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# Evaluation of desalination and groundwater supply sources for future water resources management in Riyadh city

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**ABSTRACT**

This paper aims to investigate the developments in water demand and use in Riyadh city between 2017 and 2030. It examines the effectiveness of desalination and groundwater supply on water demand based on the Water Evaluation and Planning (WEAP) model. Five scenarios are considered based on future water development strategies planned by Saudi national water authority to evaluate and manage the Riyadh water system to enable precise predictions. This investigation also explores the best combination of various water resources management alternatives that meet future water demands in 2030. This study evaluates the performance of Riyadh's water system by calculating the reliability, resiliency, and vulnerability indicators on unmet demand. The results demonstrate that the pressure will increase on the current water supply system in Riyadh by having an unmet demand of 1,076 MCM in 2030. After implementing several proposed strategies by the National Water Company (NWC) including water conservation in conjunction with leak reduction and reuse of recycled water, the unmet demand in 2030 reduced to a level below to those happened in the baseline of 2017. Moreover, the prevention of future unmet demand requires a combination of water conservation, leak reduction, and the use of new water supplies.

*Keywords:* Desalination; Groundwater; Demand; Water conservation; WEAP; Riyadh city

## 1. Introduction

Water shortage and the unbalanced municipal water supply-demand situation is the main issue facing Riyadh city, the capital of Saudi Arabia. The fast-growing population, urbanization, and the growth of residential and economic development in Riyadh city is a major challenge facing the existing water resources. Water resource system models are useful tools for assessing future water deficits [1,2]. Water supply and demand simulations provide useful insights for decision makers for regional water resource development [3,4]. Sustainable water resources are mainly concerned with the allocation of limited water sources. Traditional simulation and optimization models are not always sufficient. The water evaluation and planning (WEAP) model represent a comprehensive system for water supply and demand while considering various demand and supply development alternative for sustainable water resources preservation.

Water supply sources in Riyadh city are originated from desalinated water and groundwater wells. The two desalination plants provide water for Riyadh city. The first one is called Jubail Desalination Plant (JDP), which is located in Jubail city, and the second one is called Ras Al-Khair Desalination Plant (RADP), which is located in Ras Al Khair city. Both desalination plants provide the city with 62% of the total water supply. The groundwater wells are the second water supply source for Riyadh city. There are nine major wells located

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across Riyadh city which provides Riyadh city with 38% of its total water supply [4,5]. Hydrological investigations showed a large quantity of replenishable groundwater of more than 200 million $m^3$ (MCM) and primarily existed inside Riyadh city [6,7]. Construction of new wells is strictly prohibited with a permit from the Ministry of Water Environment and Agriculture (MWEA). This is to reduce exploitation of the groundwater storage. Water consumption in Riyadh city increases rapidly in the last few years. The average annual water consumption of Riyadh City is about 83.6 $m^3$/cap year in 2017 (Fig. 1). Population in Riyadh was about 1.39 million in 1987, and increased to 8.77 million in 2017.

The WEAP model is preferred over the other water resources models because it is being used at both spatially and temporarily scales. It has the capability to include surface water, groundwater, and recycle water to build and analyze various water management scenarios. The water allocation system between water users is one of its major roles. It handles variable time step, and enable users to control data input, model operation, and output results.

WEAP is a software used for integrated water resource management system that operates the basic principles of mass balance and distributes the water based on user priorities [8]. WEAP can create a simulation model for water demand and supply management system to analyze water use within water management system to forecast the water shortage by analyzing the impact of long- and short-term water management strategies on demand and supply equilibrium system that can be visualized in GIS interface to present schematic easily for non-technical users and decisions makers. It was created in 1988 by Stockholm Environmental Institute (SEI). Demand and supply analysis is a major parameter for WEAP. Demand includes water patterns, reuse, and price. Supply deals with availability and allocation using desalinated water, reservoirs, reuse of treated wastewater, and transferring water among districts [8,9]. Generally, WEAP includes several steps that will be applied to this study, as follows: (1) the time frame for the current account and last year scenario, spatial information for the study area; the system components for the water system and interrelated pattern of the problem are recognized. (2) Brief about the actual water demand, supplies and resources for the current system expect to develop (i.e., current situation). The current situation can be shown as a calibration footstep in the expansion of an application. (3) Various alternative assumptions about plan based inconsistent set of assumption that impact policies and costs for the water system. (4) The evaluation of each scenario for water sufficiency, costs and benefits that will meet environmental targets.

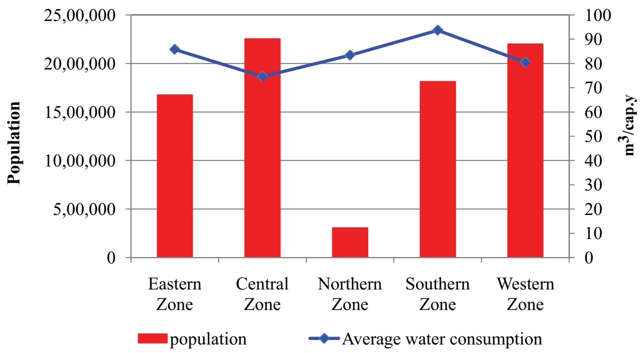


Fig. 1. Population and average water consumption ($m^3$/cap year) for Al-Riyadh zones in 2030.

There are many previous published works that addressed the relationship between supply and demand in Saudi Arabia. Ouda et al. [4] proposed a stochastic model to anticipate desalinated water demand for domestic purposes in for Riyadh. Abdulrazzak and Khan [10] explored the effect of water conservation on water demand in Saudi Arabia. Abu-Rizaiza et al. [11] studied water demands and the water resources of the western region of Saudi Arabia until 2010. Al-Zahrani and Baig [12] evaluated water demand in Saudi Arabia while considering various socio-economic and environmental aspects. Al-Shutayri and Al-Juaidi [13] examined the water supply system in Jeddah city by conducting several water resources development measures to precisely predict future water demand. Chowdhury and Al-Zahrani [14] conducted an extensive water resources review through recognizing all type of existing water supply resources in Saudi Arabia (desalination, groundwater and reuse of recycled water). The previous work described the water situation in Riyadh city and focused primarily on water use pattern and the future gap between supply and demand.

There are many published papers that are supported by WEAP Applications all over the world such as Ali et al. [15]; Gao [16]; Li et al. [17]; Mehta et al., [18]; Kiniouar et al., [19]; Arsiso et al. [20]. For example, Ali et al., [15] investigated the impact of higher growth rate on water resources system in Malaysia. Gao [16] studied planned water alternatives on local water resources in China. Li et al. [17] employed (WEAP) model for water resources management strategy to estimate water demand/ and supply to predict the required water for the year 2050 in coastal Binhai area in China. Mehta et al. [18] used WEAP to meet increasing demand in Lake Victoria by developing planning framework to include land use change and climate change alternatives. Kiniouar et al. [19] used WEAP to manage the water demand of the semi-arid catchment in Algeria. Arsiso et al. [20] investigated the impact of climate change on water resources for the city of Addis Ababa using the WEAP model.

This paper mainly focusing on water demand management to help decision support system to control water quantity and developing an integrated water resources management (IWRM) model to identify the water allocation problems between users and thus to identify where is the misuse of water, and development of sustainable management options for water resources. The uniqueness of this study is its inclusiveness of non-conventional water planned strategies by the NWC and investigates the effectiveness of the current water supply system (desalination and groundwater supply) to eliminate future water shortages. The demand on water resources for Riyadh city is considered on a finer-scale assessment until 2030. This study also tests the capabilities of the WEAP as water demand management tools and how to apply it for IWRM problems. This will be performed by testing the ability of the tool to respond to different water development management strategies. These challenges were analyzed through different WEAP scenarios taking into account the present situation and the proposed non-conventional water resources development strategies. Furthermore, the study allows to re-operate the water system throughout finding the best combinations of NWC planned strategies that reduce future water deficits in Riyadh city. Last, this study also evaluates the efficiency of Riyadh's water supply system by calculating reliability, resilience, and vulnerability indicators on the unmet demand until 2030. Therefore, it provides more insights for decision-makers about the best combination of water supply/demand management alternatives for efficient operating Riyadh's water supply system to reduce future water shortages.

## 2. Methodology

To achieve the above-mentioned objectives, WEAP tool will be used to build an IWRM tool for Riyadh city. This will be performed after all needed GIS maps and data are collected and incorporated into the WEAP. The main steps to be applied: (a) collection of all data and information needed from national water company managers; (b) setup the GIS-based data as an input to the tool; (c) develop future management scenarios related to supply and demand changes due to the use of non-conventional water resources; (d) development of the IWRM tool using WEAP; (e) evaluation of the proposed scenarios against the reference scenario. Based on the existing conditions, the tool will be evaluated against available present conditions data, to explore the capability of the WEAP model to reflect existing conditions; (f) comparative analysis based on the different scenarios taking into consideration cost and demand management tools will be performed; (g) based on the above comparative analysis, a set of management practices and recommendations will be developed. The implications and actions needed based on the selected best management practices will be elaborated. This paper also evaluated the performance of the water system through computing the reliability, resiliency, and vulnerability indicators on water shortages of the water supply system.

### *2.1. Case study – Riyadh city*

#### *2.1.1. Population*

The current population of Riyadh city is approximately 8.25 million capita according to the General Authority for Statistics [21] (Figs. 1 and 2). The population is expected to increase to 13.8 million capita in 2030, according to a population growth rate of 4.0%.

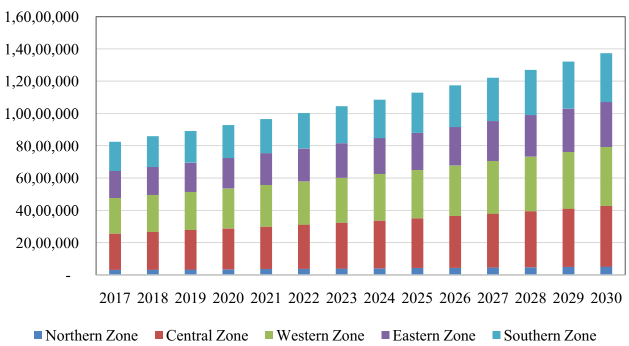


Fig. 2. Forecasted population for Riyadh zones using WEAP.

#### *2.1.2. Water resources*

The National Water Company (NWC) is the only water supplier to Riyadh city. It provides water to the city from two water supply sources, the first one is the desalinated water that covers the city by 62% of the total water supply. The second one is the groundwater that supplies the city by 38% of its total water supply. NWC distributes water to the city by networks that are carrying water from all sources to the entire zones in the city (Fig. 3). The desalinated water comes from two desalination plants, the first one is named JDP and the second one named RADP. Both desalination plants are located outside Riyadh city (Figs. 3 and 4). There are nine groundwater wells that supply the city by water. Each of them has a different location in Riyadh city and they are named as Hair wells, Malaz wells, Shemessy wells, Manfouha wells, Buwayb wells, Riyadh Water Wells Project (RWSP), Hunnai wells, and Saad wells (Fig. 5).

#### *2.1.3. Seawater desalination*

Jubail desalination Plant (JDP) was established in 1982 with an average daily production of 0.8 MCM/d. It is located approximately 469 km north of Riyadh city. Ras Al-Kair desalination plant (RADP) established in 2014 with an average daily production of 1.02 MCM/d and approximately situated 557 km east outside of Riyadh city [22].

#### *2.1.4. Groundwater wells*

Groundwater wells are the second water supply for Riyadh city. Fig. 5 shows the location of the groundwater wells and their links to the zones and reservoirs. Hair wells are located in the southern zone with a maximum withdrawal capacity of 0.051 MCM/d and supply water to the southern zone. Salboukh wells provide water to the northern zone with a maximum daily capacity of 0.0109 MCM. The water is delivered to the central zone by Malaz, RWSP, and Shemessy wells with a capacity of 0.016, 0.068, and 0.032 MCM/d, respectively. Buwayb wells are located in the eastern zone and supply a daily maximum water quantity of 0.095 MCM to the eastern zone. Hunnai and Saad Wells are located in the eastern zone and supply water to the HPT, with a total production of 0.393 and 0.218 MCM/d, respectively. Manfouha and Hair wells supply the southern zone with a water quantity of 0.045 and 0.051 MCM/d, respectively [5,23].

#### *2.1.5. Wastewater treatment plants*

Riyadh city has four wastewater treatment plants. The first one is named Al-Hayer old plant (South) and has a maximum treatment capacity of 200,000 $m^3$/d. It contains trickling filters, polishing lagoons, and anaerobic sludge digestion. The second one is called Al-Hayer new plant (North) and has a total treatment capacity of 200,000 $m^3$/d. The third one is called refinery treatment plant with a maximum treatment capability of 20,000 $m^3$/d. It has various primary and tertiary treatment units including clarification, filtration, reverse osmosis, and ion exchange. The last one served Riyadh diplomatic quarter and includes coarse screen and activated sludge system with a maximum capacity and treats a raw sewage capacity of 9,300 $m^3$/d [14].

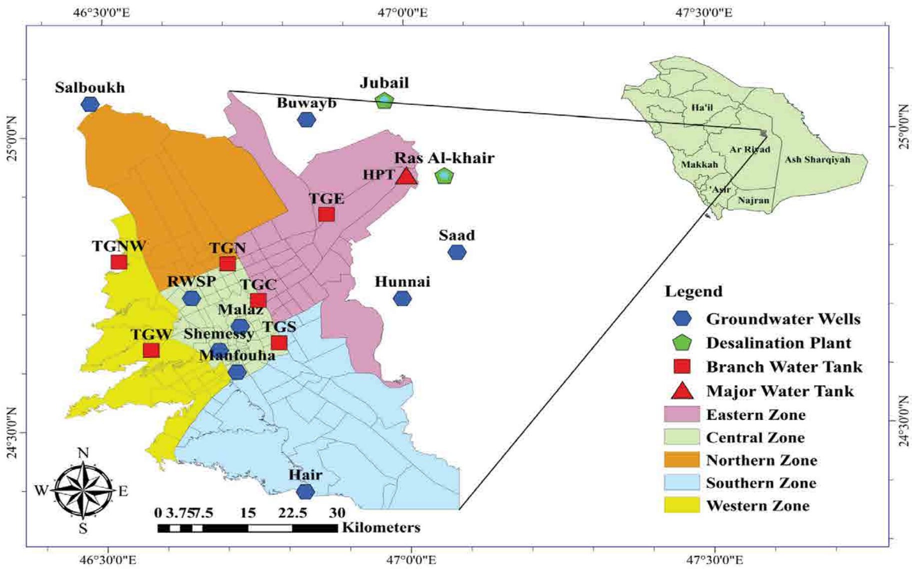


Fig. 3. Riyadh city study area.

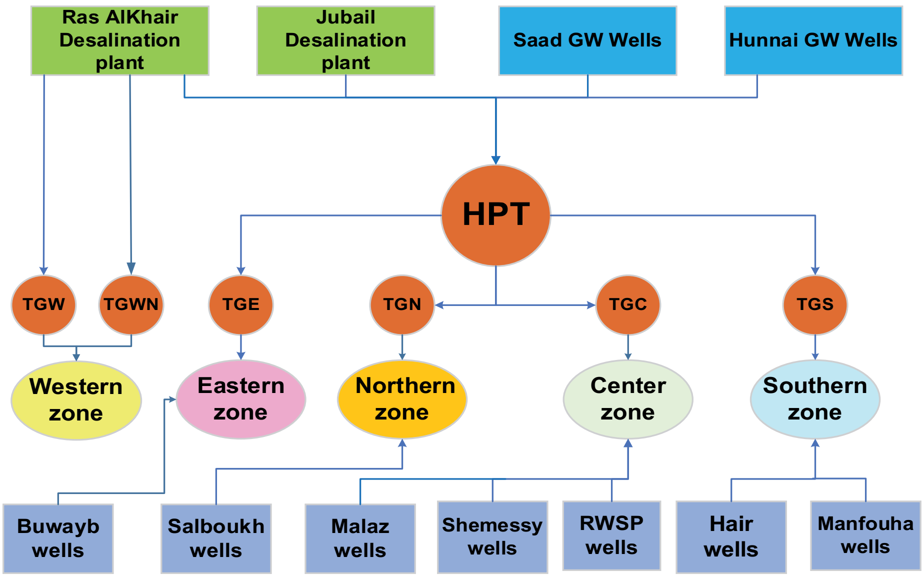


Fig. 4. Flowchart of the water allocation system in Riyadh city.

*2.1.6. Current water demand*

The total population for the Riyadh city is 8.25 million capita with a growth rate of 4%. Annual demand represents the amount of water demand (WD) by each zone. NWC is the only water supplier and responsible for water distribution for the city. The Riyadh city is divided into five zones based on their location and water use supply system, according to Riyadh's water system planning master plan (Fig. 3). The total population in 2017 for all zones is around 8.15 million capita, and distributed among the five zones. For example, the maximum current population is observed to be in the central and western zones of 2.25 and 2.2 million capita, respectively. The Northern zone has the lowest population of 0.306 million capita. Fig. 1 shows the average annual water consumption for each person per year. The central and western zones have the highest water use rates with 90 and 80 $m^3$/cap year, respectively. The use rate per capita in the central zone is observed to be around 72 $m^3$/cap year.

*2.1.7. Current water supply sources*

Water supply sources in Riyadh city are divided into two types, namely desalination and groundwater. The first type is desalinated water from JDP and RADP. The average monthly production from the JDP plant in 2017 is approximately 16.35 MCM/month. The RADP supplies the city with an average quantity of monthly around 32.97 MCM/month in 2017. Groundwater is the second source of water supply. The groundwater wells are spatially located over nine areas in the city (Fig. 3). The current average monthly water production

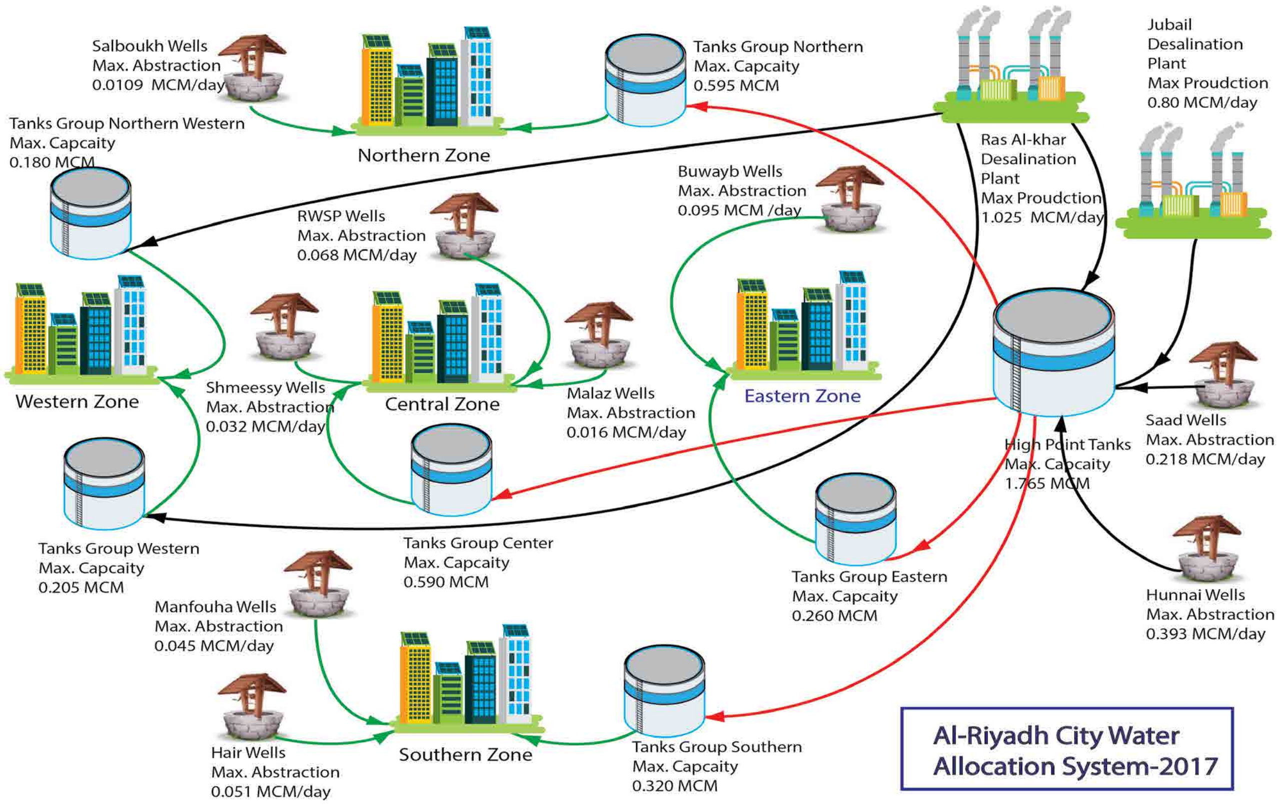


Fig. 5. Al-Riyadh city water allocation system in 2017.

for Hair, Malaz, Shemessy, Manfouha, Buwayb, RWSP, Hunnai, and Saad wells are 1.27, 0.46, 0.925, 1.24, 2.68, 1.86, 11.37, and 4.06 MCM/month, respectively. Table 1 shows the allocated monthly water from the groundwater wells to all zones in 2017. Riyadh city is divided into five zones based on their geographical locations and the source of water supply (Figs. 4 and 5).

### *2.1.8. Current water tanks*

Riyadh city has seven water tanks distributed over the entire Riyadh's city [5]. They are receiving water from all sources and distributing it to all zones (Figs. 2 and 3). The major tank is named high-pressure tanks (HPT) with total storage capacity of 1.76 MCM and is located in the eastern side of Riyadh city. It receives an average water quantity of 45.09 MCM/month in 2017 from RADP, JDP, Hunnai, and Saad wells. Then it conveys water to Tanks Group Eastern (TGE), Tanks Group Northern (TGN), Tanks Group Southern (TGS), and Tanks Group Central (TGC). The TGS tanks are located in the southern side of Riyadh city with a maximum storage capacity of 320,000 $m^3$. The TGS tanks receive an approximate average water quantity of 16.35 MCM/month in 2017 from HPT before it delivers it to the southern zone. TGC tanks are located in the central zone with a total storage capacity of 590,000 $m^3$. It receives approximately 4.06 MCM/month of water from HPT tanks and conveys it to the central zone. The TGN water tanks are located in the northern side and receive a water quantity of 11.37 MCM/month from HPT, then water is conveyed to the northern zone. The TGE water tanks are located in the eastern side part of the city with a total storage capacity of 260,000 $m^3$. It receives a water quantity of 13.29 MCM/month from HPT to be later distributed to Eastern zone. The Tanks Group West (TGW) water tanks are situated in the western side of the city with a storage capacity of 205,000 $m^3$ and distributed approximately 10.48 MCM/month of water to the western zone. The Tanks Group North-West (TGNW) tanks have a storage capacity of 180,000 $m^3$ and also convey a water quantity of 9.20 MCM/month to the western zone. Fig. 3 shows the location and capacity of all water supply sources, storage tanks, groundwater wells, and desalination plants [5]. It also shows the link between the supply sources and the demand zones.

### *2.1.9. Current water distribution*

Riyadh city is using the conveyance pipelines for the water distribution system to transport the water from sources and tanks to the five demand zones. The demand zones contain 170 districts with 8.25 million capita. The central zone has 72 districts and 2.25 million capita. It receives approximately a water quantity of 7.32 MCM/month from the TGC, Malaz wells, Shemessy wells, and RWSP wells. The TGW and TGNW tanks cover the western zone by an average quantity of 19.68 MCM/month. The western zone contains 24 districts and 2.2 million capita. The eastern zone takes water from TGE and Buwayb wells with an average quantity of 15.97 MCM/month. It serves 28 districts which have approximately 1.67 million capita. The TGN and Salboukh groundwater wells supply the northern zone by 14.21 MCM/month. The northern zone comprises of 17 districts with a total population of 0.306 million capita. The southern zone

Table 1
Monthly quantity of water in cubic meter ($m^3$) delivered to Riyadh City from all groundwater wells

| Sources | Jan-2017 | Feb-2017 | Mar-2017 | Apr-2017 | May-2017 | Jun-2017 | Jul-2017 | Aug-2017 | Sep-2017 | Oct-2017 | Nov-2017 | Dec-2017 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Buwayb wells | 2,820,289.27 | 2,290,678.32 | 2,697,987.38 | 2,779,068.43 | 2,964,618.66 | 2,840,580.00 | 2,944,488.41 | 2,923,176.00 | 2,666,785.18 | 2,701,115.59 | 2,656,969.74 | 1,937,438.00 |
| Malaz wells | 481,902.92 | 391,408.28 | 461,005.19 | 474,859.52 | 506,564.49 | 485,370.00 | 503,124.83 | 501,921.00 | 457,897.67 | 463,792.34 | 456,212.32 | 414,253.00 |
| Shemessy wells | 937,385.92 | 761,357.93 | 896,736.17 | 923,685.26 | 985,357.01 | 944,130.00 | 978,666.27 | 992,837.00 | 905,755.59 | 917,415.68 | 902,421.84 | 959,605.00 |
| Manfouha wells | 1,345,599.01 | 1,092,914.30 | 1,287,247.09 | 1,325,931.98 | 1,414,460.56 | 1,355,280.00 | 1,404,856.14 | 1,293,568.00 | 1,180,109.57 | 1,195,301.51 | 1,175,766.03 | 879,346.00 |
| RWSP wells | 2,023,432.30 | 1,643,459.96 | 1,935,686.13 | 1,993,858.18 | 2,126,982.23 | 2,037,990.00 | 2,112,539.67 | 1,773,169.00 | 1,617,644.92 | 1,638,469.40 | 1,611,690.97 | 1,807,548.00 |
| Saad wells | 2,647,681.11 | 2,150,483.56 | 2,532,864.38 | 2,608,983.08 | 2,783,177.21 | 2,666,730.00 | 2,764,278.97 | 6,384,977.00 | 5,824,952.73 | 5,899,939.29 | 5,803,513.25 | 6,729,604.00 |
| Hunnai wells | 11,604,093.70 | 9,425,006.90 | 11,100,881.98 | 11,434,490.37 | 12,197,937.66 | 11,687,580.00 | 12,115,111.64 | 12,087,117.00 | 11,026,959.87 | 11,168,913.60 | 10,986,373.75 | 11,639,322.00 |
| Salboukh wells | 2,842,032.84 | 2,308,338.74 | 2,718,788.03 | 2,800,494.20 | 2,987,474.96 | 2,862,480.00 | 2,967,189.51 | 2,999,343.00 | 2,736,271.59 | 2,771,496.53 | 2,726,200.40 | 3,396,081.00 |
| Hair wells | 1,504,058.96 | 1,221,617.69 | 1,438,835.42 | 1,482,075.91 | 1,581,029.76 | 1,514,880.00 | 1,570,294.31 | 1,059,456.00 | 966,531.46 | 978,973.94 | 962,974.01 | 1,041,600.00 |

receives water quantity of 18.82 MCM/month from TGS, Hair, and Manfouha wells. It provides water to 29 districts that have approximately a population of 1.81 million capita [5].

*2.2. Model scenario design*

In this study, five scenarios are established according to water development strategies according to Saudi National Water Company (NWC). The water resource suggestions by the WEAP model are compared with those established in the reference case. Table 2 shows detailed scenarios statements and assumptions based on NWC plans. After implementing each scenario, the WEAP model enabled analyses of four main outputs: unmet demand (UD), water demand (WD), supply delivered (SD), and supply requirement (SR). After each scenario, these parameters are compared against those obtained from the reference scenario.

## 3. Results and discussions

*3.1. Reference scenario*

WEAP program calculated the population of Riyadh city based on a population of 8.25 million capita with 4% growth rate in 2017. According to the 4% population growth rate, the WEAP model simulated the population over the years from 2018 to 2030. The population is expected to be 13.74 million capita in 2030 (Fig. 2). The base case scenario and all scenarios use a 4% population growth rate from 2017 to 2030. Table 3 shows the change of each WEAP water parameter for all demand zones between the year 2017 and the year 2030.

The reference scenario shows the current situation demand and supply for 2017 of Riyadh city and what will happen in 2030 if nothing changes. The reference scenario was constructed with data of 2017 such as daily consumption, population growth rate of 4%, current water losses and water reuse rates (Figs. 1 and 2). The WEAP model calculates the water demand, supply requirements, supply delivered and unmet demand for the next 13 years starting from 2017 to 2030.

The result shows increasing in WD for Riyadh city from 685 in 2017 to 1,452 MCM in 2030 as shown in Fig. 6a, due to the increased population growth. The unmet demand for Riyadh city increased by 93.0% from 2017 to 2030 (e.g., from 66 to 1,076 MCM) as illustrated in Fig. 7a. The SR also increased by 52% in 2030 (from 913 MCM in 2017 to 1,936 MCM) due to an increase in water demand (Table 3). The SD is observed to be equal to the maximum total volume of existing water tanks of 860 MCM in 2019. Therefore, the NWC needs to build new water reservoirs starting from 2019 to reduce water shortages.

*3.1.1. Scenario-1: (reduce leakage from 25% to 10%)*

The NWC faces leakage problem during the supply of water to different zones of Riyadh city and this leakage reaches up to 25% of the total water supplied. This scenario explains if

Table 2
Scenarios and assumption of Riyadh city WEAP model

| Scenario | Main assumption |
|---|---|
| Reference scenario | The reference scenario corresponds to the existing practices, which depend mainly on desalinated water and groundwater supply (Fig. 3). A population growth rate of 4% is taken based on the most likely scenario proposed by the NWC. The reference considered all water use and supply quantity based on 2017 practices. No reuse of recycled water for irrigation of public gardens. The leakage from the water pipeline system is considered to be 25%. It starts simulations from 2017 until 2030. |
| Scenario 1 | The leakage in Riyadh's distribution system represents 25%, due to, illegal connections, non-metered old housings, and leaks in water pipelines. Here, NWC plans to launch new rules and projects to reduce leakage from 25% to 10% through maintaining the water distribution system and reducing illegal connection. |
| Scenario 2 | The Saudi Ministry of Water Agriculture and Environment (SMWAE) recommends considering household water appliance retrofits (i.e., water conservations) to reduce the water use from 30% to 40% [23]. The SMWAE developed a master's plan to implement water conservation plan through retrofitting water appliances to all existing and new [5,23]. In this study and according to SMWAE regulation, implementing water conservation could reduce water consumption per capita per year by 32%. |
| Scenario 3 | Riyadh city comprised five centralized wastewater treatment plants. There are plans by the SMWAE to reuse recycled water (rRW) (i.e., treated wastewater) of tertiary treatment level to irrigate the public gardens. The SMEWA is planning to launch training courses for farmers to educate them about the benefits of treated wastewater reuse in Riyadh. In this scenario, reuse of recycled water increased from 0% to 20%. Therefore, 20% of reuse of recycled water in agriculture is considered starting 2018 until 2030. |
| Scenario 4 | The water conservation is implemented by retrofitting household water appliances simultaneously with reducing leakage in the water distribution network. Those two water-demand measures are considered for demand years from 2018 to 2030. |
| Scenario 5 | This scenario recommends implementing reuse of recycled water from nothing to 20% in conjunction simultaneously with leakage reduction measures in the water pipeline network from, and introduces conservation through retrofitting house appliances (washer machine, faucet, toilet, and dishwasher). |

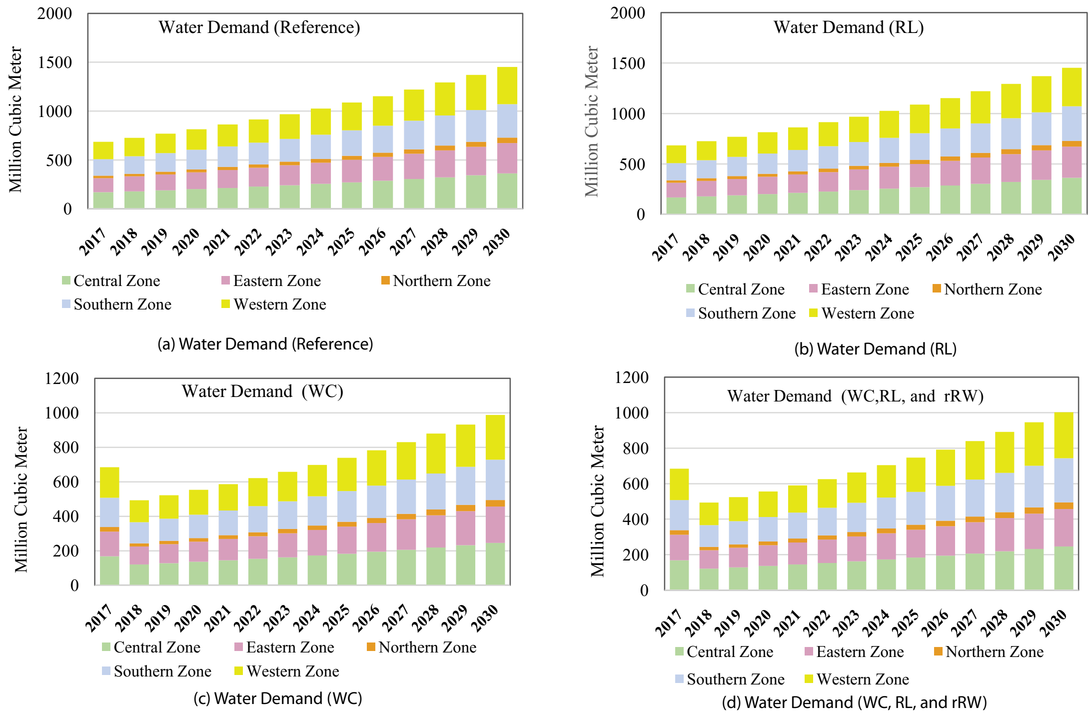


Fig. 6. Computed water demand for reference scenario, scenario 1, scenario 2, and scenario 5.

the leakage reduced to 10% will appear positively on supply requirements and unmet demand for 2017 and 2030. Table 3 shows the total SR from 2017 to 2030 when the leakage is reduced. The total SR in this scenario is found to be 1,613 MCM in 2030 while in the reference scenario was 1,936 MCM in the same year. The same impact is visible in the total UD if the leakage is reduced from 25% to 10%. The total UD was 66 MCM in 2017 and reached 1,076 MCM in 2030. When leakage reduction is introduced, the UD reduced by 30% from the reference scenario (e.g., from 1,076 to 753 MCM). Results show that the total WD and total SD for Riyadh city increased gradually in this scenario starting from the year 2017 to the year 2030 and both of them were not affected by the reduction of leakage in the water distribution system (Table 3).

### 3.1.2. Scenario-2: (water conservation plan)

This scenario investigates the effect of household appliance retrofitting (water conservation plan) on the water demand. Applying the water conservation plan aims is to reduce the water demand which will ultimately help to reduce the WD and the UD. When household appliance retrofitting is introduced, it is expected that the water demand reduced by 32% based on MEWA plan.

The result shows that the increase of WD with a water conservation plan with years will be less than those obtained in the reference scenario. The water amount saved between both scenarios is 465 MCM, which is the difference between 1,452 and 987 MCM in 2030 (Table 3). The SR decreased due to the reduction in the WD. The SR is reduced from 1,936 MCM in the reference scenario to 1,316 MCM in 2030 (Table 3). In this scenario, the SD reached its maximum capacity of 846 MCM starting from 2026 until 2030. Therefore, the water authorities must establish new water reservoirs starting from 2026. Here, the total UD starts with shortages of 1,076 MCM in the reference scenario and reduced to 456 MCM in 2030 when water conservation is considered.

### 3.1.3. Scenario-3: (reuse of recycled water)

This scenario investigates to increase the reuse of recycled water for agriculture from zero to 20%. The results established that the WD did not change when compared with the reference scenario in demand zones (Table 3). Model results show that SR decreased by 53% (from 1,936 to 913 MCM) if the reuse of recycled water is executed (Table 3). The results show that SD value is equal to the total storage capacity of water tanks in 2023. However, in the reference scenario, SD reached its maximum in 2019. Here, the UD started from the year of 2018 and reached 689 MCM in 2030. In the reference scenario, the unmet demand began in 2018 and reached 1,076 MCM in 2030.

### 3.1.4. Scenario-4: (water conservation plan and reduce leakage by 10%)

In this case water conservation management plan and reduce leakage from 25% to 10% are combined as advised by NWC decision makers. The results indicated that WD will highly be affected in this scenario by applying a water conservation plan and reduce leakage by 10%. The WD reduced from 1,452 MCM in the year 2030 in the reference scenario to 1,003 MCM in this scenario (Table 3). In this case, the SR decreased due to a reduction in WD. Here, the SR reduced from 1,936 MCM in the reference scenario to 1,114 MCM in 2030 (Table 3). In this scenario, the SD reaches its maximum capacity of reservoirs 860 MCM per

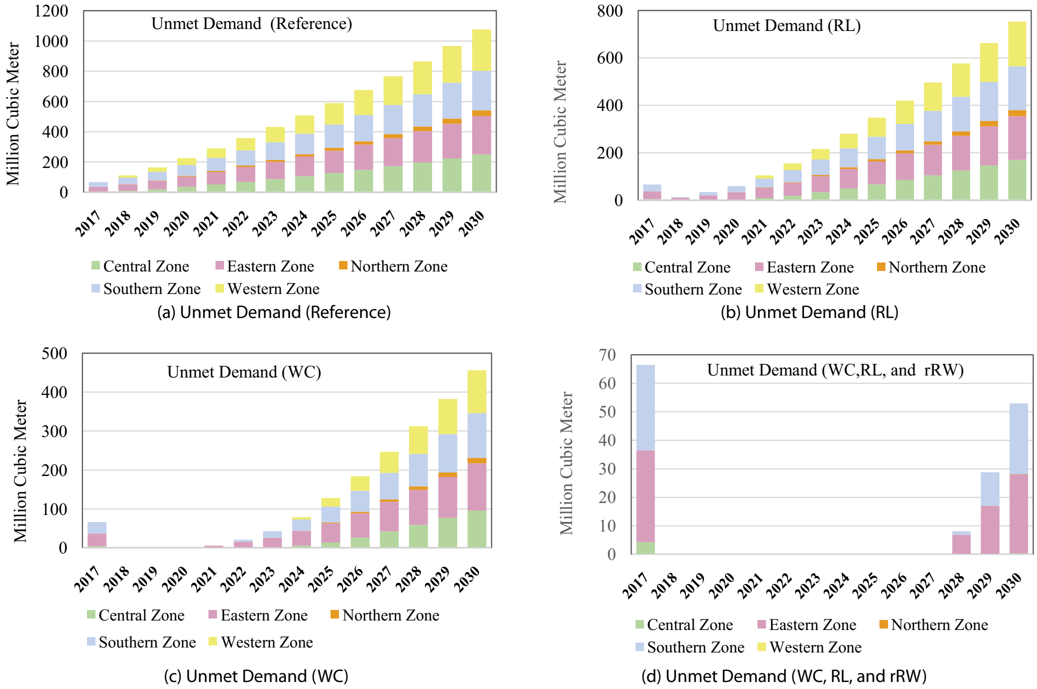


Fig. 7. Computed water demand for reference scenario, scenario 1, scenario 2, and scenario 5.

Table 3
Computed WEAP output parameters for all scenarios in 2017 and 2030 in MCM

| WEAP output water parameter (MCM) | Year | Reference scenario | Scenario 1 (RL) | Scenario 2 (WC) | Scenario 3 (rRW) | Scenario 4 (WC + RL) | Scenario 5 (WC + rRW + RL) |
|---|---|---|---|---|---|---|---|
| Water demand | 2017 | 685 | 685 | 685 | 685 | 685 | 685 |
| | 2030 | 1,452 | 1,452 | 987 | 1,452 | 1,003 | 1,003 |
| Supply requirement | 2017 | 913 | 913 | 913 | 913 | 913 | 913 |
| | 2030 | 1,936 | 1,613 | 1,316 | 1,549 | 1,114 | 891 |
| Supply delivered | 2017 | 846 | 846 | 846 | 846 | 846 | 846 |
| | 2030 | 860 | 860 | 860 | 860 | 860 | 838 |
| Unmet demand | 2017 | 66 | 66 | 66 | 66 | 66 | 66 |
| | 2030 | 1,076 | 753 | 456 | 689 | 254 | 53 |

year in 2029 (Table 4). It implies that NWC should consider building new water reservoirs in 2029. Here, the UD starts from the year of 2024 and reached 254 MCM in 3030. In the reference scenario, the UD starts in 2017 and reached 1,076 MCM in 2030 (Fig. 7c).

### *3.1.5. Scenario-5: (water conservation plan, reduce leakage by 10% and reuse of recycled water to 20%)*

Results found that the scenario is the most effective alternative one for Riyadh city. The previous three water development alternatives are combined in this case which are water conservation, leakage reduction, and reuse of recycled water. The results achieved the highest reduction in WD for all demand zones when evaluated against the reference scenario. The water demand decreased by 31% from the reference scenario in 2030 (i.e., from 1,452 to 1,003 MCM) as shown in Table 3 and Fig. 7d. However, the SR decreased considerably from 1,936 MCM in the reference scenario to 891 MCM as shown in Table 3. The value of SD did not reach the total storage amount of water storage tanks 860 MCM. Therefore, there is no need to build new water storage tanks when considering water conservation jointly with the leak reduction and reuse recycled water. The UD reached 53 MCM in the year 2030 while in the reference scenario it reached 1,076 MCM in the same year (Fig. 7d and Table 3).

## *3.2. Evaluation of water system performance*

To evaluate the effectiveness of Riyadh water supply system, three indicators are conducted on the unmet demands over 13 years (from 2017 to 2030). The three indicators are the reliability, resiliency, and vulnerability indicators [24,25]. These indicators are also used to compare the performance of each scenario on for each zone between 2017 until 2030.

Table 4
Supply delivered parameters for all scenarios from 2017 until 2030 in MCM

| Supply delivered (MCM) | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reference scenario | 846 | 856 | 860 | 860 | 860 | 860 | 860 | 860 | 860 | 860 | 860 | 860 | 860 | 860 |
| Scenario 1 (RL) | 846 | 793 | 820 | 845 | 854 | 860 | 860 | 860 | 860 | 860 | 860 | 860 | 860 | 860 |
| Scenario 3 (rRW) | 846 | 770 | 801 | 828 | 849 | 856 | 860 | 860 | 860 | 860 | 860 | 860 | 860 | 860 |
| Scenario 2 (WC) | 846 | 658 | 697 | 738 | 776 | 808 | 835 | 851 | 858 | 860 | 860 | 860 | 860 | 860 |
| Scenario 4 (WC and RL) | 846 | 549 | 582 | 617 | 655 | 695 | 737 | 777 | 806 | 833 | 850 | 857 | 860 | 860 |
| Scenario 5 (WC, RL, and rRW) | 846 | 439 | 466 | 494 | 524 | 556 | 590 | 626 | 664 | 704 | 747 | 784 | 811 | 838 |

#### *3.2.1. Reliability indicator*

The reliability indicator can be measured by knowing months of having no shortages (i.e., unmet demands) over the total number month [24]. The highest percentage of reliability represents a reliable water development scenario when supply meets demand.

#### *3.2.2. Resiliency indicator*

Resiliency represents how quickly is the water system is returning to recovery after a shortage has happened. The resiliency is defined as the number of occurrences that did not experience unmet demand followed by a month having an unmet demand. It can be defined as the number of times where demand meets supply followed by unmet demand.

#### *3.2.3. Vulnerability indicator*

When shortages occurred and the supply system failed to meet water demand, how significant the consequences of this failure would be [24,25]. It is estimated based on the total shortages occurring from 2017 until 2030. It is defined as the sum of unmet demands over the number of unsatisfactory instances from 2017 until 2030.

Results show that the highest reliability index of the water system is achieved for the northern zone for all scenarios. Therefore, the northern zone will not have water shortages in the next 13 years. On the other hand, the central zone has the lowest reliability indicator in all scenarios, which indicates that this zone will face water shortage and unmet demands in the next 13 years (Table 5 and Fig. 8). The result also shows that the highest reliability index has been achieved for the northern zone for all scenarios. It indicates that water will be delivered to the Northern zone, for the entire planning horizon, without any unmet demand. Table 4 shows the resiliency index for three selected scenarios in all demand zones. The result shows that the shortages that happened in the Eastern, Southern, and Western zones, in scenario 5, have recovered after failure occurrence with various percentages of recovery. The highest vulnerability indicator is found to be 74,397,826 MCM for the reference scenario. In the reference scenario, the total shortage is 12,489,834,801 MCM occurred in 168 months for all demand zones. Vulnerability indicates that the shortages for the Riyadh city in all demand zones could reach 74,397,826 MCM per month. Furthermore, the results also show that the Northern zone shows zero vulnerability due to the abundant quantity of water from different source that cover this zone (Fig. 9). It is found that scenario 5 produced the least vulnerable solution with total shortages of 2,646,768,215 MCM occurred in 168 months. Therefore, the corresponding vulnerability is 15,754,573 MCM per month. This is because of considering several water development measures including reducing leakage jointly with the reuse of recycled water and water conservation (Fig. 9). Results also show that vulnerability for water conservation and leak reduction scenarios are 36,764,436 and 54,169,161 MCM, respectively. In other words, results suggest that water conservation measure is less vulnerable to water shortages when compared with the leak reduction one. Therefore, water conservation should be given higher priority over the leak reduction measure.

### *3.3. Practical implication*

The main challenge of this research is lacking of published data about Riyadh water resources supply and demand. Most of the data have been collected by conducting several interviews and questionnaires with the water authority managers. Therefore, it is highly recommended that the (Al-Riyadh Municipality) has a better and well-arranged database that summarizes and contains all the information regarding water use rates for the different sectors in the city. Since the operating of the water pipeline system is the main cause of water leakage, it is highly recommended to carry out rehabilitation activities. Installing water metering for old houses and introducing an appropriate tariff are a matter of urgency to reduce water leakage. Intensive education campaigns and public awareness should be provided to make the public aware of the water value and the importance of household water conservations. Strong coordination between all water institutions is required to implement new water resources such as water conservation and the reuse recycled water for agriculture. The implementation of already established policies, strategies, and plans regarding water management by the NWC must be a major goal. However, these policies have to be extended to incorporate stormwater collection due to flash flow in urban use. Since this is the first time to use WEAP at Riyadh city level, additional work should follow to address all the considered water development strategies by carrying out economic analysis. Since groundwater is a major water supply source for Riyadh city, it is highly imperative to link the WEAP model with MODFLOW groundwater management model to simulate the changes of groundwater levels as a result of abstraction.

Table 5
Water system performance evaluation criteria (reliability, resilience, and vulnerability)

| 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 (MCM) (Eq. (3)) = (5/3) |
|---|---|---|---|---|---|---|---|---|---|
| Reference scenario | Central zone | 168 | 2 | 166 | 0 | 5,174,209,118 | 1% | 0.00% | 31,169,934 |
| | Eastern zone | 168 | 1 | 167 | 0 | 2,473,535,849 | 1% | 0.00% | 14,811,592 |
| | Northern zone | 168 | 168 | 0 | 0 | 0 | 100% | 0.00% | 0 |
| | Southern zone | 168 | 0 | 168 | 0 | 2,401,703,213 | 0% | 0.00% | 14,295,852 |
| | Western zone | 168 | 11 | 157 | 1 | 2,449,386,621 | 7% | 0.64% | 15,601,189 |
| | Sum | 168 | 0 | 168 | 0 | 12,498,834,801 | – | – | 74,397,826 |
| Scenario 2-Conservation | Central zone | 168 | 2 | 166 | 0 | 3,366,403,229 | 1% | 0.00% | 20,279,538 |
| | Eastern zone | 168 | 25 | 143 | 3 | 1,052,655,532 | 15% | 2.10% | 7,361,227 |
| | Northern zone | 168 | 168 | 0 | 0 | 0 | 100% | 0.00% | 0 |
| | Southern zone | 168 | 45 | 123 | 4 | 908,214,377 | 27% | 3.25% | 7,383,857 |
| | Western zone | 168 | 70 | 98 | 2 | 849,152,114 | 42% | 2.04% | 8,664,817 |
| | Sum | 168 | 0 | 168 | 0 | 6,176,425,252 | – | – | 36,764,436 |
| Scenario 5 (LR, WC, and rRW) | Central zone | 168 | 2 | 166 | 0 | 2,085,874,101 | 1.00% | 0.00% | 12,565,507 |
| | Eastern zone | 168 | 86 | 82 | 3 | 275,276,205 | 51.00% | 3.66% | 3,357,027 |
| | Northern zone | 168 | 168 | 0 | 0 | 0 | 100.00% | 0.00% | 0 |
| | Southern zone | 168 | 107 | 61 | 2 | 171,753,605 | 64.00% | 3.28% | 2,815,633 |
| | Westernzone | 168 | 130 | 38 | 2 | 113,864,304 | 77.00% | 5.26% | 2,996,429 |
| | Sum | 168 | 0 | 168 | 0 | 2,646,768,215 | – | – | 15,754,573 |

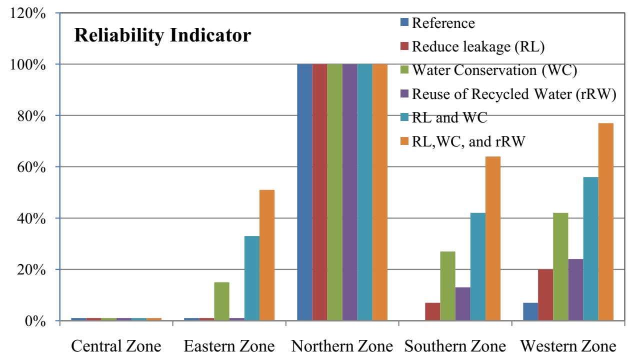


Fig. 8. Reliability index for all demand zones.

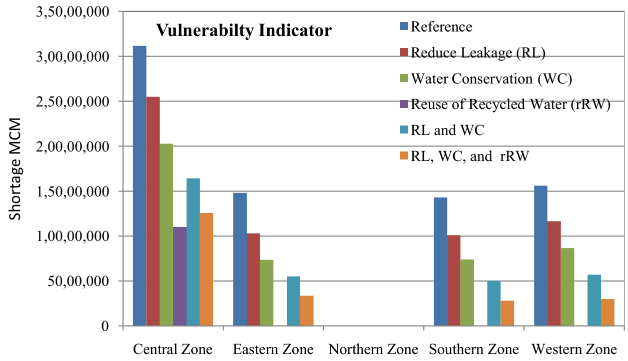


Fig. 9. Vulnerability index for all demand zones.

## 4. Conclusion

This paper attempts to develop an IWRM approach for simulating Riyadh's city water resources supply and demand. Most of the developed water management alternatives of this paper are based on the sustainability concept to avoid the depletion of available groundwater and desalinated water supply sources [26–30]. This paper evaluates the ability of the current water desalination and groundwater supply on the future water demand. It assessed five water supply and demand alternatives which are planned by the NWC to find combinations of scenarios that reduce unmet demands. The allocation of water resources for Riyadh zones was also measured for all demand years until 2013. Results showed that Riyadh water resources will face water shortage challenges in the future if current desalination and groundwater supply condition continues. In other words, the current desalination and groundwater supply are not sufficient to meet future demands and water deficits will continue to increase over the years. This is mainly due to the increase in population over the demand years from 2017 to 2030. Therefore, securing additional water supplies becomes an essential issue to meet this increase in water demand. If the current situation continues, an additional quantity of 685 MCM must be developed by the year 2030 to decrease the gap between supply and demand. Water conservation is highly beneficial to reduce the gap between water demand and supply. It was established that water conservation is a very beneficial alternative for reducing WD's and UD's. It reduced water demand by 32% (from 1,452 to 987 MCM) in 2030. The highest reduction in UD is established when introducing water conservation through household appliance retrofitting. The UD reduced by 57%, from 1,076 MCM in the reference scenario to 456 MCM. Moreover, the implementation of reduced leakage and reuse of recycled water scenarios is not beneficial in reducing the water demand. The total water demand in 2030 remains 1,452 MCM in these scenarios. However, those scenarios reduced the supply requirement. The SR decreased by 16%, from 1,936 to 1,613 MCM, when considering reduce leakage strategy. After considering the reuse of recycled water, the SR reduced from the reference scenario by 20%, from 1,936 to 1,549 MCM. Therefore, it is established that the reuse of recycled water is more beneficial than the leakage reduction as far as the SR is a concern. The lowest water and unmet demands are established after fixing leakage and implementing household conservation jointly with the reuse of recycled water. In 2030, the water and unmet demands reduced from the reference scenario by 30% (from 1,452 to 1,003) and 95% (from 1,076 to 53 MCM), respectively. In this situation, the unmet demand was only observed from 2028 until 2030. On the other hand, all water demands have been met from 2017 until 2027. After considering water conservation in conjunction with reducing leakage and reuse of recycled water, the capacity of supply reservoirs is less than the total storage of reservoirs of 860 MCM. It is concluded that this is the only water development alternative that does not require building new reservoirs. In conclusion, the current water supply system which depends on desalination and groundwater is not sufficient to meet future water demand in 2030. The execution of the household appliance retrofitting measures jointly with the reuse of recycled water and leak reduction measures reduced water shortages to a level below than those occurring in 2017 but did not eliminate the future unmet demands. Furthermore, the population increase of 4.0% in Riyadh city makes it vulnerable to water shortage problems.

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