Heliyon 9 (2023) e20543

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Water resources availability, sustainability and challenges in the GCC countries: An overview

Mohsen Sherif [a,b,*], Muhammad Usman Liaqat [c], Faisal Baig [a,b], Mohammad Al-Rashed [d]

[a] National Water and Energy Center, UAE University, P.O. Box 15551, Al Ain, United Arab Emirates
[b] Civil and Environmental Eng. Dept., College of Engineering, UAE University, P.O. Box 15551, Al Ain, United Arab Emirates
[c] Department of Civil, Environmental, Architectural Engineering and Mathematics, Università degli Studi di Brescia-DICATAM, Via Branze, 43, 25123 Brescia BS, Italy
[d] Water Resources Research Center, Kuwait Institute for Scientific Research, P.O. Box 24885, 13109, Safat, Kuwait

ARTICLE INFO

Keywords:
GCC countries
water resources
management
sustainability
climate change

ABSTRACT

The Gulf Cooperation Council (GCC) countries include Bahrain, Kuwait, Saudi Arabia, Sultanate of Oman, Qatar, and United Arab Emirates. The GCC countries are located in an arid region. They have limited renewable water resources due to scarcity of rainfall. This paper provides the most recent and accurate quantitative and qualitative assessment of available water resources and demands in the GCC countries. The annual renewable surface water, desalinated capacity, wastewater treatment capacity, and per capita water consumption in the GCC countries are assessed. The possible impacts of climate change are discussed. The annual renewable surface water, desalinated capacity, and wastewater treatment capacity in the GCC countries are estimated as 4.14, 26.4, and 10.07 billion m^3, respectively. The average per capita water consumption is around 550 l/d. The GCC countries have high water footprints. Although tertiary treated, the reuse of treated wastewater is limited and constrained to the development of forests and green areas. Water demand trends reveal the need for the implementation of sustainable water management programs. Emerging solutions include imposing a new tariff system, improving irrigation efficiency, controlling agricultural water consumption, developing innovative desalination and treatment technologies, maximizing treated wastewater utilization and rainwater harvesting, eliminating leakage in networks, and considering virtual water concepts in the water budget and planning.

1. Introduction

The development and prosperity of nations depend on the availability of water with the required quantity and quality to meet the demands of the different sectors [1]. The spatial and temporal distribution of world water resources is dependent on the climate and topography of the region. The proper assessment of the total quantity and quality of conventional and nonconventional water resources and consumption rates are important for integrated water resources planning and management.

Despite the lack of renewable water resources, the Gulf Cooperation Council (GCC) countries (Fig. 1), including Bahrain, Kuwait,

* Corresponding author. National Water and Energy Center, UAE University, P.O. Box 15551, Al Ain, United Arab Emirates.
E-mail address: MSherif@uaeu.ac.ae (M. Sherif).

https://doi.org/10.1016/j.heliyon.2023.e20543
Received 9 March 2023; Received in revised form 20 May 2023; Accepted 28 September 2023
Available online 29 September 2023

Saudi Arabia, Sultanate of Oman, Qatar, and United Arab Emirates, have witnessed rapid economic and social developments over the last few decades. The economic prosperity of the region is supported by the oil industry and huge reserves of crude oil and gas [2]. However, during the last few years, significant attention has been devoted to the development of renewable and clean energy. Through economic diversification, the GCC countries are becoming less dependent on oil and gas industry. Table 1 presents a snapshot of the population, GDP real growth and Human Development Index (HDI).

The rapid population growth and socioeconomic developments in the GCC countries have been associated with a tremendous increase in water demands. However, the lack of renewable (conventional) water resources may impede ambitious developmental plans. Water-related challenges in GCC countries include extended drought periods, extreme events, development of vast green areas in cities and residential areas, increase in living standards, depletion of aquifers, seawater intrusion in coastal aquifers, climate change and temperature increase, high use of fossil fuel in desalination plants, and limited utilization of treated wastewater [2].

Currently, treated wastewater is squandered rather than fully utilized. The domestic water supply is highly dependent on desalination of seawater. Most of the GCC countries subsidize the water sector, and hence, consumers pay far less than the actual cost of water production. Groundwater pumping for irrigation is not adequately monitored or controlled.

To understand and address water scarcity problems in the GCC countries, a full exploration and an accurate assessment of the available resources are needed. In this paper, the most recent information and data related to conventional and nonconventional water resource availability, utilization and challenges in GCC countries are discussed and analyzed. The main characteristics of groundwater systems and shared water resources are presented. The changes in rainfall patterns, groundwater recharge and possible impacts of climate changes are discussed. The impacts of virtual water and climate change are outlined, and measures to address water sustainability are presented.

2. Literature review

Due to scarcity of data, limited research on water resources management and sustainability in the GCC counties have been published. Sharma [4] provided a qualitative and quantitative assessment of available freshwater resources in Saudi Arabia and their optimal use. The study elaborated that water demand prediction should be analyzed based on intelligent and multi-criterial optimization and suggested a framework to allocate water resources based on future changing scenarios. Alshehri and Abdelrahman [5] utilized electrical resistivity tomography to survey the availability of groundwater resources in Madinah area, Saudi Arabia. A reliable water bearing formations in the alluvial sediments was found. They elaborated that local communities can be supported by adequate freshwater resources from local resources. Alrwis et al. [6] demonstrated the adverse effects of water scarcity on the agricultural sector in Saudi Arabia by developing various economic indicators. They provided various policy recommendations including termination of virtual water exports and development of a viable framework for economic accounting of water. Alkhudiri et al. [7] showed an

Fig. 1. Geographical location of the GCC countries (database, National Water and Energy Center, UAE University).

Table 1
Growth indicators in GCC countries, [3].

Indicator	UAE	Saudi Arabia	Oman	Bahrain	Kuwait	Qatar
Population (million)	9.9	34	4.61	1.5	4.5	2.87
Growth Rate (%)	1.5	1.6	1.96	2.08	1.27	1.55
GDP real growth rate[a] (%)	1.7	0.3	−1.6	1.8	0.4	0.8
Human development index (HDI)	0.84	0.847	0.796	0.824	0.8	0.856

[a] Based on the records of World Bank Data for annual change in 2020.

increasing trend in production and utilization of treated wastewater in Saudi Arabia which is expected to rise by 4% until 2050. They also revealed an annual increase of 3% in the industrial water demand and elaborated that more focus should be given to properly treat and use the wastewater for industrial uses. Chandrashekharam [8] focused on developing alternative resources for freshwater such as desalination and elaborated that the geothermal sources can be used to run desalination plants and produce freshwater.

UAE relies heavily on desalination and groundwater resources to secure its freshwater needs. As such, the viability of various desalination processes and techniques were investigated and critically analyzed [9–14]. Groundwater resources in UAE were evaluated qualitative and quantitative by Refs. [15–17]. They concluded that the groundwater resources are depleting rapidly due to over exploitation and lack of recharge [18–21]. mapped the potential groundwater zones in different parts and provided an assessment for the groundwater resources in UAE. Alzaabi and Mezher [22] reviewed the strategies related to water, energy, and food nexus for UAE. The consensus among several stakeholders in the nexus was assessed to evaluate the policies related to each sector of the nexus. Owing to the extreme rainfall events in the country, the applicability of remote sensing precipitation products over UAE to better understand the rainfall regime [23,24].

Oman is mainly relying on groundwater resources to secure its fresh water demands for agriculture and domestic purposes. The water supply is supplemented by desalination plants commissioned in the certain municipalities and villages [25]. Asker et al. [26] studied the groundwater in the coastal aquifers of Oman and pointed out various salinity sources that could potentially deteriorate the quality of the groundwater. Barghash [27] presented a low-cost natural treatment method for domestic wastewater to be further used in urbanized plantation and gardening purposes. An evaluation of past and present water resources management strategies was conducted by Ref. [28] while considering the effects of climate change, water stress, population growth and developmental activities. various efficient techniques have been proposed by other researchers to enhance the desalination productivity of existing desalination plants in Oman [29–31].

Al-Huwaishel et al. [32] studied the likelihood of developing an underground aquifer by using treated wastewater while maintaining various injection/pumping scenarios and thereby analyzing the pumped water quality in Dammam aquifer of Kuwait. Al-Sulaili et al. [33] assessed the fresh water use in Kuwait under various meteorological factors and proposed near-future consumption scenarios. Baalousha and Baalousha et al. [34,35] developed groundwater vulnerability maps using advanced techniques and studied different groundwater protection and management scenarios.

A number of researchers [36–38] studied the groundwater resources in Qatar with a focus on managed aquifer recharge and groundwater depletion. The anthropogenic stress was analyzed considering the energy food nexus under changing climate conditions. Haji et al. [39] proposed a framework for energy water food nexus grid based on computational modeling to enhance the food security in Qatar. Analytical Hierarchy Process (AHP) was used to include GIS modeling and optimization algorithms to model the energy-water-food nexus in a spatial and temporal domain.

Bahrain has witnessed a sharp decline in groundwater levels and quality during last decade due to excessive abstraction. Kadhem and Zubairi [40] proposed optimum locations for managed aquifer recharge in Bahrain to replenish the dwindling groundwater resources. The main purpose of the study was to harvest the excess rainwater that could have been lost otherwise. The water cycle of Bahrain in terms of sanitation, drinking water, water scarcity, water related ecosystems and water management, was recently monitored by Ref. [41]. The study outlined several reasons hindering the achievement of efficient water management in the country and offered potential solutions. Mutawa et al. [42] developed a benchmark system to assess the effectiveness of wastewater sector in Bahrain. The factors included wastewater collection, treatment, and subsequent discharge of sewage treatment plants. Bani [43] investigated different crop water management practices and identified optimum approach for crop production in Bahrain.

3. Geography and geology

The Arabian Peninsula (AP) covers an area of approximately 2.4 million km^2. Except for some mountainous regions or areas in the vicinity of coastlines, arid conditions prevail. Saudi Arabia is the largest country in the AP, with an area of 2.15 million km^2 (approximately 85% of the peninsula) and a population of 34 million (Table 1). The topography of Saudi Arabia ranges from mountains, scattered saltpans, valleys, sandy and rocky deserts and coastal areas [2]. The lowest land elevation is at sea level near the Red Sea and the Arabian Gulf, and the highest elevation point is approximately 3000 m (Jabal Sawda). The Sarawat Mountains, recognized as rain-fed highlands, cover the western and southwestern parts of the country. The interior desert land is composed of the Najd Plateau (Brown et al., 1989).

The Sultanate of Oman is located in the southeast of the AP, with a total area of 0.309 million km^2 and a population of 4.61 million. The largest part of the country is composed of sand with limestone mountains rising to an average of 2100 m and deeply separated by wadis [44]. The highest elevation point is almost 3000 m above mean sea level (Jabel Shams). The Ummer Radhuma Dammam aquifer (south) system extends from northern Iraq to the southern coast of the AP over a distance of 2200 km. The aquifer system in this area comprises three Paleogene, i.e., the Rus, the Dammam and the Paleocene-Eocene formations in which Rus is least important. The central part of the aquifer stretches a 400 km-wide structural platform that extends into Qatar, Bahrain and Saudi Arabia [45]. A major portion of Ummer Radhuma aquifer is in the western low plateau areas, whereas in the eastern side, it becomes more complex when the Dammam formation is isolated by the Neogene-Quaternary units in the Rus Formation [46].

The United Arab Emirates (UAE) has an area of 83,600 km^2 and a population of 9.90 million. Most of the area of the UAE is desert and is predominantly composed of an aeolian landform system. The northern part is mountainous, and its highest peak is 1934 m above sea level (Jabel Jais). The main aquifers in the UAE include the limestone aquifer, located in the northern and eastern parts of the country, the gravel aquifers toward eastern mountain, the fractured ophiolite rocks in the east, and the sand dunes in the south and west [1].

Kuwait has a total area of 17,818 km^2 and a population of 4.5 million. It is located in southwest Asia bordering the Arabian Gulf between Saudi Arabia and Iraq. The northeastern part of the AP is characterized by four major systems of aquifers: including (1) the Palaeozoic-Triassic System, (2) the Cretaceous System, (3) the Eocene System, and (4) the Neogene-Quaternary System. The last two aquifers contain useable water, while the other deeper aquifers have connate water. Thus, the principle aquifer system in Kuwait consists of the Kuwait Group and the Dammam Formation of the Hasa Group [47].

Qatar is located in the northeastern side of the Arabian Gulf, forming a small peninsula with a land area of 11,610 km^2 and a population of 2.87 million [3]. There are two main aquifers in Qatar. The Rus aquifer is in the northern part of the country and is composed of chalky limestone, and the Abu Samara aquifer in the southern part of the country, which consists of granular limestone rocks [48].

Bahrain comprises many low-lying islands and is the smallest country in the AP. The population of the country increased rapidly from 0.55 million in 2000 to almost 1.5 million in 2018 [3]. The land area amplified by almost 12% from 695 km^2 in 2000 [2] to approximately 780 km^2 in 2018 through coastal reclamation to meet the increasing demographic demands. The geological map of the AP is given in Fig. 2.

4. Water resources in GCC countries

The availability and sustainability of freshwater resources in GCC countries have always been a challenge due to scarcity of rainfall, limited renewability of groundwater resources, high evaporation rates, and wasteful use of water. Renewable water resources, including aflaj water systems, springs, and ponding areas of dams, are present in small amounts. Active aflaj and springs are becoming rare due to a lack of recharge and excessive pumping. Limited amounts of fresh groundwater are encountered in shallow and deep aquifers. Nonconventional water resources, such as desalinated water and treated wastewater, have been introduced to bridge the gap

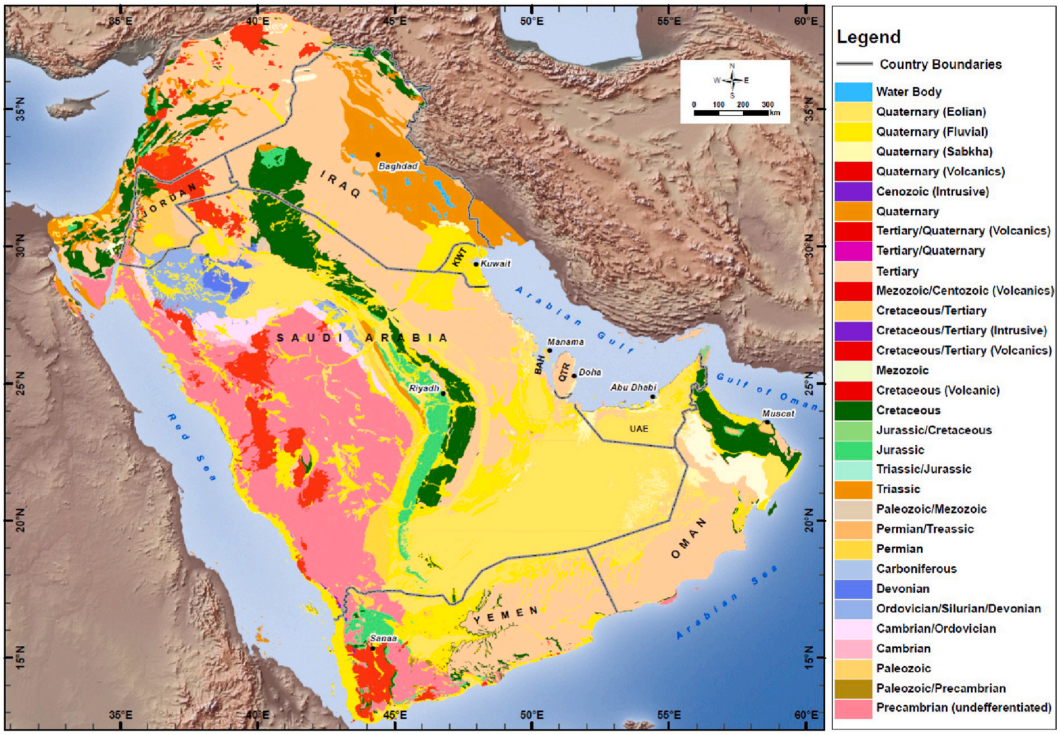

Fig. 2. Geological map of the Arabian Peninsula (database, National Water and Energy Center, UAE University).

between renewable resources and water demands. The most up-to-date information on available water resources in the GCC countries, consumption rates, and future opportunities is provided hereafter.

4.1. *Surface water*

Surface water is a scarce and nonperennial entity in all GCC countries due to geographical location and topography. Saudi Arabia has the highest annual renewable water resources of 2.4 km^3, followed by Oman and UAE, with values of 1.4 and 0.15 km^3, respectively. Renewable surface water is mostly absent in other GCC countries, i.e., Kuwait, Bahrain and Qatar [49]. The average annual rainfall varies between 70 and 130 mm except in the vicinity of the Gulf of Oman, the eastern shore, and the coastal zone along the Red Sea in southwestern Saudi Arabia, where the orographic rainfall may reach 500 mm/year. The region is dominated by an extremely hot climate, low rainfall frequency and high evaporation rate (greater than 3000 mm/year). In the southern parts of the AP, including the UAE, Oman and Saudi Arabia, surface water runoff is generated in low-lying areas due to scattered heavy rainfall events in winter and summer seasons [1,49].

The spatiotemporal distribution of hydroclimatic variables, such as the mean annual rainfall and temperature, represent the key parameters of regional water resource management and planning. The AP experiences a diverse spatial and temporal distribution of rainfall, with most areas receiving annual rainfall in only a few months and with no rainfall otherwise. Occasionally, the rainfall is only encountered in a few days in the form of intense bursts of rain over a short duration. Fig. 3 provides the average annual temporal distribution of rainfall and temperature over the last 30 years in the GCC countries.

The total annual precipitation volume in GCC countries varies significantly from one year to another. This variation has been more pronounced during the last two decades. For example, in 2008, the total annual precipitation volume was 115 billion m^3 (BCM). In 2013, the total volume of annual precipitation was estimated as 249 BCM, and in 2017, it was estimated as 172 BCM [50].

The highest rainfall in UAE is encountered in February and March. Spatially, the least rainfall is observed in the desert foreland, whereas the highest rainfall is recorded in the mountains and east coast regions. The highest temperature is observed in July and August. Bahrain, Kuwait and Qatar receive their major rainfall shares during January and December. The rainfall in the Sultanate of Oman is mostly encountered within the period March to June. The highest rainfall in Saudi Arabia is observed in March and April. In

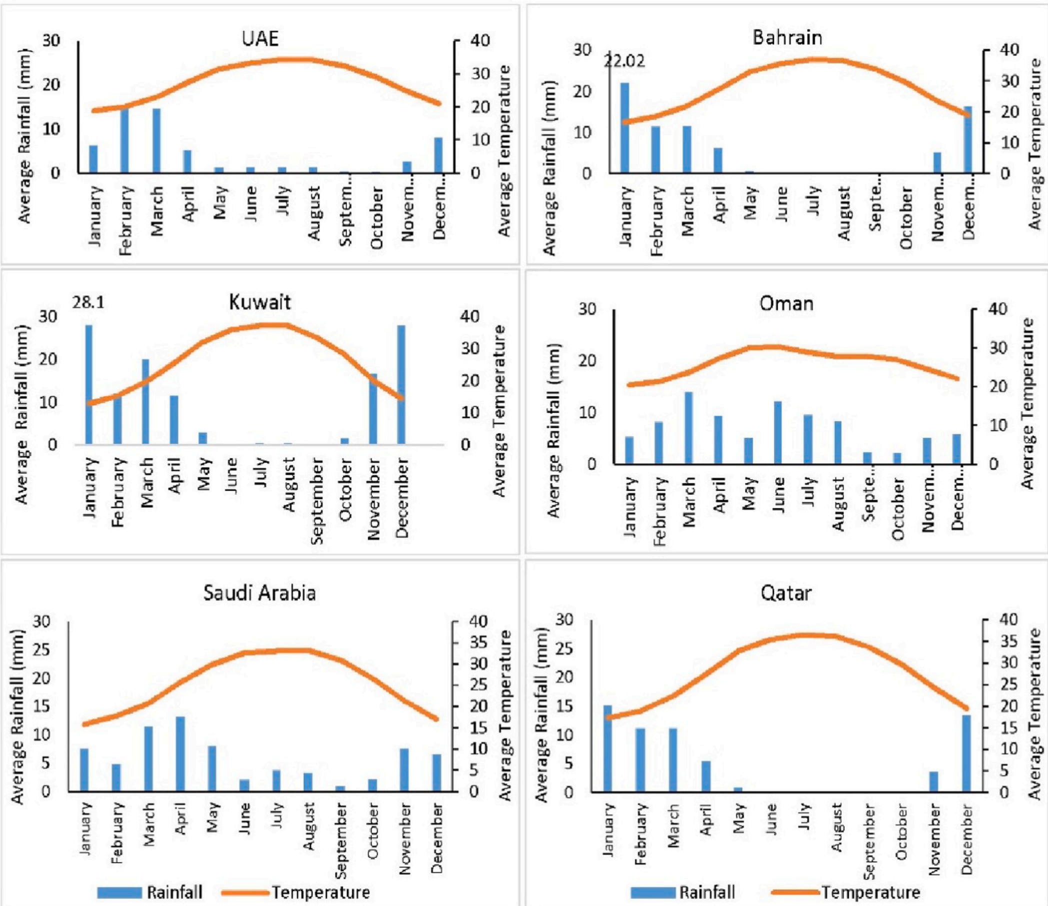

Fig. 3. Average annual variation in rainfall and temperature in GCC countries from 1991 to 2018 (source: [3]).

Table 2
Available surface water resources in the GCC countries.

Country	Area Km^2	Mean annual rainfall mm/y	Total dams' capacity MCM	Annual renewable surface water Km^3	Total annual renewable water resources Km^3	Annual renewable water per capita m^3
UAE	83600	78	61.07	0.1	0.15	15.2
Saudi Arabia	2149160	59	1004.06	2.2	2.4	70.6
Oman	309501	125	88.4	1.1	1.4	303.7
Kuwait	17818	121	0	0	0.02	4.7
Bahrain	652	83	0	0	0.116	77.33
Qatar	11610	74	0	0	0.05	17.42

Source [3,53]:

general, the southwestern areas of the AP receive the highest rainfall, while the northeastern and northwestern areas receive limited rainfall [51]. The highest temperature of the AP is reported during July and August, while the lowest temperature is encountered in January.

Considering the average annual precipitation, Saudi Arabia and Oman have the highest volumes of precipitation estimated at 126.8 and 38.7 BCM, respectively. UAE has an average precipitation volume of 6.5 BCM. Kuwait, Qatar, and Bahrain receive small amounts of precipitation volumes of 2.15, 0.9, and 0.054 BCM, respectively. Donat et al. [52] conducted a regional analysis of climatic extremes in the Middle East and showed a strong interannual variability in precipitation.

Due to rapid population growth, expansion in agriculture and industrial activities, and increase in living standards, the water demands in the GCC countries continued to increase. Despite the lack of renewable water resources, the per capita water consumption is approximately 200 m^3/year [9,49]. Oman has the highest renewable per capita freshwater (303.7 m^3/year), while Kuwait, UAE and Qatar have the lowest per capita renewable freshwater resources (Table 2). Fig. 4 provides the per capita water consumption in the GCC countries compared to other developed countries. Saudi Arabia, Oman and the UAE have the highest water consumption, mainly due to agricultural activities, followed by Bahrain, Qatar and Kuwait.

Many dams have been constructed across the main wadis in the GCC countries for surface water harvesting, groundwater recharge and protection from the hazards of flash floods. The storage capacity of all dams in the GCC countries is 1.155 BCM. A total of 302 detention and retention dams with a storage capacity of 1.004 BCM were built in Saudi Arabia [54]. In Oman, a total of 146 dams were constructed with a storage capacity of 0.088 BCM. The UAE has 130 dams with a storage capacity of 0.06 BCM [55].

4.2. Groundwater resources

Groundwater constitutes the primary source of natural water in the GCC countries. Renewable groundwater is encountered in shallow aquifers where the recharge is encountered through the alluvial deposits along the flood plains of drainage basins as well as main wadi channels. The total water storage in the shallow aquifers of the GCC countries, in addition to Yemen, is estimated as 131 BCM, while the average annual recharge is on the order of 3.5 BCM [56]. These shallow aquifers represent vital sources of portable water supply in urban and rural areas, primarily in Oman and Saudi Arabia. However, they are threatened by various anthropogenic activities (agriculture, industrial and domestic).

Non-renewable fossil groundwater is stored in sedimentary deep aquifers; mostly encountered in Saudi Arabia and Oman, with a small extent in other GCC countries. The fossil groundwater was formed during the rainy Pleistocene and Pliocene geological periods. The water storage in the deep aquifers is on the order of 2175 BCM, and the annual recharge that might be encountered through outcropping areas is approximately 2.7 BCM. The water quality in deep aquifers varies from one allocation to another and might be suitable for agricultural purposes [57].

The overexploitation of groundwater resources in the GCC countries to meet the surface water deficiency has caused a significant decline in groundwater levels, abandonment of production wells, dryness of springs, and acceleration of seawater intrusion into coastal aquifers. In 2013, the total pumping of groundwater resources in Saudi Arabia reached 22.65 BCM. In UAE and Oman, the total groundwater pumping during the same year was on the order of 2.013 and 1.30 BCM, respectively. The accumulative pumping from the other three GCC countries, including Kuwait, Bahrain and Qatar, was less than 0.65 BCM. The green desert policy and self-sufficiency in food products were associated with overexploitation of groundwater resources. Such policies have adversely affected the sustainability of groundwater resources in the region. Recently, Saudi Arabia considered corrective actions to preserve fossil groundwater resources by abandoning its 30-year program in the food self-sufficiency program after exhausting four-fifths of its deep fossil water.

4.2.1. Shared groundwater resources in GCC countries

Shared aquifers play an important role in water resource planning and management. Unlike surface water systems, aquifers are three-dimensional underground reservoirs with large storage capacities. Aquifers do not have visible linear features like surface water systems [58]. The proper understanding of groundwater systems requires a wide spectrum of geological information, including

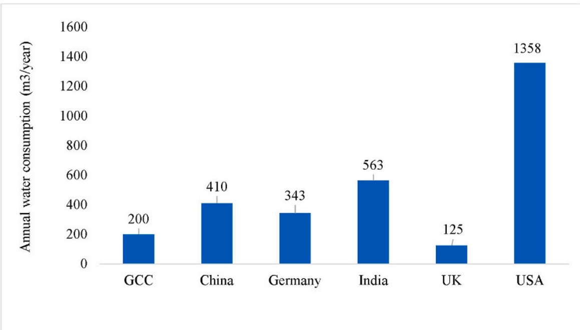

Fig. 4. A comparison of water consumption m^3/capita/year in GCC countries compared with other developed nations [53].

lithostratigraphy, geological structures and many other hydrogeological parameters. As a result, the transboundary groundwater flow is often unknown and not well defined. This situation is also applicable in the AP, where limited information is available on groundwater systems and pumping and recharge events [59].

Arid environment, scarce rainfall, high evaporation rates and absence of surface water resources are among the main challenges in the region. As such, the GCC countries are becoming more dependent on groundwater resources and the desalination of seawater [52]. Therefore, quantitative estimates of the temporal and spatial variability of groundwater storage can be useful in maintaining socio-economic development and managing the limited water resources [60]. Table 3 provides basic information related to transboundary aquifers (TBA) in GCC countries.

The Umm er Radhuma-Dammam (URD) is one of the largest TBA in the AP, extending into eight Arabian countries for 2200 km from northern Iraq to the southern coast of the AP. The aquifer is divided into three subsections (northern, central and southern). The URD aquifer consists of three Paleogene formations (the Dammam, the Rus and the Umm er Radhuma), which are spreading across the six GCC countries, Yemen and Iraq [63]. The southern part of the URD, covering an area of (797,987) km^2, is mainly replenished by Hadhramaut-Dhofar and from the Oman Mountains [64]. Sultan et al. [61] reported that Al-Rub al Khali groundwater basin has a recharge rate of 6–16 mm/year. The average annual abstraction volume varies between 7.7 and 45 MCM. The general distribution of salinity indicates that aquifers are being used as a potential source of freshwater in Oman and UAE.

The central portion of the URD covers an area of 345,213 km^2 (approximately 23% aquifer area), forming a wide structural platform extending from the Najd Plateau to Qatar, Bahrain and Saudi Arabia. It represents the only source of groundwater in Bahrain and Qatar. The average annual recharge of the central zone of the URD is 5.9 mm/yr [65]. Excessive groundwater extractions of 97, 91 and 608 MCM/yr from Bahrain, Qatar and Saudi Arabia have rendered the groundwater resources in this aquifer vulnerable to salinization. The major part of the Northern URD lies in Iraq, Kuwait and Saudi Arabia, covering an area of (297,943) km^{2,} where the average annual groundwater abstraction varies between 45 and 90 MCM. Excessive pumping from the central and northern parts of the URD caused a significant deterioration of its groundwater quality.

Saudi Arabia and Jordan's transboundary aquifer, known as the Saq aquifer, is located in the northern part of the AP, covering an area of 560,000 km^2, of which 15% of its area (82000 km^2) lies in Jordan with a storage reserve of 4–10 BCM. Eighty-five percent of its area (478,000 km^2) is located in Saudi Arabia with a water storage of 740 BCM [46]. The Saq aquifer system is composed of thick consecutive layers of Cambrian sandstone that overlie the crystalline basement rocks of red sea hills [66]. The water quality in the Saq aquifer is generally good and suitable for agricultural purposes, with total dissolved solids within the range 1000–1200 mg/l

Table 3
Transboundary groundwater aquifers in GCC countries. Source [46,61,62].

Aquifer Characteristics	Riparian Countries	Average Annual Abstraction MCM (Countrywise)	Aquifer Storage Volume BCM (Countrywise)	Rock type	Water Quality TDS (mg/l)	Water Use
Umm er Radhuma-Dammam Aquifer System (North)	Iraq, Kuwait, Saudi Arabia	45 90 NA	N/A	Fractured /karstic	Fresh to Hypersaline	Agriculture Industrial 'and Domestic
Umm er Radhuma-Dammam Aquifer System (Center)	Bahrain Qatar Saudi Arabia	97 91 608	90 2.5 235	limestone and dolomite, with some Evaporites	Mostly Fresh to Hypersaline in Coastal areas	Agricultural Irrigational Use Domestic and Industrial
Umm er Radhuma-Dammam Aquifer System (South)	Oman, Saudi Arabia, UAE, Yemen	45 NA 7.7 NA	180-1100 (For Najd Area)	Fractured /karstic	Fresh to hypersaline	Agriculture, Domestic and oil injection
Neogene Aquifer System (South-East),	Iraq, Kuwait, Saudi Arabia	370 88 NA	1.26 NA NA	Sand and Gravel	Brackish to Hypersaline	Mainly Agriculture
Tawil-Quaternary Aquifer System	Jordan, Saudi Arabia	100 3500	Total 22	Basalt, alluvium limestone	Fresh to Saline	Irrigation
Wasia-Biyadh-Aruma Aquifer System (North)	Iraq, Saudi Arabia	30–35 200–300	NA 500	Calcareous or argillaceous	Fresh to slightly brackish	Domestic and Irrigation
Wasia-Biyadh-Aruma Aquifer System (South)	Saudi Arabia, Yemen	Unknown, Very limited	500 [Total]	Siltstones sandstones	Fresh	Desert Nomads
Saq-Ram Aquifer System (West)	Jordan, Saudi Arabia	90 >1000	4–10 740	Sandstones	Mostly Fresh	Mainly Agriculture
Wajid Aquifer System	Saudi Arabia Yemen	2260 100	30–225 4–6	Sandstones	Fresh to slightly brackish	Agriculture, Industrial and Municipal

dominated by calcium (Ca2+) and bicarbonate (HCO3-). Annually, Saudi Arabia and Jordan abstract around 1000 and 90 MCM, respectively. The Wajid aquifer system is located at the crystalline edge of the Arabian Shield covering an area of 307,000 km^2 in Saudi Arabia, while its remaining area of 146,000 km^2 is in Yemen. The groundwater abstraction in Saudi Arabia is 2260 MCM/yr, whereas the abstraction in Sadad's plain of Yemen is on the order of 100 MCM/yr [67]. The water quality of this aquifer varies between fresh and slightly brackish. The groundwater quality in the Wajid aquifer of Yemen is still good.

The Neogene aquifer system (south-east) covers an area of 179,370 km^2 [66]. The average annual rainfall is 100 mm/yr, while in some areas, the rainfall exceeds 200 mm/yr, causing floods in Wadi al Batin. The average annual abstractions from Kuwait and Saudi Arabia are on the order of 88 and 378 MCM, respectively. The water quality in the Neogene aquifer is generally brackish to saline with notable lateral and vertical variations. The groundwater salinity increases vertically along the different lithological units as well as horizontally along the flow direction [46]. The Tawil Quaternary aquifer system lies between Jordan and Saudi Arabia and covers an area of 56,039 km^2.

The Wasia-Biyadh-Aruma aquifer, the largest sand dune aquifer in the world, is situated in the southwestern part of the Rub'al Khali depression, where sand dunes reach hundreds of meters in high stretches toward the Saudi-Yemen border. The water quality of the aquifer is fresh with a TDS within the range of 400–800 mg/l. The northern part, located in Iraq and Saudi Arabia, covers an area of 103,778 km^2 with calcareous or argillaceous deposits. The water in the northern part of the aquifer is brackish and is used for irrigating date palms [68].

4.2.2. Seawater intrusion

Seawater intrusion in the coastal aquifers represents a major challenge in the GCC countries. Alshehri et al. [69] collected groundwater samples from 115 boreholes and dug wells to document the influence of seawater intrusion and heavy metals contamination on the groundwater quality of Al Qunfudhah region along the Red Sea coast, Saudi Arabia. They concluded that dissolution, gypsum, halite, fluorite, silicates, agricultural activities and seawater intrusion were the key issues affecting groundwater quality and chemistry in this area. Alfaifi et al. [70] examined the level of saline water intrusion in the Ad-Darb region of southwestern Saudi Arabia by utilizing an integrated approach of geochemical and geophysical techniques. The base ion exchange, linear mixing, and seawater intrusion were identified as the main factors influencing the groundwater chemistry in this area. The seawater intrusion was mostly encountered in the unconsolidated Quaternary zone.

Kacimov et al. [71] studied the seawater intrusion in the shallow alluvial aquifer in the Bathinah area of Oman, experimentally, analytically, and numerically. The water table was proved to have a trough caused by intensive pumping from the fresh groundwater zone and evaporation from the saline phreatic surface. The seawater intrusion extended several kilometres inland. Resistivity traverses perpendicular to the shoreline indicated no fresh groundwater recharge into the sea. Shamas [72] investigated the seawater intrusion in the Salalah coastal aquifer of Oman. He reported that under the prevailing conditions, the groundwater levels in Salalah area would drop significantly allowing for the inland advancement of seawater. Ahmed and Askeri [73] studied the seawater intrusion impact on the groundwater quality of the northwest coast of Oman. The seawater intrusion was reported to extend inland up to 8 km from Oman's coast.

Sherif et al. [74] used MODFLOW to study the seawater intrusion in Fujairah Emirate, United Arab Emirates. Due to the significant increase of the groundwater pumping from Kalbha well field and the lack of natural replenishment from rainfall, groundwater levels have declined causing an intrusion of seawater in the coastal aquifer of Wadi Ham. As a result, many pumping wells in the coastal zone have been terminated and a number of farms have been abandoned. Sowe et al. [75] developed a 3D finite element model to investigate the possibility of pumping of brackish water from the costal aquifer of Wadi Ham to mitigate the seawater intrusion. The results indicated that the seawater intrusion might be halted by pumping brackish water.

Baalousha [34] investigated the optimum location, design and maximum yield of beach wells in Qatar using sweater intrusion model (SWI2), coupled with MODFLOW. It was found that a maximum pumping of 1600 $m^3/day/km^2$ of brackish water, with a total dissolved solid of less than 10,000 mg/l, would result in an obvious change in the saline-groundwater interface after 20 years of continuous pumping. The pumping of the brackish water has moved the interface downward. The pumped water can be used for reverse osmosis desalination plants.

The seawater intrusion from the Arabian Gulf as well as brackish/saline intrusion from underlaying groundwater zones pose a challenge for groundwater management in Bahrain. A significant net inflow of the seawater from the Arabian Gulf to the Khobar zone has been observed. Vast low-lying areas in the vicinity of the shoreline would be lost under the conditions of seawater level rise due to climate change extrapolating the seawater intrusion problem.

4.2.3. Managed aquifer recharge

Managed aquifer recharge (MAR) is the on-purpose recharge of water to aquifers for subsequent recovery or for environmental benefit. It is a key tool for regional water management, providing water supply resiliency and helping balance out the seasonal and periodic decreases in water availability with increasing demands. Parimalarenganayaki [76] presented a comprehensive review of the MAR techniques in the GCC Countries. Seven techniques were reported including dams, aquifer storage and recovery (ASR), aquifer storage transfer and recovery (ASTR), ponds, soil aquifer treatment (SAT), rooftop rainwater harvesting, and Karez/Ain system.

Many recharge dams were constructed in Saudi Arabia, UAE and Oman. Recharge dams are not common in Bahrain, Kuwait, and Qatar due to the relatively flat topography of those countries. The major disadvantages of recharge from dams in the GCC countries are high evaporation rates and siltation. The efficiency of recharge from dams was investigated by Ref. [77] and was found to vary significantly from one dam to another based soil type, accumulation of clay and slit layers, soil moisture and subsurface geology. The recharge efficiency can be improved by the use of injection wells.

Aquifer Storage and Recovery (ASR) has also been practiced in the GCC Countries to store water in aquifers and restore it when needed. Dawoud [78] reported that two recharge schemes using injection wells and infiltration basins were used for injecting desalinated water into the shallow groundwater system in Abu Dhabi. The recovery efficiency ranged between 85% and 90%. The lateral migration of the boundary of the freshwater plume was in the order of 0.2 m/d after 250 days of constant recharge. Khezri [79] indicated that for the large-scale ASR system in Liwa area, UAE, high efficiency can be achieved with multiple cycles of injection and recovery. Stuyfzand et al. [80] investigated the hydrogeological and hydrogeochemical stratification of the target aquifer in Liwa area and the changes in the water quality of the injected desalinated seawater. The pilot observations and modelling results indicated that under one of the investigated scenarios, the recovered water quality satisfied the drinking water quality standard with a recovery rate of up to 85%.

Missimer et al. [81] indicated that ASR systems are feasible only to meet peak day demands and short-term operation needs. The treated wastewater has been used as a sources water for ASR in the alluvial aquifer of western Wadi Qidayd in Saudi Arabia [82]. reported that the use of MAR for treatment and reuse of treated wastewater represents a feasible method to minimize the cost to supply safe drinking and irrigation water to rural areas in arid regions.

Alrukaibi and McKinney [83] indicated that efficiency of ASR systems would increase if the storage period (time between injection and recovery) is reduced. In Kabd area, Kuwait, the ASR operation involved 9 months of injection followed by 3 months of recovery with a rate of 100,000 m^3/day from 8 ASR wells with an efficiency of 77.42%. Through a pilot project in Sulaibiya area, Kuwait, a total of 16,790 m^3 of tertiary treated wastewater was injected through an open basin. The quality of the water has improved except for nitrate content [84]. Another study in Bahrain [59] reported that proper attention should be given to health, environmental, ecological, and social issues before using treated sewage effluent as a water source for MAR application.

El-Rawy et al. [63] investigated the hydrological and economic feasibility MAR using treated wastewater (TWW). MODFLOW was used to simulate different MAR scenarios and assess their efficiency in mitigating the seawater intrusion in the coastal aquifer of Jamma, Oman [85]. studied the effects of MAR using TWW in Al-Khawd coastal aquifer. The results showed that the relocation of pumping wells, better management of irrigation wells, and implementation MAR using TWW, the abstracted water for drinking purposes could be doubled.

4.3. Desalination

The desalination technology was introduced in the GCC countries in the mid-fifties of the last century. It gained popularity to encounter water shortages, achieve less reliance on dwindling groundwater resources and meet qualitative water requirements for domestic and industrial purposes [86]. The GCC countries are using multistage flash distillation (MSF) and multi-effect distillation (MED) technologies. A portion of the available fossil fuel is consumed by power desalination plants. Recently, reverse osmosis (RO), as well as other more advanced technologies, have been implemented. The dependence on desalination water continued to grow during the last two decades. Fig. 5 shows the annual capacity and production volume of desalinated water in GCC countries from 2007 to 2019. A gradual increase in both the capacity and production can be realized until 2016, with a sharp upsurge in 2017. Saudi Arabia

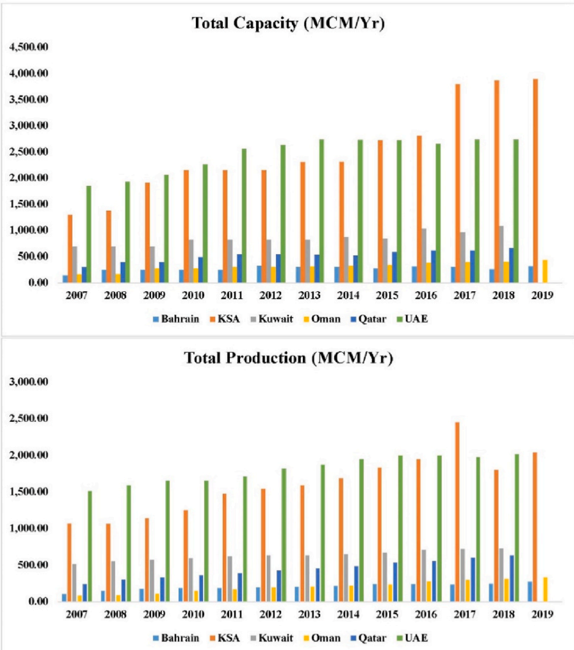

Fig. 5. Desalination capacity and production in the GCC countries, 2007–2019, in MCM [3,87]. [[,87] [][3,87][].

and the UAE have the highest desalination capacities, followed by Kuwait, Qatar, Bahrain, and Oman. Data for some countries are not available for 2019.

The GCC countries have the highest water desalination capacity at the global level. The net desalination capacity of the GCC countries amounts to approximately 26.4 MCM/day. The majority of the desalination plants are installed in Saudi Arabia (35%) and the UAE (33%) [87]. Fig. 5 further reveals that approximately 10% of the global production of desalination water is in Saudi Arabia, fulfilling 50% of the country's water demands. UAE is also focusing on increasing the capacity of its desalination plants. For instance, the Taweelah plant in Abu Dhabi (to be completed in 2022) will have a capacity of approximately 9.08 MCM per day and will constitute the world's largest reverse osmosis plant [88].

In terms of consumption, 87% of the water consumption in Qatar is supported by desalination water, followed by Saudi Arabia 50%, UAE 42%, Bahrain 36%, and Oman 27%. In addition, Oman is increasing its desalination capacity by 5% per year, with 86% of the country's domestic water being produced by desalination plants. Oman's desalination capacity is expected to increase steadily to reach 600 MCM/year in the next decade [89]. All GCC countries have made significant investments to upgrade existing desalination plants and establish new mega plants to meet the rising water demands in the different sectors. The distribution of the water consumption in the different sectors is provided in Table 4.

The desalinated water is dominantly used in the municipal sector except in Qatar and Bahrain, where consumption is biased toward industrial use (Table 4). Individually, the GCC countries aligned their water requirements according to local demands. For instance, the consumption of desalinated water in the military sector of KSA and UAE is relatively high. Overall, the municipal, industrial and tourist sectors consume more than 90% of the desalinated water in the GCC countries.

Desalination technologies are based on two main processes, i.e., thermal and membrane. Thermal-based multistage distillation technology is particularly preferred in GCC countries for two main reasons. First, it integrates water and power generation using residual heat from power plants, which greatly improves the economics of desalination. Second, it does not require costly water treatment processes that are needed for membrane-based technologies (reverse osmosis). In addition, proper maintenance and refurbishment can double the life of MSF plants [91]. The second energy-efficient thermal-based technology, especially used for small-scale plants in the GCC region, is known as multiple effect distillation combined with thermal vapor compression (MED). Saudi Arabia and the UAE have the largest production of desalinated water (1.1856 and 1.0858 MCM/day, respectively) by MED. However, with rising population and economic growth, Saudi Arabia and UAE are investing in large-scale RO plants. In the last ten years, a clear shift in adopting membrane-based desalination technology has been observed in the Middle East.

Hybrid desalination technology (HDT), merging thermal and membrane technologies, has been recently introduced in the GCC countries. The HDT is cost-effective and has the potential to dominate. The Ras Al-Khair plant in Saudi Arabia, with a capacity of 1.036 million m^3/day, is the largest plant in the world. It uses both thermal multistage flash (MSF) and reverse osmosis (RO) technologies [92]. The Fujairah-2 desalination plant is a hybrid plant with a capacity of 591,000 m^3/day, encompassing 450,000 m^3/day thermal production, 136,500 m^3/day RO facility and a 2000 MW power plant. Hybrid MED-RO helps to match seasonal water and power demands [92]. Other examples include the Umm Al Houl plant in Qatar with a production of 60 MIGD from RO and 76 MIGD from MSF systems [93] and Al-Jubail and Yanbu cogeneration plants in Saudi Arabia [94]. Currently, Saudi Arabia has the highest capacity for desalination (5.654 MCM/day) using RO, followed by UAE and Kuwait, Table 5.

Desalination plants entail considerable ecological and environmental impacts due to the release of the rejected water to oceans and emission of greenhouse gases. The urban air quality of GCC countries is showing signs of rising levels of pollution. Significant amounts of heavy metals are observed in the vicinity of fossil fuel-operated desalination plants. The high salinity and temperature of the discharged brine lower the dissolved oxygen concentration in seawater, which can adversely influence neighbouring ecosystems. Furthermore, the high concentration of chlorine in brine can add toxic substances that have a substantial impact on both aquatic flora and fauna [96].

The use of renewable energy in desalination, especially solar energy, is very promising due to its abundant availability in the GCC region. Masdar's Renewable Energy Desalination Pilot Program in the Ghantoot area, Abu Dhabi, is expected to accelerate the commercialization of renewable energy desalination systems. The project achieved energy efficiency improvements of up to 75% as compared to thermal desalination plants in UAE. The major challenge in commercializing large-scale plants is reducing the dependence on grid power as back-up when there is insufficient solar energy. In 2018, King Abdullah Economic City (KAEC) initiated the development of a solar desalination plant with a capacity of 30,000 m^3/day, expandable to 60,000 m^3/day. In 2019, the Kuwait Institute for Scientific Research (KISR), Kuwait, initiated a project to launch desalination plants using solar energy in northern Kuwait Bay. The Dubai Electricity and Water Authority (DEWA), UAE, has set an ambitious target to make a major shift toward the solar energy desalination plants by 2030. The GCC countries are expected to exceed the global target of 20% of new desalination plants

Table 4
Distribution trends of desalinated water consumption by sector (MCM/day) in Gulf countries [90].

Countary	UAE	Oman	Saudi Arabia	Kuwait	Bahrain	Qatar
Muncipal	2.691	0.374	2.159	0.946	0.159	0.570
Industary	2.142	0.223	1.959	0.705	0.377	0.789
Power	0.110	0.020	0.100	0.056	0.020	0.044
Miltary	0.165	0.000	0.201	0.037	0.000	0.000
Tourist	0.330	0.033	0.402	0.056	0.066	0.073
Irrigation	0.055	0.007	0.201	0.037	0.040	0.044

Table 5
GCC desalination capacities[a] (MCM/day) and breakdown per technology.

Country	Total Capacity	MSF	MED	RO	Other
UAE	8.9	6.0698	1.0858	1.7266	0.0178
Saudi Arabia	11.4	4.28	1.1856	5.6544	0.2736
Oman	1.1	0.3993	0.0836	0.6149	0.0022
Kuwait	2.6	1.8902	0.0026	0.7046	0
Bahrain	0.6	0.1014	0.2772	0.2214	0
Qatar	1.8	1.2492	0.3582	0.1764	0.0144
Total	26.4	13.9899	2.993	9.0983	0.308

[a] Source [95].

powered by renewable energy by 2025.

4.4. Treated wastewater in GCC countries

The capacity and production of wastewater treatment plants in the GCC countries are provided in Fig. 6. Some data are missing for 2018–2019, and hence, a downfall in the overall annual production in recent years is observed. Treated wastewater in the GCC is also linked to the total capacity and production of desalinated water. Saudi Arabia has the highest production of treated wastewater among the GCC countries [49,50]. UAE has a steady increase in its production capacity. The treatment of wastewater depends on numerous factors, including geography, population density in cities, and location of treatment facilities. For instance, the collection of domestic and industrial wastewater from densely populated areas would be more feasible and cost effective than that from low density and sparsely populated cities.

The produced wastewater contains harmful substances, such as heavy metals, bacteria, a range of pathogens, and viruses that deplete oxygen levels in marine ecosystems and cause the accumulation of nitrous oxide and the emission of methane. Eutrophication is also a common phenomenon along the Kuwaiti shorelines, which is frequently expanding and causing the red tide phenomena that are repeatedly observed along the coasts of GCC countries [98,99]. The red tide phenomenon is also occurring in Oman Sea and is spreading with higher frequency toward the Arabian Gulf as well as the western coast of UAE [100]. The use of treated wastewater is becoming indispensable for all GCC countries, given the cost of the production of desalinated water and the adverse impacts of desalination plants on the environment as well as the current rapid depletion of groundwater resources.

Treated wastewater is primarily used for irrigation, roadside landscaping, the development of parks, green areas, and fodder crops. There are approximately 300 plants installed in the GCC countries [49], and the majority of plants include secondary and tertiary treatments. Some plants in Kuwait are using ultrafiltration (UF) membranes and reverse osmosis (RO) water purification facilities to treat domestic wastewater with a capacity of 0.5 MCM/day [101].

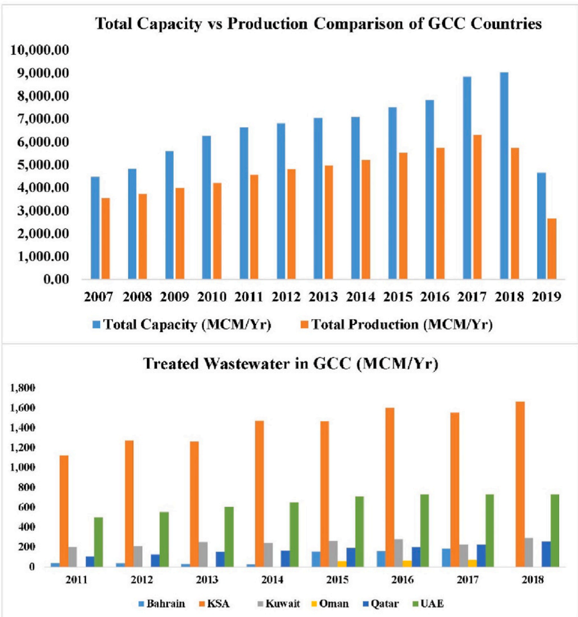

Fig. 6. Comparison of Capacity vs Production (a), Treated Wastewater in GCC countries by year (b), and treatment capacity vs volume of treated wastewater in each country (c) Sources [49,90,97].

A total of 97 sewage treatment plants, with a capacity of 1970 MCM/yr, are installed in Saudi Arabia, and other plants are under construction [97]. The overall reuse of treated wastewater at the country level is 43% [102]. reported that the reuse of treated wastewater can save up to 29% of the total industrial water withdrawals. The capacity of wastewater treatment plants in UAE is approximately 840 MCM/yr with an overall treatment volume of 653 MCM/yr (Fig. 6(c)). The majority of plants in UAE are run and owned by the Water and Electricity Authority of Abu Dhabi [3]The UAE is the leading country in the GCC region in privatization of the water and energy sector [98].

Kuwait was the first country to introduce wastewater treatment plants in the Middle East in the 1950s. The plants' treatment quality has shifted from secondary to tertiary processes. Currently, Kuwait is using advanced RO technology (Al-Sulaibiya plant) to treat water to attain potable water quality. The wastewater treatment capacity of Kuwait is 300 MCM/yr while the volume of treated wastewater reaches around 250 MCM/yr, Fig. 6(b and c). The "Zero Release" project was launched by the Ministry of Public Works in Kuwait, aiming to reuse all treated wastewater [98]. In Oman, around 67% of the total wastewater treatment capacity is utilized on annual basis while the government plans to double the capacity of the treatment plants by 2030 [87].

Bahrain installed 11 aeration-based wastewater treatment plants with an overall capacity of 135MCM/yr. The treated wastewater is used in agriculture, landscaping and sand washing. The overall capacity of wastewater treatment plants in Qatar is around 100 MCM/yr. The produced water is used in landscaping, crop irrigation and to recharge the limestone aquifer.

Although GCC countries are utilizing wastewater treatment technologies effectively, the use of treated wastewater is limited to agriculture, landscaping, feed, aquifer injection, and certain industries [54]. The major hurdles for the development and usage of treated wastewater include social acceptance, psychological aspects, unavailability of necessary infrastructure for redistribution of treated effluent, and religious issues. Options for the use of treated wastewater in the GCC countries include toilet flushing, air conditioning, recreational purposes, fountains, fire extinguishing and some highly water-intensive industries, such as boiler feeding and cooling [103]. Currently, huge volumes of treated and untreated wastewater are disposed into the sea. Major efforts are needed to raise awareness among the public about the acceptance and safety of the use of treated wastewater. Farming communities may also need to be encouraged to utilize sewage sludge instead of artificial manure, as it does not have harmful impacts on crops. Water distribution costs can be significantly reduced by creating multiple sector-based decentralized treatment plants to treat and reuse the wastewater where it is generated.

4.5. *Virtual water*

The term virtual water is defined as the total amount of water that is used to produce imported or exported products. Importing countries usually have water scarcity and lack rain-fed systems, whereas exporting countries usually have abundant rainfall and surface water systems [104]. The net virtual water traded is estimated by multiplying the unit water consumption of products by the annual volume of crops or livestock imported based on a trade matrix [105]. Agricultural and industrial water demands can be minimized through virtual water trades. For example, in 2000, Egypt's maize imports saved approximately 2.7 BCM of water [106]. In the GCC countries, water security is partially addressed through importing water-intensive agricultural and industrial products. Although groundwater is heavily used to reduce dependence on foreign food items, the GCC countries marked the highest net importers of virtual water.

Fig. 7 illustrates the total virtual water imports and water dependency ratio of individual GCC countries. A country's water dependency (defined as the ratio between external water footprint and total water footprint) represents an important factor in countries water resources management. A higher value of water dependency (on a scale of 100) indicates a high dependence on the water resources of other countries [107]. Fig. 7 shows that Saudi Arabia and UAE have the highest net imports of virtual water, with annual net values of 17.1 and 11.95 BCM, respectively. However, Bahrain and Kuwait have the highest water dependency among the GCC countries. The problem is further confounded by the fact that the internal water footprints are met largely through energy-intensive desalination and non-renewable groundwater. The demand for water in the GCC countries is increasing, with a proliferation of investment in supply capacity to meet the growing demands.

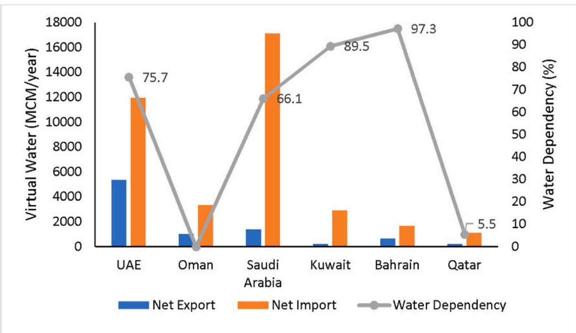

Fig. 7. Virtual water imports and exports and water dependency ratio for GCC countries.
Source [108]:

[109] elaborated that the cost of the long-distance water transfer would be in the range of 0.83 US$ per cubic meter and may reach up to 2.35 US$ when sustainability considerations are considered. On the other hand, the cost of seawater desalination has dropped from 5.5 US$ in 1979 to less than 0.55 US$ in 1999 using the RO technology. Therefore, while the concept of virtual water through importing high water consumption crops, the concept of long-distance water transfer (import water from other countries) might not be feasible.

5. Impacts of climate change

The GCC countries have a fragile desert environment. They hold 49.6% and 29.1% of the global oil and natural gas reserves, respectively. The success of climate mitigation and adaptation plans in the GCC countries is dependent on their ability to shift toward renewable clean energy sources such as solar and wind. The rapid increase in population and notable improvements in living standards have imposed additional demands for water and energy, specifically during summer seasons. Significant subsidies on water and energy consumption are provided. As a result, it is estimated that GCC countries are emitting CO2 higher than the average per capita in the world. This includes other industries and transportation emissions and is not limited to desalination [110]. Table 6 provides the current and historical trends of GHG emissions in the Arabian Gulf region. Saudi Arabia is ranked highest among the GCC countries in GHG emissions, with 660 million tons/year (Mt/year), followed by the UAE and Qatar, with 260 (Mt/year) and 250 (Mt/year), respectively. It is estimated that GHG emissions in the GCC countries increased by 121% from 1994 to 2005. The highest emissions have been observed in the industrial sector, with approximately 174% resulting from energy generation. Internationally, the three main sources of GHG emissions include industries, transportation and electricity and water generation. The contribution of each to the total emissions varies from one country to another.

Global climate change simulation models exhibited significant average warming trends in the GCC countries, with an increase of 0.81 °C per decade in UAE, 0.57 °C in Kuwait, 0.65 °C in Qatar, and 1.03 °C in Oman, considering the period from 1960 to 2010. In addition, an overall decrease in total annual precipitation of approximately 19.1 mm was observed in the AP during the same period [112]. An increase in warm days and a decrease in cold days and nights were also observed throughout the entire peninsula during the period 1960–2003 [113]. A study on heat wave extremes in GCC countries indicated that the intensity of these waves might reach beyond human survival by 2070 if no mitigation measures are implemented [114]. Similarly, the IPCC fifth assessment report indicated that coastal areas might be subjected to land submergence due to sea level rise [112].

Climate change may cause adverse impacts on water resources in the GCC countries. The expected environmental impacts would lead to groundwater depletion and salinization. For example, the Dammam aquifer (a shared aquifer by all GCC countries) might be depleted due to the expected reduction in rainfall and recharge and the increase in groundwater pumping. This raises concerns regarding the sustainability of groundwater resources in GCC countries [115]. As such, the desalination of seawater and brackish groundwater resources and the reuse of treated wastewater represent a feasible alternative to meet the increasing water demands under the conditions of climate change. On the other hand, the discharged brine water of the desalination plants has adverse impacts on the environment. It lowers the dissolved oxygen concentration and endangers the coral reef, fish spices and other marine life [116].

The increase in temperature due to climate change will lead to water losses and high evaporation. However, there is a high uncertainty regarding the magnitude of future changes in rainfall [117]. reported that climate models are projecting hotter, drier and less predictable climate, resulting in a drop-in water run-off by 20–23% in most MENA regions by 2050, mostly due to rising temperature and lower precipitation. Predictions reported that under the conditions of climate change, the overall groundwater recharge is expected to reduce by 5%–15%, but there is a high level of uncertainty associated with these values [57] The effects of climate change on groundwater include, a long-term decline in groundwater storage, increased frequency and severity of groundwater droughts, mobilization of pollutants due to seasonally high rainfall events, and saline water intrusion in coastal aquifers due to seawater level rise and recharge reduction.

The global shift toward renewable energy resources and low carbon economy provides opportunities for GCC countries to seek new economic positions by investing in the clean energy market [118]. Although fossil fuels still represent the main driver for the development, there is a clear shift toward the use of solar, nuclear and other sources of energy that minimize the emission of greenhouse gases. The GCC countries are committed to the Paris Agreement, and there is growing interest in studying the status of climate change in the region and its possible impacts. The governments of the GCC countries implemented a number of measures for assessment, mitigation and adaptation of the impacts of climate change.

The UAE established its green economy strategy for a sustainable future in 2012 [118]. The Emirate of Abu Dhabi aims to add 7% of

Table 6
Trends of GHG Emissions (million ton/year) in GCC Countries.

Year	UAE	Saudi Arabia	Oman	Kuwait	Bahrain	Qatar
1990	70	190	15	46	14	60
1995	91	260	19	57	18	76
2000	110	290	27	78	24	100
2005	160	370	33	110	30	150
2010	210	520	52	130	39	200
2016	260	660	76	159	47.1	250

Source [111]:

renewable energy in the system as a part of Integrated Energy Strategy 2030. A huge nuclear power plant with four reactors has been installed in the Baraka area, Abu Dhabi. The Plant's four APR1400 design nuclear reactors will supply up to 25% of the UAE's electricity needs once fully operational. Saudi Arabia has taken measures to minimize the impacts of climate change on water availability by using a high-efficiency irrigation system in 66% of the country's irrigated areas and encouraging farmers to use treated wastewater as an alternative source for groundwater [119]. A number of desalination plants are operated using solar energy [120].

The Government of Bahrain implemented certain measures to reduce the adverse impacts of climate change by following Kyoto Protocol, 2006, and the Statute of IRENA (the International Renewable Energy Agency). A National Authority has been established to use clean energy sources in future water projects. Kuwait has recently witnessed substantial growth in water and energy demands and is considered the world's third largest emitter of CO_2 [91]. The Kuwaiti Government has ratified the Kyoto Protocol 2006 and Paris Agreement to minimize the impacts of climate change. Mitigation and adaptation measures are considered, and renewable energy has been integrated into water-energy sectors. A comprehensive framework for socioeconomic sustainability was also prepared [121]. The 2035 vision of Kuwait indicates that 15% of energy sources should come from renewable energies by 2030 [122].

The Omani government prepared the National Water Resource Master Plan considering the impacts of climate change to meet rising water demands. Regulations have been set to achieve conservation and sustainable utilization of water and energy resources [123]. Although Qatar has doubled its desalinated water production since 2005, the country is still facing challenges in satisfying its demands. The increase of water and energy demands, under the influence of climate change, has a negative impact on country's economy. A number of studies have suggested utilizing concentrated solar power systems (CSP) and photovoltaic (PV) systems as renewable energy resources due to their suitable meteorological conditions [124,125].

6. Water resources challenges in the GCC countries

The annual natural water deficit in the GCC countries is estimated as 20 BCM. This deficit in the water budget is bridged by overexploitation of groundwater resources, installation of expensive desalination plants for municipal uses, and limited reuse of treated wastewater in the agricultural sector [126]. The Key challenges pertaining to water resources of GCC countries include.

1. The scarcity of water resources continues to increase over time due to population growth, agricultural practices, and general aridity.
2. Inefficient use of water in the domestic and agriculture sectors (high per capita water use, leakage from the distribution network, wasteful use in agriculture and archaic irrigation methods).
3. Rampant overuse of the groundwater resources leads to quality deterioration and introduce a variety of negative effects on ecosystems.
4. Negative impacts of climate change on already stressed water resources under the prevailing of extreme weather conditions
5. Acceleration of seawater intrusion in coastal aquifers due to excessive pumping.
6. Lack of groundwater recharge due to scarcity of rainfall and clogging of recharge ponds.
7. Leakage of contaminants from various industrial and domestic sources.

Considering above, it is concluded that the main water resources challenges are the scarcity of rainfall associated with the absence of surface water resources as well as the overuse of the non-renewable groundwater resources. Despite such limitations, the per capita use of water in the GCC countries is relatively high as compared to other countries in humid areas. These sustained problems have ramifications on the socioeconomic progress of the GCC countries and place a significant financial strain along with a detrimental effect on the environment. If the current groundwater pumping continues, its quality will deteriorate, and it might not be suitable for the different uses.

Most GCC countries depend heavily on non-renewable fossil groundwater, and the challenge of "sustainability" of non-renewable

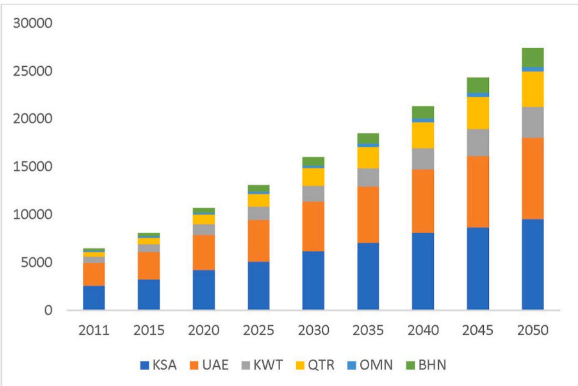

Fig. 8. GCC Water demand Forecast 2011–2050 km^3/year [127].

resources requires special attention. Currently, the water challenges in the GCC countries are commonly addressed through the management of the supply side rather than demand side. Another key problem is that, despite the GCC countries' current and projected reliance on desalination to supply residential and drinking water, desalination is considered an imported technology, with limited effort to develop these technologies within the region.

7. Future assessment and management for the year 2050

The future water demands of the GCC countries, based on current trends and projections, are shown in Fig. 8 [127]. Water shortages are expected to increase as a result of the increased demands and limited renewable supplies. Water resources from groundwater, desalination plants, and reclaimed wastewater are insufficient to meet the expected demands. The expected increase in domestic and industrial needs during the next 30 years necessitates the construction of additional desalination and wastewater treatment plants.

The water supply limitations and the increase in the water demands in all countries of the AP require the implementation and enhancement of water management practices and investment in efficient low-cost water desalination and wastewater treatment technologies [128]. The efficient management of water resources in GCC countries may include, among others, supply and demand management, surface water harvesting, augmentation of groundwater recharge, treatment and full utilization of wastewater, strengthening institutional arrangements and capacity building, and integrated plans to formulate and implement water policies and strategies. The feasibility of the implementation of improvements and studies related to cost-benefit analysis vary significantly from one country to another based on the specificity of each country, including local hydrology and hydrogeology, topography, water consumption per sector, available infrastructure, desalination and wastewater treatment plants, level of current government subsidies and others.

To meet the anticipated future water shortages, the GCC countries need to address three major challenges that will ultimately lead to sustainability. These challenges include optimum management of current and future water demands, strengthening the institutional framework, and increasing the water supply. A possible framework to address the future water challenges in the GCC includes the following.

7.1. Regulation of tariff structure

The regulations of water and wastewater tariffs represent a critical element in water demand management. The GCC governments are currently providing high subsidies for delivery and consumption of water and specifically for domestic and agricultural uses. Excessive water consumption by different users has a negative impact on water conservation and management policies. Therefore, appropriate water and wastewater tariffs may need to be imposed gradually to allow for the recovery of a major portion of investment while providing affordable water to all citizens. Fig. 9 shows the relationship between gross domestic product (GDP) and water tariffs in GCC countries and other developed nations.

7.2. Behavioural change

Extensive awareness campaigns and programs for different water users need to be implemented to prompt the behavioral change of consumers to value the water and avoid the wasteful use of potable water. Drinking and desalination water should not be used for other purposes, such as irrigation of backyards and care washing, where less quality water might be used.

Although several GCC ministries and water authorities have initiated such awareness activities, including advertisements, media

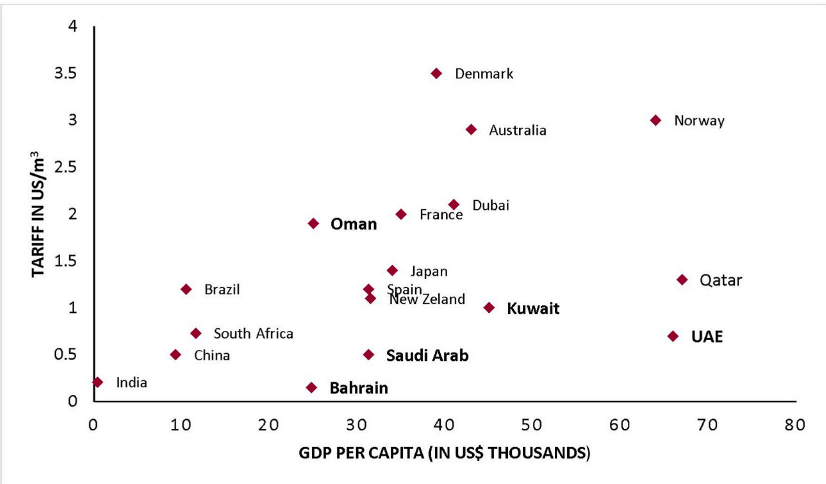

Fig. 9. Water tariff compared to GDP per capita, World Bank Indicators (2016) and GWI 2021 Strategy analysis.

campaigns, water days, and in some cases the distribution of efficient water fixtures, the outcomes are still not satisfactory. Educational programs at the different levels in schools and universities may need to be revised to include materials related to water resource conservation and sustainability. Incentives may need to be provided to promote water conservation practices.

7.3. *Water use efficiency in agriculture*

The agriculture sector in the GCC countries consumes more than 80% of the total available water resources, with highest consumption in Saudi Arabia, United Arab Emirates and Oman. In the meantime, the contribution of the agriculture sector to the economy is rather limited except for Saudi Arabia, in which the gross domestic product (GDP) contribution from the agricultural and fishery sector exceeded 17 billion $US in 2017. During the last two decades of the twentieth century, Saudi Arabia allowed the agriculture sector to consume large volumes of fossil groundwater to achieve food security. Vast areas were cultivated with wheat and other high-water demand crops. This has resulted in the depletion of major non-renewable groundwater reservoirs in Saudi Arabia. The water use efficiency in the agriculture sector is relatively low compared to other parts of the world due to extreme climatic conditions, high evaporation rates and less availability of monitoring practices in irrigation systems. Therefore, the GCC countries are currently focusing on reducing irrigation consumption by using efficient, precise, and smart irrigation systems for water conservation, subsurface irrigation and the use of soil additives to improve the soil characteristics. Fig. 10 provides the percentage of water consumption in the agriculture, domestic, and industrial sectors.

Recently, several GCC countries started to implement strict regulations to reduce water consumption in the agriculture sector. For instance, the Saudi Food Authority banned the cultivation of wheat in 2016 to conserve non-renewable groundwater resources. Abu Dhabi Food Control Authority, UAE, decided to replace rhodes grass with more water-efficient crops, such as buffelgrass. Several GCC countries are moving toward virtual water trade, i.e., acquiring agricultural lands in developing countries to conserve their own limited water resources. Table 7 provides land investment initiatives of GCC countries.

7.4. *Supply side management*

Supply-side management involves maximizing the usage of all available renewable water resources by constructing dams across the main wadis for water harvesting, flood prevention, and domestic and agricultural uses. Dams are also used for recharging groundwater resources if there is no direct use of the collected water after rainfall events. It is also important to identify communities and sectors whose water demands remain steady throughout the year and to build treated wastewater plants near such areas to reduce transportation costs.

Wastewater treatment plants (WWTPs) would be most efficient if large volumes of wastewater are collected from relatively small areas and the treated wastewater is reused in the same areas. A good example for efficient WWTPs can be seen in Dubai, UAE, where approximately 95% of the collected wastewater is treated and reused in the city. The other supply side management is related to minimizing the losses from water distribution networks. During the last decade, major projects have been implemented in the GCC countries to rehabilitate and upgrade water distribution systems. Monitoring devices have been installed to detect any leakage from water networks. This has significantly reduced the water losses.

Managed aquifer recharge (MAR) technology and its derivatives Soil Aquifer Treatment (SAT) and Aquifer Storage and Recovery (ASR) represent a new technique for supply side management [63,73,82]. A number of GCC countries started to investigate the use of MAR/SAT/ASR to improve water supply management and sustainability, including small- and large-scale flood capture and banking (MAR and ASR), tertiary wastewater treatment through SAT, and banking of desalination water in brackish aquifers (ASR).

The UAE has one of the world's largest operational ASR facilities, which is located in the Liwa area, Abu Dhabi Emirate. The surplus of desalinated water is infiltrated into the aquifer system through subsurface pipes to eliminate evaporation losses. The project aims to recover freshwater with a total dissolved solids (TDS) of approximately 400 ppm from more than 300 wells. It represents a benchmark for water management in desert regions and is set to redefine ASR international standards.

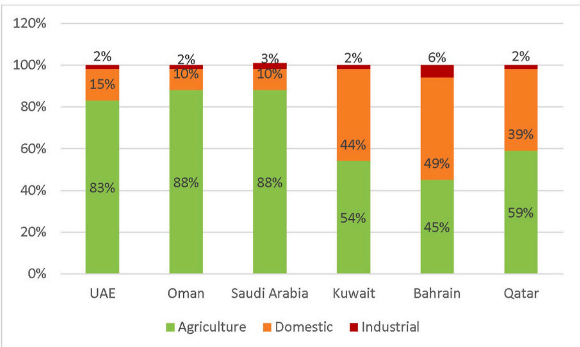

Fig. 10. Agricultural, Industrial and Domestic Water Consumption in GCC countries ([53,126]).

Table 7
GCC land investment in other countries for agriculture purposes [129].

Investor Countries	Host Countries	Crops Grown	Area (Ha)
UAE	Romania, Pakistan, Indonesia, Tanzania, Ghana, Sudan, Namibia, Egypt, Algeria, Morocco	Potato, citrus, fodder, rice, sugarcane, alfalfa, cereals, cotton, sunflower, peanuts and sorghum	188,27,39
Saudi Arabia	Philippine, Mali, Russia, Sudan, Pakistan, Zambia, Argentina, Nigeria and Ethiopia	Wheat, soybean, poultry items, mango, vegetables, banana, rice, fodder and pineapple	1,713,357
Oman	Philippine	Rice	N/A
Bahrain	Philippine	Rice and Banana	N/A
Kuwait	Philippine, Cambodia and Load	Rice and maize	N/A
Qatar	Australia, Sudan, India, Pakistan, Brazil Vietnam, Ghana, Cambodia	Poultry items, meat, wheat, barley, rice, cereals and citrus	642,630

7.5. Research and development

Research activities contribute to availability and sustainability of water resources. In the 1970s, when desalinated technology was introduced at the commercial scale, the cost of producing one cubic meter was US$ 5.5 compared to the current cost of less than US$ 1. However, further research is needed to reduce the energy consumption in desalination plants and solve problems related to membrane clogging. The use of renewable energy in desalination will resolve problems related to high emission of greenhouse gases from desalination plants. Significant research is currently in progress to improve the efficiency and reduce the cost of desalination plants incorporating hybrid systems and using solar energy. On the other hand, the current research and developments in treated wastewater technologies for municipal use and irrigation offer great opportunities to reduce the burden on other water resources. Similarly, the use of geothermal and solar energy will help reduce the cost of desalination and water treatment, and hence, nonconventional water resources will most likely become more dominant in the GCC countries during the coming two decades. Other ongoing innovative research includes cloud seeding to enhance rainfall and water harvesting from atmosphere.

7.6. Potential economic, social and political Constraints

A number of economic, social and political limitations might hinder the proposed framework and initiatives to resolve water resources challenges in the GCC Countries. The cost of producing freshwater through desalination is high as compared to other conventional water resources and in some cases may have undesirable environmental impacts in relation to disposal of brine water. Surface water harvesting would also require construction of huge dams and infrastructure and would require high investments, operational and maintenance cost. In addition, due to the flat nature of vast areas in the GCC Countries. Due to the lack of natural recharge, fresh groundwater resources might also be encountered hundreds of meters below the ground surface. In addition, the groundwater in coastal aquifers is subjected to seawater intrusion problem and possible deterioration due to climate change impacts.

The rapid population growth and the remarkable increase of foreign professionals and skilled labours continue to exert pressure on the limited available freshwater resources. High living standards and the excessive use of water to develop vast areas of green zone in the major cities and housing compounds may continue to pose a challenge for water conservation plans. In most GCC countries, the water is heavily subsidized by governments and the consumers pay less than half of its actual cost. Increasing the water tariffs might not be easily acceptable by the population.

The GCC Countries share the same aquifers and both surface and groundwater resources are transboundary in nature. However, water policies, regulations and price differ significantly from one country to another. In most cases, relevant water data, including groundwater levels and quality, groundwater pumping, aquifers characteristics and hydrological properties, rainfall intensities and durations, and others, are not fully shared among the water authorities in the different countries and hence hindering the proper planning and management of the water resources. Overall, a unified vision and approach might be needed to address water resources management and sustainability in the GCC Countries.

8. Conclusions

This paper provides a comprehensive review and assessment of water resources availability and demands of the different sectors in the GCC countries. The AP covers an area of 2.8 million km^2, with Saudi Arabia occupying 85% of this area. Based on the 2020 records, the population of the GCC countries was estimated at 57.38 million. Freshwater availability constitutes the main challenge to the sustainability of current economic prosperity. Various factors contribute to the limited availability of water resources, including scarcity and randomness of rainfall, limited natural recharge of aquifers, population growth, increase of living standards, increase of industrial water demands, wasteful use of water in the agriculture sector, and climate change.

The total renewable surface water resources in the GCC countries are estimated at 3.95 km^3, including 2.4 km^3 in Saudi Arabia, 1.4 km^3 in Sultanate of Oman, and 0.15 km^3 in UAE. The three countries have 578 dams with a total capacity of 1.155 BCM. The total surface water resources in Bahrain, Kuwait and Qatar is mostly insignificant (less than 0.075 km^3). Due to the flat topography, the three countries have no dams.

The total storage of potable groundwater resources in the shallow aquifers of GCC countries and Yemen is estimated to be 131 BCM;

however, the annual recharge is on the order of 3.5 BCM. The water storage in the deep aquifers of the GCC countries (mostly in Saudi Arabia and the Sultanate of Oman) is estimated at 2175 BCM with a possible annual recharge through outcropping areas of 2.7 BCM. Groundwater resources in deep aquifers are overexploited and are subjected to quality deterioration. The aquifers of the GCC countries are, in most cases, transboundary and represent shared resources.

Thermal, membrane and hybrid desalination technologies are used in GCC countries. The total capacity of the desalination plants in the GCC countries is 26.4 million m^3/day, of which Saudi Arabia and the UAE contribute approximately 20 million m^3/day. Desalinated water is mostly used for municipal, industrial and tourist activities, while limited amounts are used for power generation, military and irrigation activities. The GCC countries produce approximately 4000 MCM of wastewater per year, while the total capacity of treatment plants is on the order of 3675 MCM/y. Although tertiary treated, significant amounts of treated wastewater are disposed to the sea. Saudi Arabia and the UAE have the highest net imports of virtual water in the GCC countries, while Kuwait and Bahrain have the highest dependency on virtual water. Limiting the cultivation of water-intensive crops and increasing imported crops and livestock would help achieve water sustainability in the region.

Due to high dependency on fossil fuel, the emission of greenhouse gases has increased significantly during the last few decades. This has been associated with an increase in temperature and a decrease in annual precipitation. Low land coastal zones might be subjected to submergence due to sea level rise. However, the current shift toward renewable energy and low carbon industry provides feasible mitigations for undesirable impacts of climate change.

The water demands in the GCC countries will continue to increase. To meet the anticipated water challenges, the current water and wastewater tariffs may need to be reviewed to ensure the recovery of investments on the long term. Water losses from networks should be eliminated. Extensive awareness campaigns and educational programs need to be initiated to promote behavioural changes to eliminate wasteful use of water. The agriculture sector consumes more than 80% of the available water in the GCC countries, and hence water conservation in the agriculture sector has the highest priority. The use of efficient, precise and smart irrigation systems will help achieve water conservation and sustainability.

Enhancing water harvesting and groundwater recharge from rainfall events will contribute to water availability in the region. Implementation of managed aquifer recharge projects, where the excess of rainfall, desalination, and treated water can be stored and recovered during drought periods, may need to be considered at a larger scale. Further research is needed to reduce energy consumption in desalination plants and increase the use of solar, nuclear, and geothermal energy in desalination and water treatment plants.

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Data availability statement

The authors do not have permission to share data.

Declaration of competing interest

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

Acknowledgments

The authors would like to thank various ministries and water centers in the GCC countries for providing the required data used for the analysis in this paper.

References

[1] M. Sherif, Water availability and quality in the Gulf cooperation Council countries: implications for public health, Asia Pac. J. Publ. Health 22 (2010), https://doi.org/10.1177/1010539510373037.
[2] M.F. Al-Rashed, M.M. Sherif, Water resources in the GCC countries: an overview, Water Resour. Manag. 14 (2000) 59–75, https://doi.org/10.1023/A:1008127027743.
[3] World Bank The World Bank in the Gulf Cooperation Council Available online: https://www.worldbank.org/en/country/gcc.
[4] S.K. Sharma, A novel approach on water resource management with multi-criteria optimization and intelligent water demand forecasting in Saudi Arabia, Environ. Res. 208 (2022), 112578, https://doi.org/10.1016/j.envres.2021.112578.
[5] F. Alshehri, K. Abdelrahman, Groundwater resources exploration of harrat khaybar area, northwest Saudi Arabia, using electrical resistivity tomography, J. King Saud Univ. Sci. 33 (2021), 101468, https://doi.org/10.1016/j.jksus.2021.101468.
[6] K.N. Alrwis, A.M. Ghanem, O.S. Alnashwan, A.A.M. Al Duwais, S.A.B. Alaagib, N.M. Aldawdahi, Measuring the impact of water scarcity on agricultural economic development in Saudi Arabia, Saudi J. Biol. Sci. 28 (2021) 191–195, https://doi.org/10.1016/j.sjbs.2020.09.038.
[7] A. Alkhudhiri, N.B. Darwish, N. Hilal, Analytical and forecasting study for wastewater treatment and water resources in Saudi Arabia, J. Water Proc. Eng. 32 (2019), 100915, https://doi.org/10.1016/j.jwpe.2019.100915.
[8] D. Chandrasekharam, Water for the millions: focus Saudi Arabia, Water-Energy Nexus 1 (2018) 142–144, https://doi.org/10.1016/j.wen.2019.01.001.
[9] S. Albannay, S. Kazama, K. Oguma, T. Hashimoto, S. Takizawa, Water demand management based on water consumption data analysis in the emirate of Abu Dhabi, Water 13 (2021) 2827, https://doi.org/10.3390/w13202827.

[10] A. Al-Othman, M. Tawalbeh, M. El Haj Assad, T. Alkayyali, A. Eisa, Novel multi-stage flash (MSF) desalination plant driven by parabolic trough collectors and a solar pond: a simulation study in UAE, Desalination 443 (2018) 237–244, https://doi.org/10.1016/j.desal.2018.06.005.
[11] Y. Ibrahim, H.A. Arafat, T. Mezher, F. AlMarzooqi, An integrated framework for sustainability assessment of seawater desalination, Desalination 447 (2018) 1–17, https://doi.org/10.1016/j.desal.2018.08.019.
[12] N. Nedaei, S. Azizi, L.G. Farshi, Performance assessment and multi-objective optimization of a multi-generation system based on solar tower power: a case study in Dubai, UAE, Process Saf. Environ. Protect. 161 (2022) 295–315, https://doi.org/10.1016/j.psep.2022.03.022.
[13] T. Salameh, A.G. Olabi, M.K.H. Rabaia, M. Alkasrawi, E. Abdelsalam, M. Ali Abdelkareem, Economic and environmental assessment of the implementation of solar chimney plant for water production in two cities in UAE, Therm. Sci. Eng. Prog. 33 (2022), 101365, https://doi.org/10.1016/j.tsep.2022.101365.
[14] T. Shivakumar, V. Razaviarani, An integrated approach to enhance the desalination process: coupling reverse osmosis process with microbial desalination cells in the UAE, Water Sci. Technol. Water Supply 21 (2021) 1127–1143, https://doi.org/10.2166/ws.2020.375.
[15] M. Batarseh, E. Imreizeeq, S. Tilev, M. Al Alaween, W. Suleiman, A.M. Al Remeithi, M.K. Al Tamimi, M. Al Alawneh, Assessment of groundwater quality for irrigation in the arid regions using irrigation water quality Index (IWQI) and GIS-zoning maps: case study from Abu Dhabi emirate, UAE, Groundwater for Sustainable Development 14 (2021), https://doi.org/10.1016/j.gsd.2021.100611.
[16] S. Elmahdy, T. Ali, M. Mohamed, Regional mapping of groundwater potential in Ar Rub al Khali, arabian peninsula using the classification and regression trees model, Rem. Sens. 13 (2021), https://doi.org/10.3390/rs13122300.
[17] M.U. Liaqat, M.M. Mohamed, R. Chowdhury, S.I. Elmahdy, Q. Khan, R. Ansari, Impact of land use/land cover changes on groundwater resources in Al ain region of the United Arab Emirates using remote sensing and GIS techniques, Groundwater for Sustainable Development 14 (2021), https://doi.org/10.1016/j.gsd.2021.100587.
[18] R. AL-Ruzouq, A. Shanableh, T. Merabtene, Geomatics for Mapping of Groundwater Potential Zones in Northern Part of the United Arab Emiratis-Sharjah City 40 (2015) 581–586.
[19] R. Al-Ruzouq, A. Shanableh, T. Merabtene, M. Siddique, M.A. Khalil, A. Idris, E. Almulla, Potential groundwater zone mapping based on geo-hydrological considerations and multi-criteria spatial analysis: north UAE, Catena 173 (2019) 511–524, https://doi.org/10.1016/j.catena.2018.10.037.
[20] S.I. Elmahdy, M.M. Mohamed, Probabilistic frequency ratio model for groundwater potential mapping in Al jaww plain, UAE, Arabian J. Geosci. 8 (2015) 2405–2416, https://doi.org/10.1007/s12517-014-1327-9.
[21] I.B. Salem, Y. Nazzal, F.M. Howari, M. Sharma, J.K. Mogaraju, C.M. Xavier, Geospatial assessment of groundwater quality with the distinctive portrayal of heavy metals in the United Arab Emirates, Water (Switzerland) 14 (2022), https://doi.org/10.3390/w14060879.
[22] M.S.M. Alasam Alzaabi, T. Mezher, Analyzing existing UAE national water, energy and food nexus related strategies, Renew. Sustain. Energy Rev. 144 (2021), 111031, https://doi.org/10.1016/j.rser.2021.111031.
[23] M.T. Mahmoud, M.A. Hamouda, M.M. Mohamed, Spatiotemporal evaluation of the GPM satellite precipitation products over the United Arab Emirates, Atmos. Res. 219 (2019) 200–212, https://doi.org/10.1016/j.atmosres.2018.12.029.
[24] Y. Wehbe, D. Ghebreyesus, M. Temimi, A. Milewski, A. Al Mandous, Assessment of the consistency among global precipitation products over the United Arab Emirates, J. Hydrol.: Reg. Stud. 12 (2017) 122–135, https://doi.org/10.1016/j.ejrh.2017.05.002.
[25] R. McDonnel, Groundwate Use and Policies in Oman, IWMI Project Report, 2017.
[26] B. Askri, A.T. Ahmed, R. Bouhlila, Origins and processes of groundwater salinisation in barka coastal aquifer, sultanate of Oman, Phys. Chem. Earth 126 (2022), https://doi.org/10.1016/j.pce.2022.103116.
[27] H. Barghash, Preliminary evaluation of an on-site, low-energy, in: Natural Treatment of Domestic Wastewater: Case Study of Selected Constructed Wetland in Oman, vol. 2409, 2021.
[28] O. Ragab, OMAN WATER RESOURCES CHALLENGES BETWEEN THE PRESENT AND THE FUTURE, 2015.
[29] B. Al Maqbali, Z. Rahimi-Ahar, H. Mousa, G.R. Vakili-Nezhaad, Proposing an ultrapure water unit coupled to an existing reverse osmosis desalination plant and its exergy analysis, Int. J. Therm. 25 (2022) 39–52, https://doi.org/10.5541/ijot.930459.
[30] M. Al-Abri, H.H. Kyaw, B. Al-Ghafri, M.T.Z. Myint, S. Dobretsov, Autopsy of used reverse osmosis membranes from the largest seawater desalination plant in Oman, Membranes 12 (2022), https://doi.org/10.3390/membranes12070671.
[31] A. Wazwaz, M.S. Khan, Improved and Modified Design of Seawater Solar Desalinator Prototype, 2020.
[32] A.S. Al-Huwaishel, A. Elmi, A. Mukhopadhyay, Aquifer storage of treated wastewater for subsequent recovery as an important strategy for sustainable water security in Kuwait, Water Supply 22 (2022) 2067–2081, https://doi.org/10.2166/ws.2021.296.
[33] A. Alsulaili, M. Alkandari, A. Buqammaz, Assessing the impacts of meteorological factors on freshwater consumption in arid regions and forecasting the freshwater demand, Environmental Technology and Innovation (2022) 25, https://doi.org/10.1016/j.eti.2021.102099.
[34] H. Baalousha, Groundwater vulnerability mapping of Qatar aquifers, J. Afr. Earth Sci. 124 (2016), https://doi.org/10.1016/j.jafrearsci.2016.09.017.
[35] H.M. Baalousha, B. Tawabini, T.D. Seers, Fuzzy or non-fuzzy? A comparison between fuzzy logic-based vulnerability mapping and drastic approach using a numerical model. A case study from Qatar, Water (Switzerland) 13 (2021), https://doi.org/10.3390/w13091288.
[36] S.B. Ajjur, S.G. Al-Ghamdi, Is Managed Aquifer Recharge a Feasible Solution for Groundwater Deterioration in Qatar? (2022) 168–175.
[37] H. Bilal, R. Govindan, T. Al-Ansari, Investigation of groundwater depletion in the state of Qatar and its implication to energy water and food nexus, Water (Switzerland) 13 (2021), https://doi.org/10.3390/w13182464.
[38] D. Jacob, P. Ackerer, H.M. Baalousha, F. Delay, Large-scale water storage in aquifers: enhancing Qatar's groundwater resources, Water (Switzerland) 13 (2021), https://doi.org/10.3390/w13172405.
[39] M. Haji, R. Govindan, T. Al-Ansari, A computational modelling approach based on the 'energy - water - food nexus node' to support decision-making for sustainable and resilient food security, Comput. Chem. Eng. (2022) 163, https://doi.org/10.1016/j.compchemeng.2022.107846.
[40] G.M. Kadhem, W.K. Zubari, Identifying optimal locations for artificial groundwater recharge by rainfall in the kingdom of Bahrain, Earth Systems and Environment 4 (2020) 551–566, https://doi.org/10.1007/s41748-020-00178-2.
[41] M.A. Al-Noaimi, SDG goal 6 monitoring in the kingdom of Bahrain, Desalination Water Treat. 176 (2020) 406–427, https://doi.org/10.5004/dwt.2020.25552.
[42] S.A. Mutawa, S.A. Jazeeri, M. Kamil, W. Zubari, A. El-Sadek, Development of benchmarking system for the wastewater sector in the kingdom of Bahrain, Desalination Water Treat. 176 (2020) 345–354, https://doi.org/10.5004/dwt.2020.25543.
[43] S. Bani, Efficient use of water for food production through sustainable crop management: kingdom of Bahrain, Desalination Water Treat. 176 (2020) 213–219, https://doi.org/10.5004/dwt.2020.25519.
[44] J. Warburton, T.J. Burnhill, R.H. Graham, K.P. Isaac, The evolution of the Oman mountains foreland basin, Geological Society, London, Special Publications 49 (1990) 419–427, https://doi.org/10.1144/GSL.SP.1992.049.01.26.
[45] H.S. Edgell, Geological Framework of Saudi Arabian Groundwater Resources, 1989.
[46] UN-ESCWA, United nations economic and social commission for western Asia. http://Waterinventory.Org/Sites/Waterinventory.Org/Files/00-Inventory-of-Shared-Water-Resources-in-Western-Asia-Web.Pdf, 2013.
[47] F.M. Al_Ruwaih, Hydrogeology and groundwater geochemistry of the clastic aquifer and its assessment for irrigation, southwest Kuwait, in: Aquifers: Matrix and Fluids, Intech Open, 2017.
[48] M. Alhaj, S. Mohammed, M. Darwish, A. Hassan, S. Al Ghamdi, A review of Qatar's water resources, consumption and virtual water trade, Desalination Water Treat. (2017) 70–85, https://doi.org/10.5004/dwt.2017.21246.
[49] A.S. Qureshi, Challenges and prospects of using treated wastewater to manage water scarcity crises in the Gulf cooperation Council (GCC) countries, Water 12 (2020) 1971, https://doi.org/10.3390/w12071971.
[50] Statista Statista, Available online: https://www.statista.com/statistics/800196/gcc-annual-precipitation-volume/.
[51] H. Hasanean, M. Almazroui, Rainfall: features and variations over Saudi Arabia, A review, Climate 3 (2015) 578–626, https://doi.org/10.3390/cli3030578.

[52] M.G. Donat, T.C. Peterson, M. Brunet, A.D. King, M. Almazroui, R.K. Kolli, D. Boucherf, A.Y. Al-Mulla, A.Y. Nour, A.A. Aly, et al., Changes in extreme temperature and precipitation in the Arab region: long-term trends and variability related to ENSO and NAO, Int. J. Climatol. 34 (2014) 581–592, https://doi.org/10.1002/joc.3707.
[53] Aquastat, F. AQUASTAT - FAO's Global Information System on Water and Agriculture Available online: https://www.fao.org/aquastat/en/(accessed on 19 May 2023).
[54] S. Chowdhury, M. Al-Zahrani, Water resources and water consumption pattern in Saudi Arabia, in: Proceedings of the Proceedings of the 10th Gulf Water Conference, At Doha, Qatar, 2012, pp. 22–24.
[55] ICOLD International Commission on Large Dams Available online: https://www.icold-cigb.org/(accessed on 19 May 2023).
[56] W. Al-Zubari, The Cost of Municipal Waster Supply in Bahrain, vol. 1, MENA Network of Water Centers of Excellence, 2014.
[57] UNDP, United nations development programme, Available online, https://www.undp.org/. (Accessed 19 May 2023).
[58] J. Davies, N.S. Robins, J. Farr, J. Sorensen, P. Beetlestone, J.E. Cobbing, Identifying transboundary aquifers in need of international resource management in the southern african development community region, Hydrogeol. J. 21 (2013) 321–330, https://doi.org/10.1007/s10040-012-0903-x.
[59] Ahmed; Al-Zubari, W.; El-Sadek, A.; Al-Noaimi, M.A. The feasibility and health risk assessment of groundwater recharge by TSE in the kingdom of Bahrain. In Proceedings of the Proceedings of the WSTA; Qatar, April 2012.
[60] J.S. Famiglietti, M. Lo, S.L. Ho, J. Bethune, K.J. Anderson, T.H. Syed, S.C. Swenson, C.R. de Linage, M. Rodell, Satellites measure recent rates of groundwater depletion in California's central valley, Geophys. Res. Lett. 38 (2011), https://doi.org/10.1029/2010GL046442.
[61] M. Sultan, N. Sturchio, S. Al Sefry, A. Milewski, R. Becker, I. Nasr, Z. Sagintayev, Geochemical, isotopic, and remote sensing constraints on the origin and evolution of the Rub Al Khali aquifer system, arabian peninsula, J. Hydrol. 356 (2008) 70–83, https://doi.org/10.1016/j.jhydrol.2008.04.001.
[62] M.J. Abdulrazzak, P.D. Oikonomou, N.S. Grigg, Transboundary groundwater cooperation among countries of the arabian peninsula, J. Water Resour. Plann. Manag. 146 (2020), 05019023, https://doi.org/10.1061/(ASCE)WR.1943-5452.0001140.
[63] M. El-Rawy, A. Al-Maktoumi, S. Zekri, O. Abdalla, R. Al-Abri, Hydrological and economic feasibility of mitigating a stressed coastal aquifer using managed aquifer recharge: a case study of Jamma aquifer, Oman, J. Arid Land 11 (2019) 148–159, https://doi.org/10.1007/s40333-019-0093-7.
[64] W.W. Bank, Beyond Scarcity: Water Security in the Middle East and North Africa, World Bank Publications, 2017.
[65] Y. Harhash, Groundwater in Qatar, Summary of Hydrological Studies and Results, 1985.
[66] N. A.E, A.S. Alsharhan, Sedimentary Basins and Petroleum Geology of the Middle East, first ed., Elsevier, USA, 1997, p. 6, 1.
[67] A. Al Shami, S. Al Dubby, Yemen-Saudi Shared Aquifer, Wajid Sandstone), 2004.
[68] Vincent, P. Saudi Arabia: an Environmental Overview; CRC Press; ISBN 978-0-367-38781-5.
[69] F. Alshehri, S. Almadani, A.S. El-Sorogy, E. Alwaqdani, H.J. Alfaifi, T. Alharbi, Influence of seawater intrusion and heavy metals contamination on groundwater quality, Red Sea coast, Saudi Arabia, Mar. Pollut. Bull. 165 (2021), 112094, https://doi.org/10.1016/j.marpolbul.2021.112094.
[70] H. Alfaifi, A. Kahal, A. Albassam, E. Ibrahim, K. Abdelrahman, F. Zaidi, S. Alhumidan, Integrated geophysical and hydrochemical investigations for seawater intrusion: a case study in southwestern Saudi Arabia, Arab J Geosci 12 (2019) 372, https://doi.org/10.1007/s12517-019-4540-8.
[71] A. Kacimov, S. Al-Jabri, M. Sherif, S. Al-Shidi, Slumping of groundwater mounds: revisiting the polubarinova-kochina theory, Hydrol. Sci. J. 54 (2009) 174–188, https://doi.org/10.1623/hysj.54.1.174.
[72] M.I. Shamas, Sustainable Management of the Salalah Coastal Aquifer in Oman Using an Integrated Approach, Thesis, Royal Institute of Technology, KTH, Sweden, 2007.
[73] A.T. Ahmed, B. Askri, Seawater intrusion impacts on the water quality of the groundwater on the northwest coast of Oman, Water Environ. Res. 88 (2016) 732–740.
[74] M. Sherif, A. Kacimov, A. Javadi, A.A. Ebraheem, Modeling groundwater flow and seawater intrusion in the coastal aquifer of wadi Ham, UAE, Water Resour. Manag. 26 (2012) 751–774, https://doi.org/10.1007/s11269-011-9943-6.
[75] M.A. Sowe, S. Sadhasivam, M. Mostafa Mohamed, S. Mohsen, Modeling the mitigation of seawater intrusion by pumping of brackish water from the coastal aquifer of wadi Ham, UAE, Sustain. Water Resour. Manag. 5 (2019) 1435–1451, https://doi.org/10.1007/s40899-018-0271-3.
[76] S. Parimalarenganayaki, Managed aquifer recharge in the Gulf countries: a review and selection criteria, Arabian J. Sci. Eng. 46 (2021), https://doi.org/10.1007/s13369-020-05060-x.
[77] R. Parimala, Managed Aquifer Recharge an Integrated Approach for Assessing the Impact of a Check Dam, Faculty of Civil Engineering, Anna University, 2014.
[78] M. Dawoud, Strategic water reserve using aquifer recharge with desalinated water in Abu Dhabi emirate, Desalination Water Treat. 176 (2020) 123–130, https://doi.org/10.5004/dwt.2020.25505.
[79] S. Khezri, Evaluation of the Aquifer Storage and Recovery Pilot Project in Liwa Area, Emirate of Abu Dhabi, UAE. thesis, 2010.
[80] P.J. Stuyfzand, E. Smidt, K.G. Zuurbier, N. Hartog, M.A. Dawoud, Observations and prediction of recovered quality of desalinated seawater in the strategic ASR project in Liwa, Abu Dhabi, Water 9 (2017) 177, https://doi.org/10.3390/w9030177.
[81] T.M. Missimer, W. Guo, R.G. Maliva, J. Rosas, K.Z. Jadoon, Enhancement of wadi recharge using dams coupled with aquifer storage and recovery wells, Environ. Earth Sci. 73 (2015) 7723–7731.
[82] T.M. Missimer, R.G. Maliva, N. Ghaffour, T. Leiknes, G.L. Amy, Managed aquifer recharge (MAR) economics for wastewater reuse in low population wadi communities, kingdom of Saudi Arabia, Water 6 (2014) 2322–2338, https://doi.org/10.3390/w6082322.
[83] D. AlRukaibi, D.C. McKinney, Conceptual Designing and Numerical Simulation of the ASR Technique Operations - Case Study Kuwait, 2013, pp. 2601–2613, https://doi.org/10.1061/9780784412947.258.
[84] m Al-Otaibi, M. Al-Senafy, Recharging aquifers through surface ponds: hydraulic behaviour, Emirates Journal for Engineering Research 9 (2004) 21–27.
[85] A. Al-Maktoumi, M. El-Rawy, S. Zekri, Management options for a multipurpose coastal aquifer in Oman, Arab J Geosci 9 (2016) 636, https://doi.org/10.1007/s12517-016-2661-x.
[86] H. Hashemi, R. Berndtsson, M. Kompani-Zare, M. Persson, Natural vs. Artificial groundwater recharge, quantification through inverse modeling, Hydrol. Earth Syst. Sci. 17 (2013) 637–650.
[87] GCC STAT GCC Statistical Center - Home Available online: https://www.gccstat.org/en/(accessed on 19 May 2023).
[88] A. Al Bloushi, A. Giwa, T. Mezher, A. Hasan, Environmental impact and technoeconomic analysis of hybrid MSF/RO desalination: the case study of Al Taweelah A2 plant, in: Sustainable Desalination Handbook, 2018.
[89] A. Zapata-Sierra, M. Cascajares, A. Alcayde, F. Manzano-Agugliaro, Worldwide research trends on desalination, Desalination 519 (2021), 115305, https://doi.org/10.1016/j.desal.2021.115305.
[90] A. Gcc, GCC Statistical Atlas (2019) 2020.
[91] R. Ferroukhi, A. Khalid, D. Hawila, D. Nagpal, L. El-Katiri, V. Fthenakis, A. Al Fara, Renewable Energy Market Analysis—The GCC Region, 2016.
[92] Water purification systems - wastewater treatment, Available online, https://www.aquatech.com/. (Accessed 19 May 2023).
[93] S. Javaid Zaidi, Desalination in Qatar: present status and future prospects, 6, in: Proceedings of the Civil Engineering Research Journal, 2018. December 7.
[94] O.A. Hamed, Overview of hybrid desalination systems — current status and future prospects, Desalination 186 (2005) 207–214, https://doi.org/10.1016/j.desal.2005.03.095.
[95] IRENA – International Renewable Energy Agency Available online: https://www.irena.org/(accessed on 19 May 2023).
[96] J. Morillo, J. Usero, D. Rosado, H. El Bakouri, A. Riaza, F.-J. Bernaola, Comparative study of brine management technologies for desalination plants, Desalination 336 (2014) 32–49, https://doi.org/10.1016/j.desal.2013.12.038.
[97] O.K.M. Ouda, Treated wastewater use in Saudi Arabia: challenges and initiatives, Int. J. Water Resour. Dev. 32 (2016) 799–809, https://doi.org/10.1080/07900627.2015.1116435.
[98] E. Aleisa, W. Al-Zubari, Wastewater reuse in the countries of the Gulf cooperation Council (GCC): the lost opportunity, Environ. Monit. Assess. 189 (2017) 553, https://doi.org/10.1007/s10661-017-6269-8.

[99] M.R. Jumat, N.A. Hasan, P. Subramanian, C. Heberling, R.R. Colwell, P.-Y. Hong, Membrane bioreactor-based wastewater treatment plant in Saudi Arabia: reduction of viral diversity, load, and infectious capacity, Water 9 (2017) 534, https://doi.org/10.3390/w9070534.

[100] G. Ceriola, V. Avgikou, P. Manunta, Integrated Use of MERIS and Other EO Data for Water Quality and Red Tide Monitoring along United Arab Emirates Coasts, Bonn, Germany, 2013.

[101] E. Aleisa, A. Al-Jadi, S. Al-Sabah, A Simulation-Based Assessment of a Prospective Sewer Master Plan 11 (2015) 272–281.

[102] A. Kajenthira, A. Siddiqi, L.D. Anadon, A new case for promoting wastewater reuse in Saudi Arabia: bringing energy into the water equation, J. Environ. Manag. 102 (2012) 184–192, https://doi.org/10.1016/j.jenvman.2011.09.023.

[103] A.N. Angelakis, S.A. Snyder, Wastewater treatment and reuse: past, present, and future, Water 7 (2015) 4887–4895, https://doi.org/10.3390/w7094887.

[104] A.Y. Hoekstra, P. Hung, Virtual Water Trade. A Quantification of Virtual Water Flows between Nations in Relation to International Crop Trade, 2002.

[105] S. Tamea, M. Tuninetti, I. Soligno, F. Laio, Virtual water trade and water footprint of agricultural goods: the 1961–2016 CWASI database, Earth Syst. Sci. Data 13 (2021) 2025–2051, https://doi.org/10.5194/essd-13-2025-2021.

[106] D. Renault, Value of Virtual Water in Food: Principles and Virtues, 2002.

[107] T. Oki, S. Yano, N. Hanasaki, Economic aspects of virtual water trade, Environ. Res. Lett. 12 (2017), 044002, https://doi.org/10.1088/1748-9326/aa625f.

[108] M. Mekonnen, A.Y. Hoekstra, National Water Footprint Accounts: the Green, Blue and Grey Water Footprint of Production and Consumption, 2011.

[109] M.A. Dawoud, Water import and transfer versus desalination in arid regions: GCC countries case study, Desalination Water Treat. 28 (2011) 153–163, https://doi.org/10.5004/dwt.2011.2156.

[110] A.A. Rafindadi, I.M. Muye, R.A. Kaita, The effects of FDI and energy consumption on environmental pollution in predominantly resource-based economies of the GCC, Sustain. Energy Technol. Assessments 25 (2018) 126–137, https://doi.org/10.1016/j.seta.2017.12.008.

[111] M. Ge, J. Friedrich, L. Vigna, Charts Explain Greenhouse Gas Emissions by Countries and Sectors, 2020.

[112] T.F. Stocker, D. Qin, G. Plattner, M. Tignor, S. Allen, J. Boschung, P. Midgley, Climate Change 2013: the Physical Science Basis. Intergovernmental Panel on Climate Change, Working Group I Contribution to the IPCC Fifth Assessment Report (AR5), 2013.

[113] F.M. Al Zawad, A. Aksakal, Impacts of climate change on water resources in Saudi Arabia, in: I. Dincer, A. Hepbasli, A. Midilli, T.H. Karakoc (Eds.), Global Warming: Engineering Solutions, Green Energy and Technology, Springer US, Boston, MA, 2010, pp. 511–523, 978-1-4419-1017-2.

[114] J.S. Pal, E.A.B. Eltahir, Future temperature in southwest Asia projected to exceed a threshold for human adaptability, Nature Clim Change 6 (2016) 197–200, https://doi.org/10.1038/nclimate2833.

[115] H.M.S. Al-Maamary, H.A. Kazem, M.T. Chaichan, The impact of oil price fluctuations on common renewable energies in GCC countries, Renew. Sustain. Energy Rev. 75 (2017) 989–1007, https://doi.org/10.1016/j.rser.2016.11.079.

[116] H.D. Ibrahim, E.A.B. Eltahir, Impact of brine discharge from seawater desalination plants on Persian/arabian Gulf salinity, J. Environ. Eng. 145 (2019), 04019084, https://doi.org/10.1061/(ASCE)EE.1943-7870.0001604.

[117] L.S. Al Blooshi, S. Alyan, N.J. Joshua, T.S. Ksiksi, Modeling current and future climate change in the UAE using various GCMs in MarksimGCM, Open Atmos. Sci. J. 13 (2019), https://doi.org/10.2174/1874282301913010056.

[118] D. Yates, F. Flores, S.J. Galaitsi, National Water-Energy Nexus Climate Change: Final Technical Report from AGEDI's Local National and Regional Climate Change Programme, 2016.

[119] T. Lippman, Saudi Arabia's Quest for Food Security, 2010.

[120] M. Yamada, Vision 2030 and the Birth of Saudi Solar Energy, Middle East Institute Policy Focus, 2016.

[121] S. Pathirana, K. Perera, H. Sanaa, Impact of climate change on water resources in MENA countries: an assessment of temporal changes of land cover/land use and water resources using multi-temporal MODIS and landsat data and GIS techniques, in: Proceedings of the Proceedings of the International Symposium on Remote Sensing, Banglore, India, 2015.

[122] SCPD KUWAIT General Secretariat of Supreme Council for Planning and Development (GSSCPD) Available online: https://scpd.gov.kw/home.aspx?popup=1 (accessed on 19 May 2023).

[123] M.T. Chaichan, K.A. Al-Asadi, Environmental impact assessment of traffic in Oman, Int. J. Sci. Eng. Res. 6 (2015) 493–496.

[124] N. Ayoub, F. Musharavati, S. Pokharel, H.A. Gabbar, Energy consumption and conservation practices in Qatar—a case study of a hotel building, Energy Build. 84 (2014) 55–69, https://doi.org/10.1016/j.enbuild.2014.07.050.

[125] D. Martinez-Plaza, A. Abdallah, B.W. Figgis, T. Mirza, Performance improvement techniques for photovoltaic systems in Qatar: results of first year of outdoor exposure, Energy Proc. 77 (2015) 386–396, https://doi.org/10.1016/j.egypro.2015.07.054.

[126] EcoMENA EcoMENA - Environmental Hub in MENA Available online: https://www.ecomena.org/(accessed on 19 May 2023).

[127] Y. AlMulla, Gulf Cooperation Council (GCC) Countries 2040 Energy Scenario for Electricity Generation and Water Desalination, Master Thesis, 2015.

[128] W. Al-Zubari, The Cost of Municipal Waster Supply in Bahrain, vol. 1, MENA Network of Water Centers of Excellence, 2014.

[129] B. Shepherd, GCC states' land investments abroad: the case of Ethiopia, CIRS Summary Report (2013).