meet future water demands. For each scenario, the water resource implications were compared with a 2017 baseline. The model enabled analyses of unmet water demands, water demand, water 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 supply condition continues. An additional quantity of more than 504 MCM is needed in 2030 to satisfy water needs and development. The unmet water demand varies through years significantly according to the proposed scenario. The implementation of the leakage reduction measures proposed by the National Water Company (NWC), 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. A careful control of the population growth rate in future demands is necessary, although this may be difficult in a rapidly developing region such as Jeddah of Saudi Arabia.

Keywords: Demand management; Integrated water resources management (IWRM); Desalinated water; TWW; Water allocation; WEAP model; Jeddah

1. Introduction

Water shortage is a major challenge faced by Jeddah city. Rapid population growth, urbanization, expansion of development and the economic activities in Jeddah city exert pressure on available water resources (NWC, 2017; SGS, 2018). 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 City of Jeddah 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 Jeddah's industrial City (NWC, 2017), while 99% of the TWW is discharged into the Red Sea.

WEAP is a water allocation model and can be used at spatial and temporal levels. 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 the household is implemented? What if various combinations of different water supply/demand options are implemented?

* Corresponding author.

Presented at the 13th Gulf Water Conference – Water in the GCC: Challenges and Innovative Solutions. 12–14 March 2019, Kuwait

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 such as 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.

2. Methodology

The study comprised 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, GIS is employed to specify the 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 GIS and inserted into 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.

3. Study area

Jeddah City is located on the west side of Saudi Arabia in the middle of the Red Sea with a total area of 5,460 km^2. The urbanized area of Jeddah city is about 1,765 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). 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).

3.1. 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 (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 (Table 1). Table 1 shows a detailed summary for the quantity of water allocated quantities from various sources across

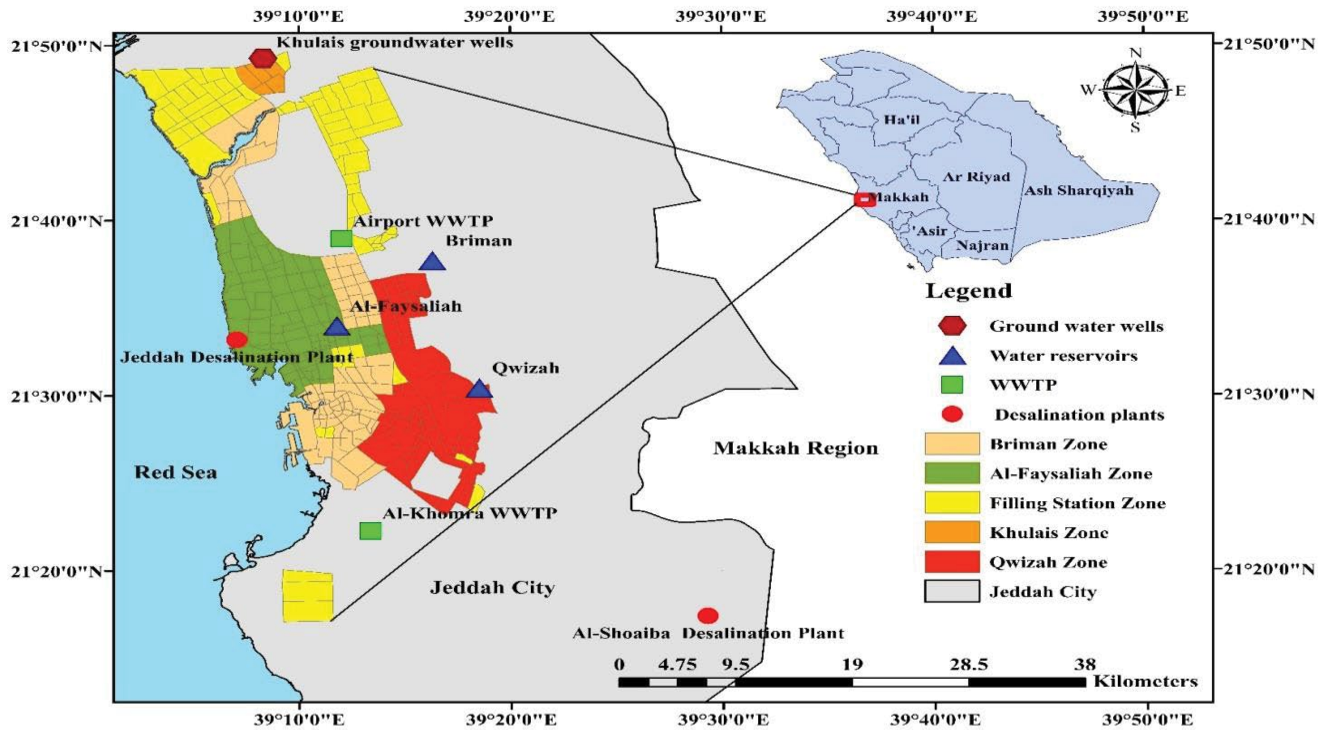

Fig. 1. Study area.

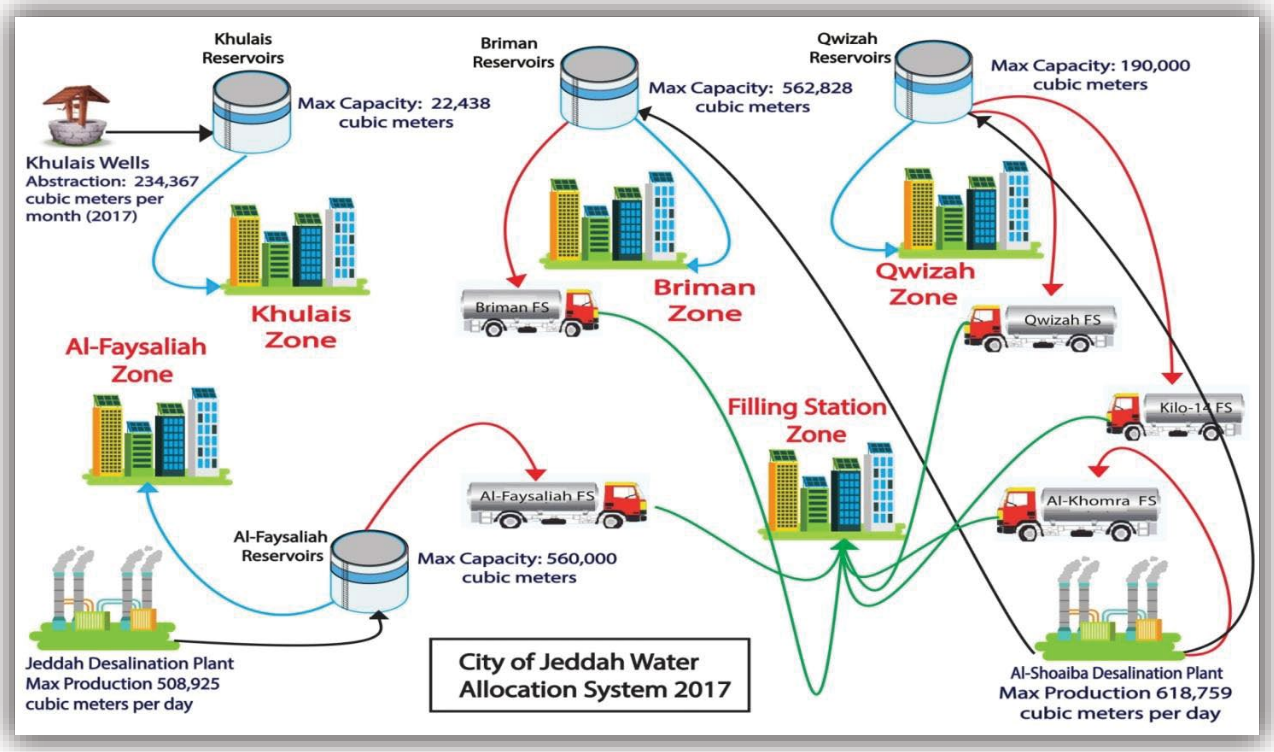

Fig. 2. Current water allocation system for all demand zones.

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

Source	Supply	Type	Quantity m³/month	Total quantity m³/month	Total m³/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		

Jeddah city in 2017. Al-Faysaliah zone received an average water quantity of 11,861,631 m^3/month in 2017. Qwizah zone received a water quantity of 6,513,028 m^3/month in 2017. The fifth 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 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 a 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.

3.2. Desalination plants

The city of Jeddah has two major desalination plants, namely, Jeddah and Al-Shoaiba Jeddah desalination plant contain three reverse osmosis (RO) desalination units. They were constructed in 1994, with a total capacity of 255,248 m^3/d. This plant has another unit of desalination using evaporation and condensation of water with a capacity of 190,000 m^3/d, owned and operated by the Saline Water Conservation Corporation (SWCC, 2017). The second desalination plant is called Al-Shoaiba, with a capacity of 582,689 m^3/d. It is located about 110 km south of Jeddah City.

3.3. Wastewater treatment plant

The total capacity of the existing two WWTP is approximately 247 MCM/year (NWC, 2017). The treated effluent from both plants is primarily discharged to the Red Sea. Currently, less than 296,000 m^3/month of TWW is reused for some factories in Jeddah industrial City. Some of Jeddah districts are not connected to the sanitary sewer system. At present, domestic wastewater is discharged into the ground via cesspits without treatment.

3.4. Water reservoirs

Jeddah city has 23 reservoirs with a total capacity of 1,312,828 m^3 per day. Al-Faysaliah zone has 16 reservoirs, 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 each reservoir), while the other eight reservoirs have a capacity of 400,000 m^3 (50,000 m^3 per each reservoir). In Briman zone, there are four reservoirs with a total storage capacity of 562,828 m^3 (i.e., 140,000 m^3 per each reservoir). Qwizah zone has three 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.

3.5. Water management scenario development

In this paper, two scenarios were set-up based on developing a process of Saudi National Water Company (NWC) and the Saudi Ministry of Environment, Water and Agriculture (MEWA). For each scenario, the water resource implications were compared with a 2017 base-case. The model allowed analyses of 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 three water management scenario.

3.6. Basic assumptions for the base-case situation

The basic assumption in the Jeddah WEAP model included population, daily consumption (liter/day), annual water consumption (m^3/capita/year), growth rate (%), losses in the network (%), and treated wastewater reuse (%). The total population for all Jeddah zones in 2017 was 4.69 Million capita. The daily consumption of water was 309.0, 247.0, 175.0, 166.0, and 290.0 liters/day for Al-Faysaliah, Briman, Qwizah, Khulais, and Filling Station zones, respectively. According to NWC, the 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 scenarios assumptions are listed in Table 2.

4. Results and discussions

4.1. Base-case scenario

WEAP result of water demand indicates that the water demand will increase from 335 MCM in 2017 to 779 MCM for the year 2030. Table 3 shows the WEAP output parameters for the base-case scenario. WEAP result of supply requirement indicates that it will increase (if no change in

Table 2
Scenarios and assumption of Jeddah city WEAP model

Scenario	Main assumptions
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 a 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 (water conservation)	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, 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-2 (water conservation and leak reduction)	NWC is planning to reduce leakage and implement water conservation plan according to SMWA guidelines. According to NWC, the water conservation plan with leakage reduction should be implemented from 2018. The current leakage in Jeddah's distribution system is more than 20% (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 20% to 10%. NWC plans to establish new projects and to hire domestic and foreign companies to reduce leakage to 10%.

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

Scenario	Water demand MCM		Supply requirement MCM		Water 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	513	418	641	418	469	0	172
Scenario 2	335	513	418	570	418	469	0	101

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 for water (Fig. 3). In this case, the maximum water delivered occurred in 2020 and remain constant until 2030. It indicates that demand zones will not receive more water in 2020 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 2030. Therefore, there is a need to consider a new water demand/supply option to reduce the increase of unmet demands.

4.1.1. Scenario-1: water conservation

Results show that the implementation of water conservation in households as suggested by NWC has a major impact on future water demand. Water demands reduced for all demand years and all demand zones. It is reduced from 779 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. When water conservation is introduced, reservoirs reached their maximum capacity in the year 2028. This means that NWC would require establishing new reservoirs to store more water to meet future demand started in 2026. Here, the unmet demand started in 2024 with a quantity of 3.8 MCM and reached 172 MCM in 2030. Results suggest that conservation is an important water management option to reduce unmet demand. WEAP result of unmet demand is reduced from 504 MCM in the year of 2030 to 172 MCM in 2030 after conservation implementation for the household.

4.1.2. Scenario-2: reduce leakages and water conservation

The 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. 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 NWC would require establishing new reservoirs in the year 2028 to meet future water demand. However, in the base-case scenario, water delivered reached its maximum capacity of reservoirs in 2025. Furthermore, the unmet demand started in the year 2023 with a quantity of 0.7 MCM and reached

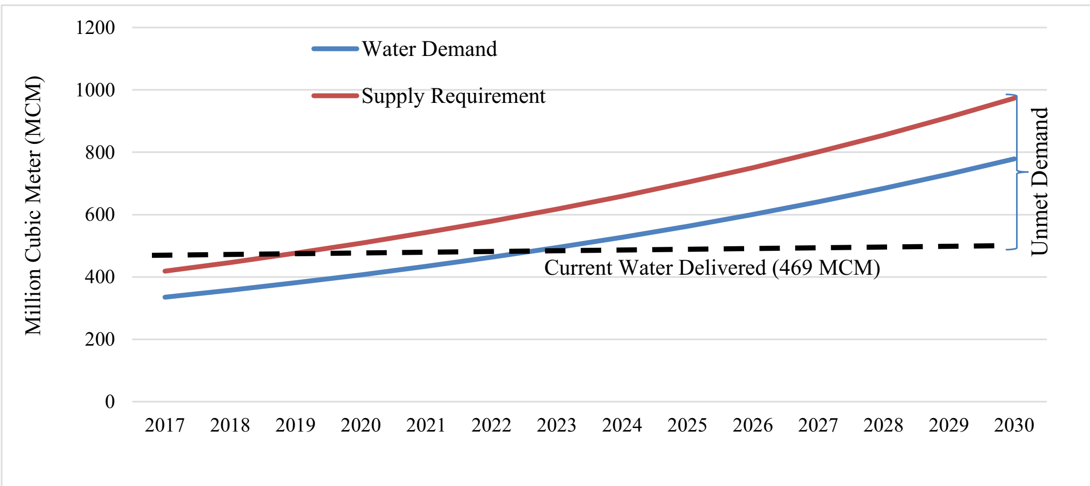

Fig. 3. Computed WEAP output parameters for the base-case scenario.

Table 4
Detailed selected results for the water system performance evaluation for the proposed scenarios

Scenario	Zone	(1) Total months	(2) Satisfactory state (months)	(3) Unsatisfactory (months)	(4) No. of successes	(5) Shortage of unsatisfactory months (MCM)	(6) Reliability = (2/1)	(7) Resiliency = (4/3)	(8) Vulnerability = (5/3)
Reference	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
	(Sum)	168	12	156	0	2,786,756,541	7%	0.00%	17,863,824
Scenario 1	Al-Faysaliah	168	127	41	6	27,902,387	76%	2.33%	1,948,839
	Briman	168	100	68	4	138,280,515	60%	2.01%	2,033,537
	Filling Station	168	85	83	1	144,357,364	51%	0.00%	1,739,245
	Khulais	168	96	72	5	10,025,022	57%	2.00%	139,236
	Qwizah	168	87	81	0	144,066,385	52%	0.00%	1,778,597
	(Sum)	168	84	84	0	516,631,673	50%	0.00%	6,150,377
Scenario 2	Al-Faysaliah	168	157	11	5	5,144,497	93%	45.45%	467,682
	Briman	168	132	36	5	35,011,127	79%	13.89%	972,531
	Filling Station	168	120	48	0	48,129,079	71%	0.00%	1,002,689
	Khulais	168	131	37	4	2,992,618	78%	10.81%	80,882
	Qwizah	168	121	47	0	48,758,173	72%	0.00%	1,037,408
	(Sum)	168	120	48	0	140,035,494	71%	0.00%	2,917,406

101 MCM in the year 2030. Result suggests that this scenario is a very effective one to reduce unmet demand and supply requirements.

5. Evaluation of water system performance

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.

The result shows when implementing scenario 2, the reliability index of water supply which meets water demand achieved the highest reliability performance of 71% for all demand zones (Table 4). Results show that highest resiliency is achieved when implemented Scenario 2. Al-Faysaliah and Briman Zones achieved the highest reliability index of 93% and 79%, respectively. The highest reliability index of 93% has achieved for Al-Faysaliah zone. It indicates that 7% of the water, for Al-Faysaliah zone, was not delivered and considered unmet demand. Interestingly, the other zones in this scenario show the highest reliability when compared against reliabilities in same zones for other scenarios (Table 4).

The vulnerability index is found to be 6,150,377 MCM when water conservation is introduced (Scenario 2). In this case, the total shortage reached to 516,631,673 MCM and has occurred in 84 months for all demand zones. That is, shortages for all demand zones could reach 27,210,108 MCM per month. On the other hand, scenario 2 was found to be the less vulnerability of 2,917,406 MCM, with total shortages of 140 × 106 MCM occurred in 48 months. Reduction of a vulnerability index, in this case, refers to considering both leakage and water conservation. In scenario 2, the resiliency for Al-Faysaliah zone is 45.45% is the highest in this scenario. This could be referred to the fact that an Al-Faysaliah reservoir receives 11,861,631 m^3/month. It is considered the highest quantity of water to be delivered to this zone from Jeddah desalination plant.

6. Summary and concluding remarks

In this paper, a WEAP-based water resource simulation model is developed for the Jeddah City water supply system and included two water demand subsystems. The allocation of water resources among Jeddah City's zones was also considered as a finer-scale assessment. Furthermore, water resources 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 follows:

- 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 469 MCM would be required in 2030 to satisfy water needs and development.
- The results show that water demand would reach about 1,000 MCM in 2030 when the population increased to 4.3%. This necessitates establishing other water supply/demand management options to meet future water demand.
- The total water demand in 2030 reduced from 779 MCM in the base-case to 513 MCM when water conservation is applied. Further, water requirements also reduced from 973 MCM in the base-case to 641 MCM.
- The water demand could be reduced from 779 MCM in the base-case to 513 MCM when considering 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.
- The lowest unmet demand is found when introducing leakage management in conjunction with water conservation (i.e., Scenario 2). The unmet demand is reduced from 504 to 101 MCM. It is also worth to mention that unmet demand is only found in the years from 2026 to 2030.
- When considering leak reduction in conjunction with water conservation practices (i.e., Scenario 2), the results suggest that considering new water supply reservoirs has to be considered in 2030 to deliver water to all demand zones. This is because the water delivered in Scenario 2 has reached the maximum capacity of reservoirs storage (469 MCM) in 2030.
- The reliability analysis indicated that scenario 2 is the most reliable option to satisfy demand. In this case, the highest reliability of 71% of meeting demand is achieved for all demand zones. This indicates that 29% of the water is not delivered and considered unmet demand.

References

DeNicola, E., Aburizaiza, O., Siddique, A., Khwaja, H. and Carpenter, D. (2015). Climate Change and Water Scarcity: The Case of Saudi Arabia. Annals of Global Health, 81(3), pp. 342–353.

Hashimoto, T., Stedinger, J., & Loucks, D. (1982). Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation. Water Resources Research, 18(1), 14–20.

Jeddah Municipality (2017). Geographical Location and Climate. Available at: http: //www.jeddah.gov.sa/English/JeddahCity/Geographical/index.php, Accessed 24 August 2017.

Loucks, D. and Van Beek, E. (2017). Water Resource Systems Planning and Management. Cham: Springer International Publishing.

National Water Company NWC (2017). «Water Supply/ Demand for Jeddah City for the year of 2017. Available at: https: //www.nwc.com.sa/English/Pages/default.aspx, Accessed 09 November 2017.

Saline Water Conservation Corporation SWCC (2005). Annual Report, Saline Water Conservation Corporation, pp. 21–37.

Saudi Geological Survey (SGS), (2018). Jeddah city Expansion. Available at: https: //sgs.org.sa/Arabic/pages/default.aspx, Accessed 26 August 2018.

Saudi Ministry of Environment Water and Agriculture MEWA (2008). Water and Electricity conservation guidelines. Available at www.mewa.gov.sa, Accessed on 20 July 2018.

SEI, (2001). WEAP (Water Evaluation and Planning): User Guide for WEAP21. Stockholm Environment Institute, Boston USA. Available from www.seib.org/weap/.