Chapter 14
The Use of Non-Conventional Water Resources in Agriculture in the Gulf Cooperation Council Countries: Key Challenges and Opportunities for the Use of Treated Wastewater

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Abstract The Gulf Cooperation Council (GCC) countries are situated in a region of severe water poverty characterized by harsh climatic conditions. The average per capita share of natural freshwater resources is among the lowest in the world at about 120 m^3/year; much less than the recognized absolute water scarcity limit (500 m^3/capita/year). On the other hand, the average per capita annual water consumption is about 800 m^3/capita/year, putting the GCC region within the world's highest water consumers. This huge deficit in their natural water resources, reaching over 15 BCM, is met mainly by extensive over-abstraction of the limited groundwater resources, vast installation of expensive desalination plants, and to a lesser extent, the reuse of treated wastewater. Treated wastewater has the potential to play an important role as a non-conventional water resource, especially for the agricultural sector, the biggest water consumer (77%), reducing pressure on the depleted groundwater, matching the continuous increase in water demand, minimizing contamination, conserving energy, and reducing the environmental footprint of wastewater treatment. However, treated wastewater still accounts for only 3% of the total GCC water demand. The wastewater sector faces three key challenges that must be carefully managed to reach full utilization, these are: public perception, health and environmental risk, and economic and cost recovery. For this to be accomplished, developing a reuse strategy/policy is a necessity for promoting the treatment efficiency and maximizing the treated wastewater reuse. Sustainable water systems can be entirely realized if everyone begins thinking about wastewater differently.

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1 Introduction

Water is an invaluable resource, and is essential for human development, well-being, and survival. It maintains the health of our ecosystems, keeps our communities running, and our economies developing. Water resources are widely considered as the most critical natural resources. Essential freshwater resources are relatively scarce, of the 1,400 million km^3 of water on Earth, 97% is in oceans, 2% is freshwater in ice, 0.6% is underground water, less than 0.3% is readily available for humans to use, with huge geographical variations even of this small fraction[1] (Pidwirny 2006; PwC 2012). Moreover, by 2050, global water demand is estimated to grow by 20–30%, due to the increased water use mostly in the agricultural sector followed by domestic and industrial sectors (WWAP and UNESCO 2019). Yet, water is often taken for granted and poorly valued, not all people recognize what it takes to deliver or produce freshwater every day or to treat wastewater so that it can be safely reused or returned to the environment. Benjamin Franklin stated that "We will never know the true value of water until the well runs dry" (IPCC 2018). Due to its importance, the UN-Water choose "valuing water" as the theme of the 2021 World Water Day (UN-Water 2021). Water resources are only sustainable if they are properly managed.

Securing freshwater availability has become one of the main challenges at national, regional, and global levels due to various factors such as population boom, climatic conditions, and the mismanagement and overuse. In a world where freshwater demand is continuously increasing, and limited water resources are progressively depleted due to over-abstraction, pollution, and climate change; reusing wastewater has become an important option to counteract these conditions. To ignore the benefits of wastewater reuse is nothing less than a lost opportunity in the perspective of a circular economy and water sustainability (UN WWAP 2017).

Six countries in the Arabian Peninsula, namely, Bahrain, Kuwait, Oman, Qatar, Saudi Arabia, and United Arab Emirates (UAE), constitute the Gulf Cooperation Council (GCC), which was founded in 1981. The cooperation is based on their geographic proximity, common political, socio-economic, and cultural affairs, natural resources from oil and gas, joint destiny, and shared objectives. The GCC countries are located in the southwestern region of the Asian continent, bordered by the Arabian Gulf in the east, the Red Sea in the west, the Arabian Sea in the south, and Iraq and Jordan in the north (Fig. 1). The GCC countries cover an area of nearly 2,410,737 km^2, about 83% of this area belongs to Saudi Arabia (GCC-STAT data

[1] Ten countries (Brazil, Russia, USA, Canada, Indonesia, China, European Union, Colombia, Peru, and India) are the world giants in terms of natural water resources, accounting for about 60% of the world's freshwater. At the other extreme, the water poorest countries, usually the arid and smallest ones, include Bahrain, Kuwait, Jordan, Libya, Maldives, Malta, Qatar, United Arab Emirates, Yemen, and Saudi Arabia (FAO 2003).

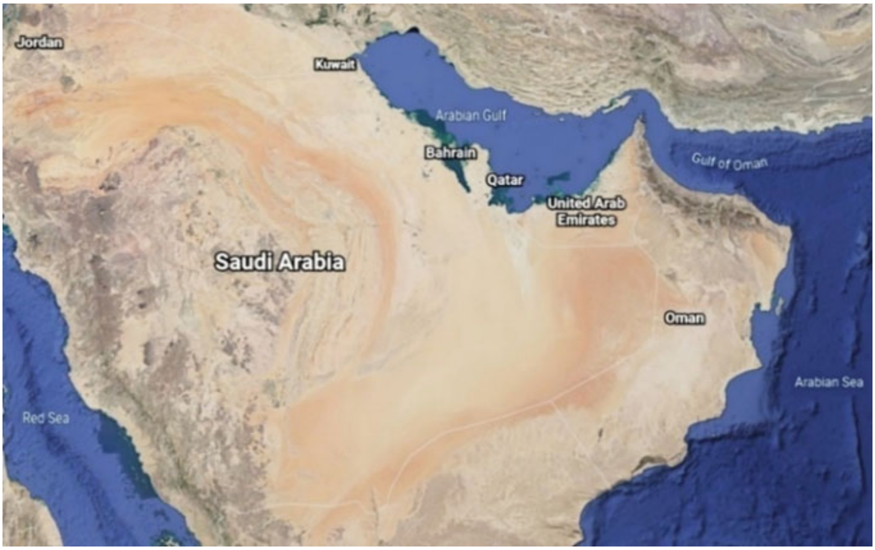

Fig. 1 Geographical location map of the GCC countries (Google Earth)

2018). Since the discovery and the start of intensive exploitation of oil fields in the middle of the twentieth century, these countries have experienced an unprecedented fast-paced transformation resulting in a rapid change in socio-economic development, an improvement in the standard of living and an increase in consumption patterns, mainly due to the sharp increase in income, which continues to this day (Al-Badi and AlMubarak 2019). The human development index (HDI), which is based on indicators such as life expectancy, education, and gross national income, for the GCC countries is 0.84/1, which is higher in rank than that for most developing countries and is continuously improving (UNDP 2020). In addition, GCC countries had a relatively high per capita GDP of USD 55,137 in 2018, approximately 20% higher than the average of the world advanced economies, ranging from USD 41,400 in Oman to USD 115,900 in Qatar (Alpen-Capital 2019). These high living standards have been associated with high per capita water consumption, putting major stresses on the limited water resources (Droogers et al. 2012).

GCC countries have the lowest water endowment of natural water resources in the world due to their location in one of the driest regions of the world. The GCC area is characterized by extreme temperatures (reaching more than 50 °C during summer daytime), low and irregular rainfall (ranging from 70 to 150 mm/year), and high evaporation rates (>3,000 mm/year). This is aligned with an annual average per capita share of natural water resources of about 119 m^3, making the GCC countries among the lowest in the world and way below the absolute water scarcity limit (<500 m^3 per capita per year, compared to a world average of 6,000 m^3)[2] and will

[2] Globally, 1,000 m^3 of water per person per year is considered the minimum amount to sustain life and ensure industrial development and agricultural production in countries where climates require

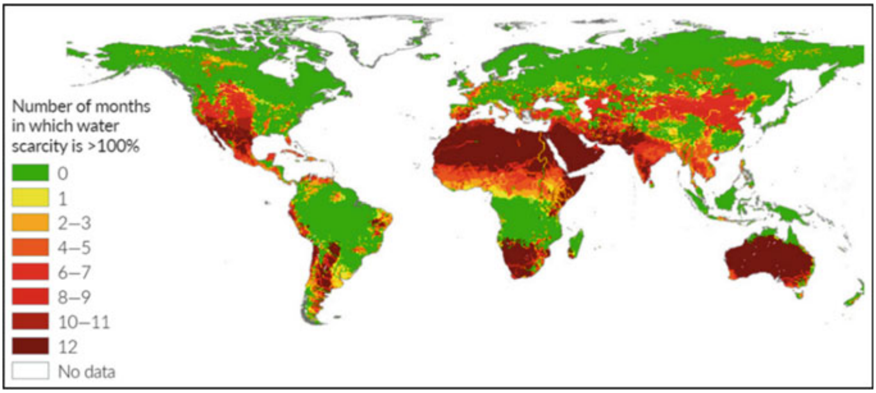

Fig. 2 Number of months per year where surface water and groundwater is withdrawn and not returned exceeds 1, at 30 × 30 arc min resolution (1996–2005) (UN WWAP 2017)

continue to decline because of the increasing population growth (Qureshi 2020; Parimalarenganayaki 2021). Figure 2 shows, on the world map, how many months per year water scarcity is > 100% (UN WWAP 2017). As can be seen, the Gulf region is characterized by water scarcity all year around. Moreover, it is evident that the climate is changing and rising temperatures are affecting the hydrological systems, like water availability and extreme events, which is expected to have an impact on communities, the environment, health, water supply, food security, human security, and economic growth (IPCC 2018).

On the other hand, the GCC total per capita water consumption is one of the highest in the world reaching about 800 m^3/capita/year (GCC-STAT data 2018), which is primarily attributed to wasteful consumption due to low water use tariffs resulting from government subsidies (Economist 2010). In addition, the per capita domestic water consumption is also considered very high, ranging from about 250 l/day (in Oman and Saudi Arabia) to more than 600 l/day (in Qatar and UAE) (Al-Zubari 2017). It should be noted that the value adopted internationally for basic human water needs is about 50 l/capita/day (Gleick 1996; Cosgrove and Loucks 2015). According to the World Health Organization (WHO), between 50 and 100 l/person/day is the optimal requirement of water to ensure basic needs, including drinking, personal sanitation, personal and household hygiene, food preparation, and washing clothes (WHO 2003a). People's feeling of this apparent water abundancy instead of real-water scarcity may arise from the expansion of constructing desalination plants and providing water all days of the year without interruption.

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irrigation, based on the Falkenmark index. This index is the most widely used tool for classifying the per capita available renewable water resources, in regions with no stress (>1,700 m^3), water stress (<1,700 m^3), water scarcity (<1,000 m^3), and absolute water scarcity (<500 m^3) per capita per year (Falkenmark 1986; Darwish et al. 2014; Gampe et al. 2016; Kummu et al. 2016).

Due to rapid population growth, expanded urbanization and industrialization, improvement in living standards, low water tariffs and governmental subsidies, relatively high distribution network losses, climate change, rising food demand, and agricultural policies of food self-sufficiency; the demand for water has dramatically increased in the past four decades in all the GCC countries (Al-Zubari 2017). As a food importing region, the GCC food imports constitute approximately 60–90% of the total food consumed (Economist 2019). Alpen-Capital (2019) indicated that about 85% of food consumption in the GCC region is imported, with 3.1% annual growth rate, and it reached USD 36.4 billion in 2015 and estimated at USD 53.1 billion in 2020 (Ben Hassen and El Bilali 2019). Moreover, a study for the MENA region (Droogers et al. 2012) expected that by 2041–2050, climate change would be responsible for 10% of the change in water demand and 22% of the water shortage. The study also revealed that there will be a 50% increase in water demand with a 12% decrease in water supply by 2050. Therefore, one of the greatest challenges facing the GCC countries is providing water to meet the domestic, agricultural, and industrial sector demands. In more detail, these challenges will be manifested in: (1) increasing pressure on the region's scarce and limited groundwater resources that are being depleted and whose quality is deteriorating due to over-exploitation; (2) heavy reliance on the energy-intensive desalination; (3) inadequate reuse of treated wastewater; (4) the import of virtual water via agricultural goods; and (5) the projected future impacts of climate change (Saif et al. 2014). It is important to point out that the report for climate change in the Arab Region (Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region [RICCAR]) indicated that the Arabian Gulf has moderate vulnerability to climate change, although remaining among the hottest areas in the Arab region and signaling rising temperatures, due to their financial capabilities (ESCWA 2017).

Under such conditions, it is expected that there will be an increase in the demand for water (i.e., groundwater and desalinated water), and treated wastewater has a great potential in supplementing the ever-growing water demand (Jasim et al. 2016). Wastewater reuse can be the predominant water supply for agriculture in the GCC countries, if treated properly and used safely. It will continuously increase with population growth and water consumption and can be considered as a renewable non-conventional water resource, especially because the agricultural sector is considered the largest consumer of water, accounting for more than 77% of the total water use (AQUASTAT data 2017) and is primarily met through the massive exploitation of groundwater (Fig. 3). This high percentage is caused by low irrigation efficiencies mainly resulting from the dominantly practiced traditional flood irrigation method, unmonitored groundwater abstraction, cultivating high-water consuming crops such as fodders, and lack of groundwater tariff in agriculture (Al-Zubari et al. 2017). Although wastewater reuse has started in the GCC countries in the early 1980s (Al-Zubari 1998), only small percentage of the large volumes of collected or treated wastewater is being reused, while the rest of both treated and untreated wastewaters is disposed to the coastal and marine environments, which represents a major lost opportunity under the GCC scarcity conditions. Additionally, the current wastewater

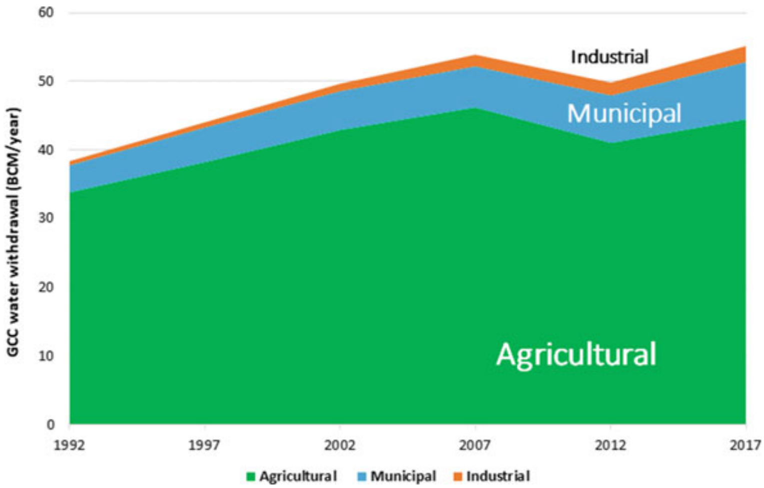

Fig. 3 Water uses in the GCC countries (AQUASTAT data 2017)

system is experiencing frequent hydraulic loadings due to lagging wastewater infrastructure behind that of the water supply, which is decreasing treatment efficiency and increasing insufficiently treated carryover volumes to the surrounding environment, negatively affecting biodiversity and threatening ecosystems. Likewise, most of the sludge generated during wastewater treatment ends up in landfills without any beneficial utilization, although it could be used in the production of energy or as fertilizers (Al-Zubari and AlAjjawi 2020).

Wastewater reuse can contribute to meeting this ever-increasing demand for water and closing the gap between demand and supply. Indeed, wastewater is regarded as a resource that is too valuable to throw away, especially in an increasingly water-scarce world. Moreover, the motivation for advanced wastewater treatment is not only providing an alternative water source when coping with water scarcity by reducing freshwater abstractions, but also conserving environmental quality by minimizing pollution, recycling nutrients, and increasing resource efficiency (UN WWAP 2017). Dr. Tedros, Director-General of WHO, stated that "Sanitation saves lives, but history teaches us that it is also one of the key building blocks of development" (WHO 2018).

This chapter aims to present the GCC's current water resources status, outline the main benefits and constraints of wastewater reuse with a focus on its reuse in agriculture, with some recent examples. Then it explores the potential future contribution of wastewater in the Gulf region and ends with recommendations for the way forward.

2 Water Resources in the GCC Countries

Most of the land in the GCC countries is classified as arid to extremely arid, with harsh weather and is mostly desert. Due to low rainfall and high evaporation rates, they are poor in natural water resources and have very limited surface water (lakes and rivers), except for Saudi Arabia, Oman, and UAE. Surface water contributes to only 0.5% of the total GCC water supply (Fig. 4). Until the early 1970s, the GCC had relied on groundwater as the primary source for all their water requirements. Currently, water demands are being met by three sources: (1) Groundwater abstraction (traditional and heavily exploited); (2) Desalination (introduced in the 1950s and expanded rapidly in the 1970s); and (3) Treated wastewater (introduced in the early-1980s) (Al-Zubari 1998). In 2018, the total water resources used had reached 36 billion cubic metres (BCM), including 28.34 BCM from groundwater and surface water (most of the groundwater used is non-renewable), and 7.6 BCM of non-conventional resources (6.5 BCM of desalinated water and only 1.11 BCM of treated wastewater) (GCC-STAT data 2018). These water resources are used to meet the demands of three main sectors: municipal, agricultural, and industrial sectors. The water requirements for the agricultural sector, the main water consumer in the GCC countries, account for 77% of the total water budget. These are being met mainly by groundwater abstraction (94%) and are complemented by desalinated water (3%) and treated wastewater (3%). The main water resource for the municipal sector, the second main consumer (18%), is from expensive desalination (>74%) of seawater to satisfy almost all of its water demands and is complemented by small quantities from groundwater (26%). Lastly, the industrial sector's water needs (5%)[3] are met primarily by groundwater abstraction (96%) and desalination (4%). Water demands from these three sectors are expected to increase in the future.

The Gulf region has witnessed an escalation in water demand during the past years, with an annual increase of 10% (Dutch Economic Network 2018). The main drivers for this increase are rapid population growth, improved living standards, and the remarkable development of various economic sectors (industry and commerce) throughout the six countries. Moreover, the free or low-priced water supply causes people to waste water without considerable concern in the UAE (Yagoub et al. 2019) and this also applies to the other GCC countries. Figure 5 shows the rapid population growth associated with the growing water supply during the period 2012–2018. There are more than 56 million inhabitants across the GCC today (GCC-STAT data 2018), with an annual population growth rate for the period from 2011 to 2017 is nearly 3.1% (Statista 2021). As the population, living standards, and water-intensive lifestyle in the GCC continue to rise, more pressure will be added on their limited water resources and the demand–supply gap is going to further widen in the future. Wastewater reuse can provide a valuable opportunity that must not continue to be wasted, to supplement the water supply, and to minimize the disposal of this water to

[3] It is important to note that this percentage does not account for the exact water utilization of the industrial sector, because the industrial sector relies on its own desalination plants.

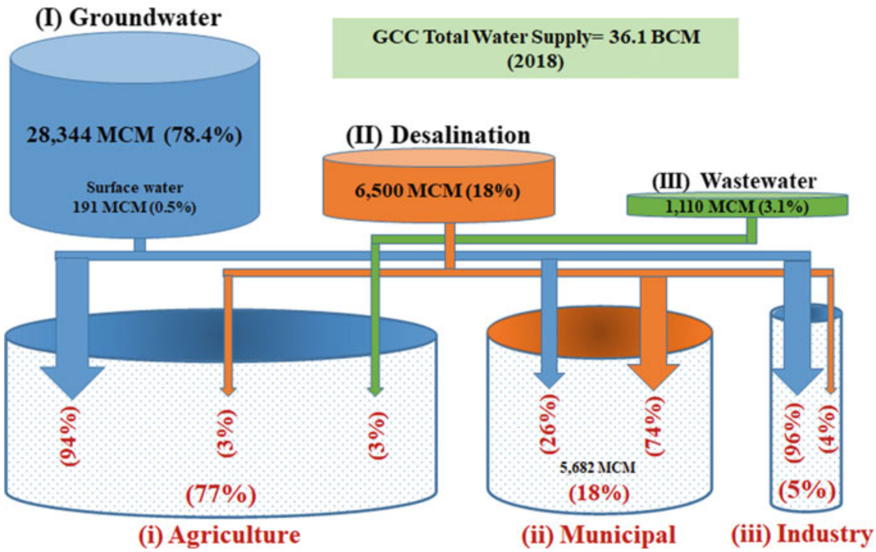

Fig. 4 GCC water resources: (I) Groundwater, (II) Desalination, (III) Wastewater (GCC-STAT data 2018), and GCC water uses: (i) Agriculture, (ii) Municipal, (iii) Industry (Al-Zubari et al. 2017) based on 2010/2012 data

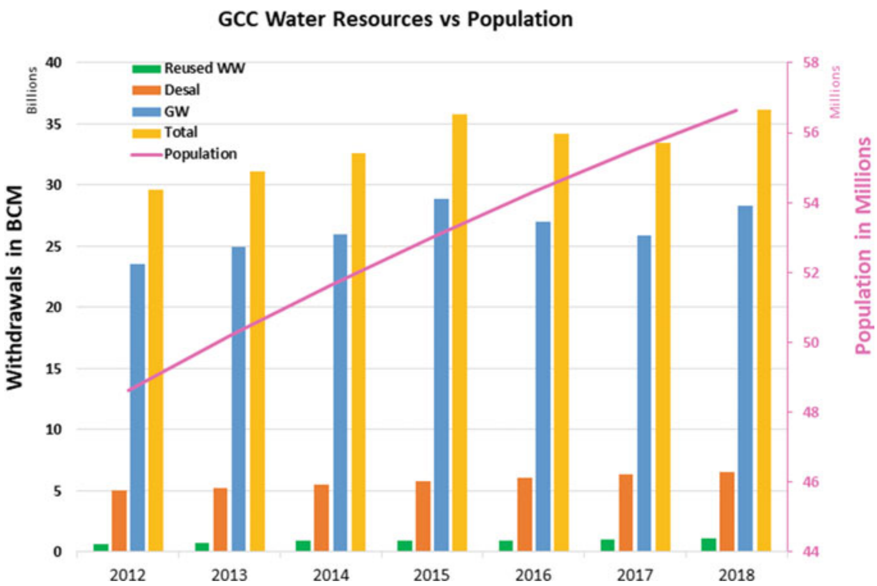

Fig. 5 Water resources (GCC-STAT data 2018) versus population (World Bank data 2020) in the GCC during the period 2012–2018

the environment without benefit. A detailed discussion of the GCC water resources is given hereafter.

2.1 Surface Water and Groundwater Resources

The GCC countries have surface water that is insignificant and cannot be relied on, except for the mountainous areas in Saudi Arabia, Oman, and UAE; it accounts for 0.5% of the total GCC water supply. The total surface water generated from rainfall, captured in dams and used, is estimated to be 191 million cubic metres (MCM) in 2018, of which 102 MCM/year are generated in Saudi Arabia, 89 MCM/year in Oman and UAE (GCC-STAT data 2018). Groundwater is the main source of water in the GCC that extends almost over all the six countries. Major shared aquifers include the Neogene Aquifer (Kuwait, Saudi Arabia, Iraq), Dammam Aquifer System (Bahrain, Saudi Arabia, UAE, Oman, Yemen), and Umm Er Radhuma aquifer (Bahrain, Saudi Arabia, Qatar). Groundwater resources in the GCC countries are classified into renewable resources and non-renewable (or fossil) resources. The renewable groundwater resources are relatively small depending on the rainfall events and surface runoff and mostly encountered in shallow alluvial aquifers, whereas the non-renewable resources are found in the deep aquifers and were formed thousands of years ago during the rainy Pleistocene and Pliocene geological periods. They cover about two-thirds of the Arabian Peninsula (Al-Rashed and Sherif 2000). Generally, it is believed that the status of aquifers depends on their renewability and storability, and that the main groundwater reservoirs are old and were recharged during the past pluvial periods. Owing to the absence of present-day recharge, sustainable development of aquifer systems is not feasible, so their exploitation must be carefully undertaken and must be within their safe yield (Alsharhan and Rizk 2020a).

All GCC countries are utilizing hundreds to thousands of times more groundwater than sustainable recharge would allow (Saif et al. 2014). The majority of groundwater resources in the GCC region, which are non-renewable, are being extensively mined and over-abstracted. The drive to achieve food self-sufficiency and maximum food production by providing generous subsidies had led to over-exploitation of these groundwater resources. While some countries were successful in achieving these goals, such as Saudi Arabia as it became the sixth largest wheat exporter in the 1980s, it was at the expense of its water resources. These agricultural policies coupled with inadequate water management had created an unsustainable water usage culture (Baig et al. 2020). Moreover, this had resulted in major groundwater depletion, while the remaining limited renewable groundwater resources are being over-abstracted beyond their replenishment rates, leading to reduction in the quantity and degradation in quality with high salinity levels due to significant saltwater intrusion (Al-Zubari 2017; Mohamed et al. 2021). During the period 2012–2015, the total groundwater recharge rate was estimated to be about 5.2 BCM (Table 1), while groundwater abstraction was estimated to be 19.8 BCM. Groundwater has been heavily over-exploited by amounts that considerably exceed their recharge rates,

Table 1 The conventional groundwater resources availability in the GCC countries, in MCM

	Groundwater (MCM)			
Country	Groundwater abstraction[a]	Groundwater Recharge[b]	Non-renewable reserve	Water Deficit from natural resources
Bahrain	103	110	Negligible	7
Kuwait	496	160	Negligible	– 336
Oman	1,215	900	102,000	– 315
Qatar	250	50	Negligible	– 200
Saudi Arabia	15,450	3,850	428,400	– 11,600
UAE	2,300	190	Negligible	– 2,110
GCC	19,814	5,260		– 14,554

[a]Groundwater abstraction average rates represent the years 2012–2015
[b]Recharge represents shallow alluvial aquifers; recharge to Kuwait and Bahrain aquifers occurs by the underflow from equivalent aquifers in Saudi Arabia and recharge is variable depending on the hydraulic gradient between the two countries. All indicated figures represent steady-state conditions (Al-Zubari et al. 2017)

resulting in a huge deficit ranging from nearly 15 BCM (Al-Zubari et al. 2017) to 20 BCM (Dutch Economic Network 2018). The large deficits in the GCC countries' water budget have not changed much since the 1990s, where it was around 13,436 MCM/year (Al-Zubari 1998), except for Bahrain that currently experiences no deficit in groundwater, mainly due to the major dependency on desalination. One of the key reasons for this unsustainable exploitation of groundwater resources is the existence of direct and indirect subsidies to well drilling, absence of monitoring metres and/or tariffs on groundwater pumping, increase of food demand, and unplanned agricultural expansion. Obviously, this has resulted in a significant decline in groundwater quantity manifested by water level drop, and quality levels represented by salinity increase, being suitable for domestic use in few areas and used mostly for agricultural activities. Such a situation necessitates an alternative approach.

2.2 Desalination

The massive imbalance between groundwater discharge and recharge, due to overpumping, is causing seawater intrusion and deterioration of groundwater. This deterioration, coupled with the prevailing freshwater scarcity condition that exists in the arid Gulf region, had forced the GCC countries to find alternative ways to satisfy the demand for freshwater. This is being met by investing heavily in non-conventional water resource, namely desalination. Desalination, both thermal and reverse osmosis (RO), was first introduced in the region in the mid-1950s (Al-Shuwaikh desalination plant in Kuwait to produce drinking water), and then increased considerably in the 1970s in all the GCC countries (Al-Mutawa et al. 2014; Alsharhan and Rizk 2020a).

The reason for the sudden expansion in desalination was the spike in oil prices that provided the required funds for water and energy infrastructure investments (Saif et al. 2014). Since then, desalinated water has proven to be a practical solution for the water-shortage problem for domestic and industrial water supply. However, desalination's relatively high cost is the main reason for not using produced desalinated water in the agricultural sector. Growing food needs water and energy at much higher price than the imported food available at the market. For instance, producing one kg of potato, which usually costs ~USD 1.5, will cost USD 3.5 when using water produced by thermal desalination (Darwish et al. 2014).

Currently, most of the freshwater demand for domestic (74%) and industrial (4%) sectors in GCC is met by desalination (accounting for 18% of total water supply) with a total capacity of 8.2 BCM in 2018 (GCC-STAT data 2018). The GCC is currently producing 5.75 BCM of desalinated water annually, from around 439 desalination plants distributed on the coast of the Arabian Gulf and inland (Qureshi 2020), which constitutes around 60% of the world's desalination plants (Mu'azu et al. 2020). Kingdom of Saudi Arabia (KSA) is the highest producer of desalinated water in the world, followed by the UAE (Ouda 2014). While UAE and KSA rely on desalinated water, to meet their municipal water supply by nearly 70 and 60%, respectively; Qatar, Kuwait, and Bahrain rely totally on desalination (Zekri and Al-Maamari 2020). So far, GCC countries have their own energy resources, i.e., oil and gas, needed for sea and brackish water desalination. However, desalination is an expensive and energy-intensive process accompanied by a significant environmental impact that is evident from the negative effects of desalination brine discharge on marine life, air pollution by gaseous emissions, as well as noise (Dawoud 2012; Yagoub et al. 2019). Moreover, given its high energy requirements, water produced by desalination is considered unsustainable, as natural gas prices and thus production costs increase, which necessitates an alternative approach (Kajenthira et al. 2012). Therefore, it is essential to lower the rate of desalination expansion to conserve the GCC countries' income of these non-renewable fuel resources and to save the environment (Darwish et al. 2009). One of the options to do this is to use renewable energy in desalination. Sustainable and long-term solutions are required to shift to renewable energy resources for saving energy and consumption of fossil fuels, something that has not been accomplished yet. Wastewater is another option that can provide cheaper alternatives than desalination, to be used at least for the agricultural and industrial sectors.

2.3 Wastewater

Treating wastewater, by building and running wastewater treatment plants (WWTPs), was introduced in the early 1980s in most of the GCC countries (Al-Zubari 1998). A correlation was found between the level of high per capita GDP and water treatment because of the higher demand for raising safety and water quality concerns (Liao et al. 2021). There has been a dramatic change in the reuse of wastewater. For example, Saudi Arabia banned importing some Jordanian fruits and vegetables, because of concerns about the use of wastewater in irrigation during the early 1990s (Lazaridou et al. 2019). However, the reuse of treated wastewater is currently receiving remarkable attention in the Gulf countries as a possible source to bridge the ever-increasing water demand–supply gap and to reduce the pressure on the fast-depleting groundwater and the energy-intensive desalination. Nearly 99% of the matter presented in wastewater is water, so treating and reusing this could be a more sustainable alternative than desalination or long distance water transfers (Kehrein et al. 2020). Great efforts were made in providing access to basic sanitation services and establishing many WWTPs.

As a part of implementing the objectives and indicators of the sixth goal of sustainable development goals (SDGs), almost 100% of the population benefit from improved and safe sanitation services (Indicator 6.2.1) in all the GCC countries (GCC-STAT 2021). Actually, this had started even before the SDGs, as the water decade (1981–1990) and the millennium development goals (MDGs) phase (2001–2015) also focused on safe water and sanitation for all. Specifically, treating wastewater and increasing its reuse (SDG 6.3.1), reducing the pressure on other water resources (SDG 6.4.2) that is groundwater in the case of GCC countries and eliminating the negative environmental impacts on the marine environment (SDGs 6.3.2 and 6.6.1) can be counted as an important incentive for considering the treatment and reuse of wastewater. Currently, by law, wastewater must be treated before reuse or disposal in the surrounding area in all the GCC countries to protect the people and environment from contamination. Saudi Arabia is currently operating modern treatment facilities with secondary and/or tertiary treatment capabilities for all types of wastewater such as domestic, industrial, and agricultural with the governmental decision (Alkhudhiri et al. 2019). In some countries wastewater is treated to advanced levels using ultrafiltration through the reverse osmosis, RO membranes, such as the Sulaibiya plant in Kuwait (Abusam and Shahalam 2013). The continuous increase in the treated wastewater flow, proportional to the growth in the population and municipal water supply rates, has encouraged the GCC countries to increasingly rely on treated wastewater as a non-conventional water resource besides desalination.

There are about 295 wastewater treatment plants in the GCC countries, most of them (102 WWTPs) are in Saudi Arabia, followed by 86 WWTPs in UAE, with mostly tertiary (activated sludge followed by disinfection) and advanced treatment capabilities. The total WWTPs designed capacity in the six GCC countries has expanded from 2.4 BCM in 2010 to about 3.7 BCM in 2018 (GCC-STAT data 2018). The majority of these WWTPs are centralized and are operated by the government, with fewer recently decentralized and run by the private sector. Treated wastewater is used to meet the non-potable water requirements such as agricultural production, landscaping, forestry, recreational, commercial, and industrial uses. However, its reuse is constrained due to health, religious, social, and environmental concerns. Wastewater can be used as long as its treatment meets the requirement for the intended use. Substantial research evidence exists that, after adopting proper management measures, treated wastewater can safely be used to grow food and forage crops under the agro-climatic conditions of the GCC countries (Qureshi 2020).

3 Current Status of Wastewater in GCC

While the produced volumes of treated wastewater have increased over the past three decades, their reuse has not reached its potential to contribute significantly to the water budget in the GCC countries. Currently, wastewater reuse accounts for only 3–4% of the water demands in all GCC countries, mainly in the agricultural sector. Table 2 displays the currently available capacities of wastewater treatment plants, collected, treated, and reused volumes of wastewater. In 2018, the total municipal water consumption was about 5,682 MCM and the total collected wastewater volume was 3,276 MCM (i.e., 57%). The total GCC-designed treatment capacity of the major WWTPs facilities was 3,730 MCM/year. The UN World Water Development Report (UN WWAP 2017) indicated that high-income countries treat about 70% of their generated municipal and industrial wastewater. Although the GCC rate of wastewater treatment of the collected rates is very high reaching more than 95%, only 35.6% (1,110 MCM) of these volumes are reused (GCC-STAT data 2018). The remaining unused treated wastewater are discharged unused to the sea, wadis, and artificial lagoons, especially on days with heavy rain because the rainwater drainage channels are connected to the wastewater network (KSA-MEWA 2018). Although there is a steady increase in the reuse wastewater as volumes, the percentage increase is lagging behind and is much less than the percentage increase in the collected and treated volumes, indicating the inadequate utilization of the potential of the treated wastewater. These figures indicate that wastewater reuse is still at its initial stages in the GCC countries. However, the expansion in utilization of the treated wastewater as a strategically alternative source to meet the GCC countries' future demands is one of the main strategic objectives and policies in the 2016–2035 GCC Unified Water Strategy (UWS) (Al-Zubari et al. 2017) as well as all their future plans. It is also part of the commitments toward some of the UN's Sustainable Development Goals by meeting a number of wastewater treatment and reuse objectives.

The average percentage of collected wastewater to generate municipal water is about 60% in the GCC countries. Analysis of wastewater volumes at the countries' level indicates that volumes of municipal consumption have increased dramatically in KSA and UAE in recent years (Fig. 6), and also the volumes of collected and treated wastewater are the highest in these two countries, followed by Kuwait and Qatar. Saudi Arabia, Qatar, UAE, and Oman are treating almost 100% of their collected wastewater, while Kuwait and Bahrain are treating 85 and 50%, respectively. The percentage of total wastewater reuse is the highest in UAE, with a volume of 513 MCM in 2018 representing 70% from collected wastewater, followed by Oman (64%), Qatar (59%), Bahrain (55%), Saudi Arabia (18%), and finally Kuwait with only 15%. In addition, the percentage of treated wastewater share in the total water budget is currently 15% in Qatar and 10% in Bahrain and UAE. The increasing reuse gives an indication of a higher level of awareness about the importance of this resource to minimize the depletion of groundwater in particular, and to reduce the fast rate of the loss of agricultural lands due to the salinization of groundwater.

Table 2 Annual total GCC wastewater collection (compared to municipal consumption), treatment and reuse volumes (in MCM), WWTPs design capacities, and percentages of collection, treatment, and reuse (GCC-STAT data 2018)

Year	Municipal consumption (MCM)	WWTPs design capacity (MCM)	Collected wastewater (MCM)	Treated wastewater (MCM)	Reused wastewater (MCM)	% Collected to municipal generated	% Treated to collected	% Reused to treated
2011	4,167.3	2,925.1	2,174.5	2,036.3	697.6	52.2	93.6	–
2012	4,409.5	2,943.1	2,410.6	2,259.8	681.3	54.7	93.7	30.2
2013	4,697.7	3,253.7	2,576.1	2,428.9	724.6	54.8	94.3	29.8
2014	4,903.8	3,300.0	2,823.2	2,652.5	879.9	57.6	94.0	33.2
2015	5,089.7	3,413.4	2,918.6	2,777.6	884.5	57.3	95.2	31.8
2016	5,171.3	3,548.3	3,112.5	2,977.3	907.2	60.2	95.7	30.5
2017	5,406.6	3,664.8	3,101.5	2,912.4	1,010.8	57.4	93.9	34.7
2018	5,682.7	3,730.5	3,276.7	3,119.5	1,110.3	57.7	95.2	35.6

Considering that lagging wastewater reuse plans will intensify financial, economic, and environmental burdens, the GCC countries have prepared ambitious plans to expand the reuse of treated wastewater as a strategic alternative resource, especially in the agricultural sector, to reduce groundwater stress and replace the deteriorating groundwater. A National Water Strategy 2030 was developed in both Saudi Arabia (2018) and Bahrain (approved recently in February 2021) that recognized treated wastewater as one of the main water sources. Moreover, Saudi Arabia's Vision 2030 identified treated wastewater reuse as a sustainable source to diminish the water demand–supply gap and also, in a complete shift in water management policy regarding wastewater reuse, the government targets privatization of its major WWTPs and achieving 100% of reuse for agricultural and other purposes in the near future (Ouda 2016; Mu'azu et al. 2020). About 120 MCM in the city of Riyadh (50% of its treated wastewater) had been used for various applications, including agriculture, recreational and ecological, landscaping activities, and industrial and groundwater recharge. It is predicted that reuse of municipal wastewater will increase in Saudi Arabia to reach 5,090 MCM by 2050 (Alkhudhiri et al. 2019). It is worth noting that this amount is more than the annual surface water volume received by Saudi Arabia (2,400–3,700 MCM). Similar strategies for increasing wastewater utilization exist in other GCC countries, such as the 4th phase of expansion in Tubli WWTP in Bahrain that will be able to double its average daily flow capacity and it is expected to be completed in 2022 (Al-Zubari et al. 2017).

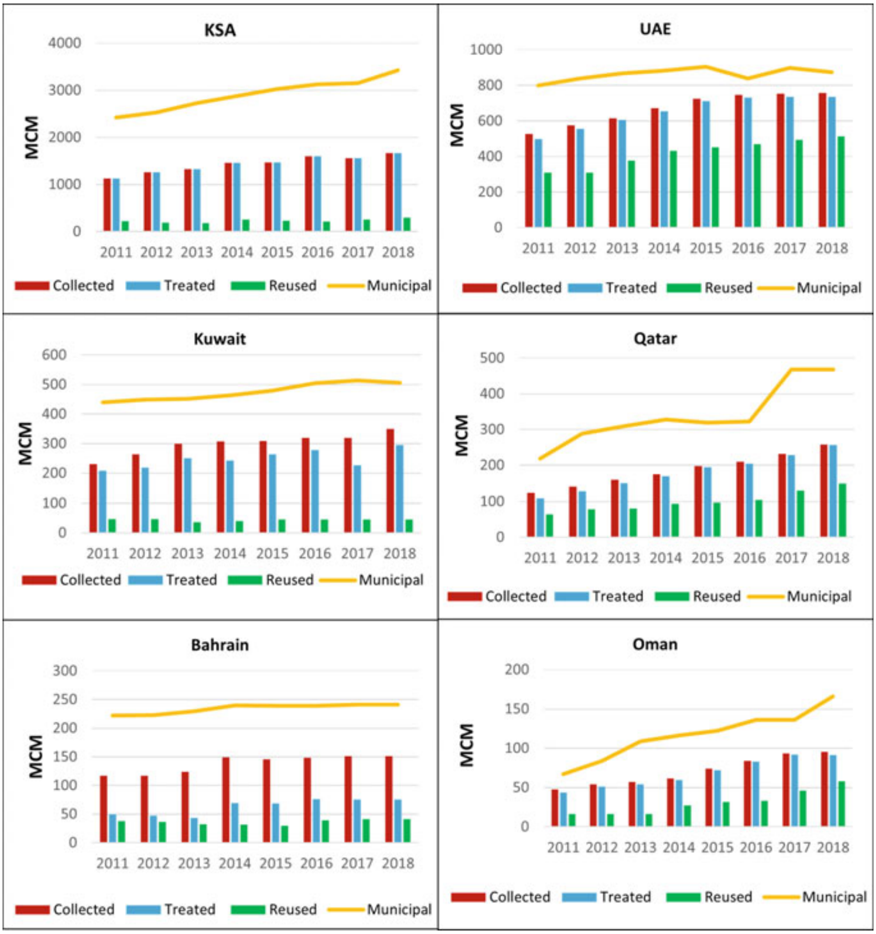

Fig. 6 Municipal consumption (line), wastewater collection, treatment, and reuse volumes (bars) in each GCC country (GCC-STAT 2018). KSA: Kingdom of Saudi Arabia, UAE: United Arab Emirates

4 Major Benefits of Wastewater Reuse

It is a major challenge to recognize the significance of treated wastewater as an important water resource. Despite some constraints that must be carefully managed to protect the public and environmental health, which will be discussed in the next section, there are various environmental, social, and economic benefits from reusing treated wastewater for non-potable purposes (Shoushtarian and Negahban-Azar 2020). FAO (2010) stated that recycling of wastewater is a major link in Integrated Water Resource Management (IWRM) and considered as a “win–win” situation, in which many different aims can be achieved, that is a solution to water demand, while additionally providing the agricultural and environmental advantages outcomes. Simultaneously, this can benefit several stakeholders: urban authorities, farmers, and the environment. Furthermore, using wastewater in irrigation can make a substantial contribution in lessening stresses of water demand by reducing the need to pump groundwater, adding/recycling nutrients, increasing crop yields, enhancing soil microorganism activities and soil health conditions, and avoiding pollutants to be disposed into the environment. In addition to energy savings and economic savings resulting from saving fertilizers and from avoiding desalination production and groundwater abstraction, reducing the carbon footprint, and contributing toward climate change adaptation and mitigation (Dery et al. 2019; Lazaridou et al. 2019). What follows is a brief discussion of the main benefits of the wastewater reuse in the GCC countries.

4.1 Matching Demand and Promoting Agriculture

The reuse of treated wastewater can be an important substitute for freshwater, creating supply-side benefits, protecting groundwater resources, and offering an additional source of water. With increasing water consumption, because of rising population and urbanization, the amount of domestic wastewater generated is expected to increase proportionally, providing additional water volumes that can match the rate of development. Due to quality considerations, this non-conventional water resource can be used especially for irrigation of agricultural lands and in industry, reserving freshwater resources for priority uses, reducing pressure on the deteriorating groundwater, and helping alleviate water scarcity in the GCC region. Complete reuse of treated wastewater can substantially reduce the country's reliance on costly desalinated water and depleted groundwater, to be used for wider purposes (Alkhamisi and Ahmed 2014).

Since agriculture is completely dependent on irrigation in the GCC countries, which consumes nearly 80% of the total water demands, reusing treated wastewater can help in expanding agriculture, diminishing the imbalance between available water resources and the need to grow more food. This can result in promoting projects that can contribute to economy investments in the agricultural sector, creating job opportunities, and can significantly improve the food security situation (Qureshi 2020).

4.2 Environmental Benefits

The UN world water report (UN WWAP 2017) indicated that over 80% of wastewater globally is discharged to the environment without treatment. Produced wastewater should be treated, due to environmental considerations, irrespective of whether or not it is going to be used. Reuse is a better option than disposal from economic and environmental perspectives to minimize contamination and reduce the environmental footprint of wastewater treatment. However, large portions (>2 BCM) of treated wastewater in the GCC countries are discharged into the sea, representing about 40% of the total groundwater recharge rate in the region. Saudi Arabia discharges >1.3 BCM of treated wastewater, this is over 60% of the total amount of treated wastewater in the GCC countries, next is Kuwait with >300 MCM, UAE (>245 MCM), Qatar and Bahrain (>100 MCM) and less than 40 MCM are being discharged to the sea and wadis in Oman (GCC-STAT data 2018).

In addition, Hanjra et al. (2012) indicated that wastewater reuse in agriculture can contribute toward climate change adaptation and mitigation by saving fertilizer use, preventing mineral fertilizer extraction from mines, and savings in energy which would reduce the carbon footprint.

4.3 Economic Benefits

By 2030, the energy consumption for producing water and recycling in the GCC countries will have tripled (Qureshi 2020). However, in comparison with desalination, it is more economical to reuse treated wastewater than produce costly desalinated water, because it is less expensive and consumes less energy (Jasim et al. 2016). The electricity demand for desalination in the MENA region (of which 70% is in Saudi Arabia, UAE, Kuwait, Algeria, and Libya) is expected to reach 122 terawatt-hour (TWh)[4] by 2030, three times higher than in 2007 (Al-Saidi and Saliba 2019). In Saudi Arabia, about 3.7 million barrels, or 30% of daily crude oil production, were consumed in 2018 for power generation, transportation, and operating desalination plants (Mu'azu et al. 2020). In the near future, the use of thermal desalination may become unsustainable since energy prices increase to represent production costs. Darwish et al. (2009) warned that more than one-tenth of oil production in Kuwait was used in the desalination plants in 2003 and that this number is almost doubling every 10 years. If this trend prevails, the country's total production of oil (or total Kuwait's income) will not be sufficient to desalt seawater for providing drinking water for its population in about thirty years, assuming constant oil production and water consumption trends. This trend in energy consumption is growing with alarming rates in all the GCC countries and is threatening the main source of income of these countries.

Typical market prices for desalinated water, based on fossil fuels, range between USD 1 to 2/m^3 for RO and thermal desalination plants. This can fall to be as low as USD 0.5/m^3 for large-scale plants, referring to economies of scale, when the capacity of the plant reaches $\gtrapprox$100,000 m^3/day (IEA-ETSAP and IRENA 2013; Zotalis et al. 2014). However, in Qatar, the actual cost rose above USD 3/m^3 (electrical cost USD 0.12/kWh and energy cost USD 2.4/m^3). Moreover, the total GCC energy cost for thermal desalination in 2012 was USD 1.552 billion. Meanwhile, the treatment of

[4] Terawatt-hour (TWh) is a measure of electrical energy, equals one trillion (10^{12}) watt-hours.

wastewater is far less costly. While costs vary according to quality, treating one m^3 of wastewater in Kuwait to potable water quality using advanced levels through ultrafiltration and RO, costs about USD 0.66, which is one-third of the cost of thermal desalination (Darwish et al. 2014). Furthermore, the estimated cost of tertiary and secondary wastewater treatment is USD 0.317 /m^3 and 0.067 /m^3, respectively (Aleisa and Al-Zubari 2017). In Bahrain, tertiary treatment of wastewater costs USD 0.53/m^3, its collection costs USD 0.4/m^3, and its distribution reuse costs USD 0.13–0.27/m^3. Kajenthira et al. (2012) indicated that reusing treated wastewater had resulted in saving USD 225 million, in six main cities of Saudi Arabia, and conserving 2% of Saudi Arabia's annual electricity consumption and 29% of total water withdrawals, as well as reducing CO_2 emissions by 1.75 billion kg CO_2. Recently, Thakur et al. (2020) reported that microalgae would be a promising treatment technology in the future, reducing the energy cost.

With respect to the wastewater nutritional value, economic savings resulting from providing higher levels of nutrients to soil and plants will reduce the need for additional chemical fertilizers, in terms of nitrogen and phosphorus (Dery et al. 2019). In fact, lowering the treatment level decreases fertilization needs and costs due to the increased levels of available nutrients left in irrigation water (Alkhamisi and Ahmed 2014). This is beneficial particularly for the soils in the GCC countries, which have a sandy texture and are deficient in organic matter and/or nutrients. Thus, using treated wastewater in irrigation will increase the economic return to farmers and farming productivity, providing another incentive for agricultural reuse.

4.4 Other Benefits

Treated wastewater can also be used in other sectors such as the industrial sector, or for enhancing groundwater storage by artificial recharge. Groundwater artificial recharge, using surplus tertiary treated wastewater, can reduce declining groundwater levels and reduce seawater intrusion. However, such reuse needs risk assessment and management studies to prevent the migration of treated wastewater to groundwater wellfield used for drinking water supply, which is site-specific. In addition, this requires the determination of safe injection locations for ensuring the removal of pollutants or pathogens in the underlying geological formations, if they exist (WHO 2003b). In fact, after some time (<400 days), a natural self-treatment process, termed soil aquifer treatment (SAT), can occur to the recharged treated wastewater, with a low spending of energy and a low carbon footprint (as result of aquifer natural processes and gravity flow). However, aquifer adequate thickness, lateral distance, and slope are required for natural treatment to occur (Missimer et al. 2012).

In Australia, a recent study on groundwater recharge (Vanderzalm et al. 2020) demonstrated that total nitrogen removal reached 40 to 60%, with 95% removal for ammonia, and total phosphorus removal was also observed to be around 90%, after 18 months from injecting two cycles of treated wastewater. Similar studies were performed in the Gulf region, particularly in Saudi Arabia and Oman. In Saudi

Arabia, wadi aquifers showed to have a major role in additional treatment, storage, and recovery of wastewater when required for areas in demand, i.e., aquifer recharge and recovery (ARR) (Missimer et al. 2012). Moreover, treated wastewater from Salalah WWTP was recharged/injected through several tube wells along the coast of Oman, and this increased the level of groundwater and reduced the intrusion of seawater from 3.4 to 2.7 km, pushing back the saline zone by 700 m (Shammas 2008).

Generally, treated wastewater can be used in the industrial sector since they do not require high-quality water. In 2009, oil refining and natural gas processing sectors were responsible for almost 40% of water withdrawals in Saudi Arabia. Riyadh Refinery can be considered as one of the best case studies of reusing secondary treated wastewater, rather than desalinated water, by the industrial sector in the GCC countries. Rather than relying on desalination, this refinery substantially reduced the water withdrawals from 12,200 m^3/day to 3,800 m^3/day, by the reuse of wastewater, reducing the cost by half and using 66% less energy compared to reverse osmosis desalination (Kajenthira et al. 2012). The case study also indicated that if similar water reuse measures are applied for all other refineries in Saudi Arabia that rely on desalinated seawater, this would save approximately 199 MCM annually, as well as savings of about USD 105 million annually, and lowering energy consumption and CO_2 emissions by 1.79 billion kWh and 1.75 billion kg CO_2, respectively. Moreover, industrial wastewater is also being treated and reused in the GCC countries. For example, Qatar Gas, the world's largest natural gas company, has increased its wastewater recycle rate to 70% (Jasim et al. 2016). Moreover, another success story is the Gulf Petrochemical Industries Company (GPIC) in Bahrain, with total water needs of 341 MCM/year, approximately recycle 66% of the total water used in the operations and the rest of the water requirements are met by the desalination unit (VNR 2018). Unfortunately, there are not many data on the use or treatment of industrial wastewater.

5 Major Constraints of Wastewater Reuse

Although treated wastewater reuse is valued as a strategic opportunity in increasing agricultural water supplies, a number of bottlenecks limit its full utilization in the GCC countries. These include social (public attitudes, reliability), health and environmental (quality of produced treated wastewater by adopting standards for reuse), and economic considerations (transportation and cost recovery), which should be considered in any reuse strategy. The following are the details of the main constraints for reusing treated wastewater in the GCC countries.

5.1 Public Acceptance

The success of planning, implementing, and attaining long-term wastewater reuse programs depends primarily on the acceptance and readiness of the public as one of the major stakeholders, especially the potential end-users for accepting reusing treated wastewater as an alternative water resource. Therefore, it is extremely crucial to explore people's attitudes and identify the factors affecting their perception, such as age, educational level, knowledge, gender, income, religious views, culture, emotional or psychological disgust, trust, health risk perception, treated wastewater quality, residential location, willingness for paying for various purposes, and many other factors (Zimmo and Imseih 2010; Fielding et al. 2018). Understanding the factors is vital for developing effective stakeholders' engagement in wastewater reuse programs and achieving the country's reuse targets (Dolnicar et al. 2011).

Logically, higher education and more basic knowledge about water scarcity threats, water production and supply costs, cleanness of wastewater treatment, and the benefits of reusing treated wastewater are associated with higher acceptance (Garcia-Cuerva et al. 2016; Akpan et al. 2020). However, this can differ between countries. Public acceptability of reusing treated wastewater has started to increase among the farmers in most of the GCC countries (Alkhamisi and Ahmed 2014). Abdelrahman et al. (2020) concluded that the majority of respondents in a survey, from 1304 UAE residents, supported the use of treated wastewater in irrigation, irrespective of their educational level, age, and income. This positive perception was observed in the UAE for outdoor activities that do not involve physical contact (Cristóvão et al. 2012). Public acceptance and willingness to implement reuse projects in the UAE are highly connected with the grade of awareness of water scarcity in the country (Kretschmer et al. 2000). Moreover, a study in Kuwait with 75% of respondents did not object to use the reclaimed water, from the advanced Sulaibiya WWTP, for agricultural irrigation, car washing, and domestic cleaning. However, 78, 77, 60, and 52% refused this water to be used for cooking, drinking, showering, and clothes washing purposes, respectively, even the ones that possessed enough knowledge, regardless of its quality and cost (Alhumoud and Madzikanda 2010). Ouda (2013) indicated that the majority of the community in Saudi Arabia is unaware about water production and distribution costs, water shortages, and water resource problems. Furthermore, a survey for studying public attitude toward wastewater reuse practices (Alataway et al. 2011) on 400 consumers in two main agricultural cities in Saudi Arabia, namely Al-Hassa and Tabouk, concluded that Al-Hassa residents were more supportive than those in Tabouk. The reason attributed to that experience or familiarity with wastewater reuse, i.e., in Al-Hassa, reduced the level of people's concern.

Some studies showed that acceptance was low with great opposition among people other than farmers, which poses a serious challenge toward efficient and sustainable reuse of treated wastewater. For instance, Dare and Mohtar's (2018) study revealed that the preference in Qatar was for fresh or desalinated water rather than treated wastewater in agriculture, as a result of being a wealthy country with high living standards. In addition, consultations with Qatari experts indicated that most people view wastewater unsafe for reuse in agriculture, and they also feel oversight and monitoring were insufficient. In Saudi Arabia, a recent study (Mu'azu et al. 2020) was conducted on 624 households to assess public perceptions investigating the socio-demographic variables influencing the reuse of wastewater and recycling of greywater for non-domestic uses, such as firefighting, swimming pools, and car washing. The results indicated that the acceptance of reusing treated wastewater, even among educated people, was low even after treatment no matter what the treatment level was and regardless of the technologies employed. However, the study indicated more acceptance of greywater recycling. The study indicated that the reasons behind this were psychological repugnance and the relatively large subsidy for freshwater supplies. It concluded that key factors for the success of large-scale adoption of treated wastewater are high literacy rate, intensive awareness campaigns for changing behavior, and the capacity for detecting pollutants and germs in the reused wastewater.

There are some indications that public awareness toward wastewater is changing positively with time in the region. For example in Bahrain, a relatively old study assessed the public's knowledge toward wastewater along with public attitudes of reuse and revealed that most of the surveyed individuals were not aware of the simple basic aspects concerning wastewater (Madany et al. 1992). The respondents strongly opposed using reclaimed water regardless of their conditions and were willing to pay in order to avoid using it. Another study, nearly twenty years later, showed that the psychological factor became the main barrier to not using treated wastewater, after the health risk factor, which means greater confidence in the efficiency of the wastewater treatment technology and its ability to eliminate microbes. Despite this, the psychological factor remained a major obstacle to the utilization of this water resource, and this was not related to gender or age, but it was often related to the level of education. This rejection decreased whenever the use was far from the human body, as in irrigating freshly eaten vegetables and gardens as well as in industry. It was also found that most of the individuals are still willing to pay more to avoid using treated wastewater under any circumstances (Al-Malood et al. 2010).

Most likely, religion is one of the main reasons for opposing the use of treated wastewater, especially in the GCC countries. Many are unaware that Islam does not contradict reusing wastewater, provided that it presents no health risk and will not cause harm (Faruqui et al. 2001) and the Quran indicates that impurities in water can be diluted to be made more pure (Wilson and Pfaff 2008). Indeed, Islam is supporting the preservation of water cleanliness and this advocates capturing, treating, and reusing wastewater (Amery and Haddad 2015). In 1978, a fatwa (Islamic juridical declaration) had been issued by Scholars of Islam in Saudi Arabia stating: "Impure wastewater can be considered pure water and similar to the original pure water, if its complete advanced treatment is capable of removing impurities with regard to taste, color and smell, as witnessed by specialized, knowledgeable and honest experts. If there are negative impacts from its direct use on human health, then it is better to avoid its use, not because it is impure but to avoid harming human beings." This fatwa lessened any religious concerns and paved the road of reusing treated wastewater in Saudi Arabia, Gulf, and Islamic countries (Ouda 2016; Dare and Mohtar 2018).

In order to make farmers and all people rethink the different aspects of wastewater and raise their acceptance toward reuse practices; awareness and education programs are needed (Dawoud 2017) to improve their knowledge of the capabilities of treatment methods and accurate detection of pollutants before reuse (Mu'azu et al., 2020). In addition, gaining public trust by assuring the good quality of treated wastewater (Alsharhan and Rizk 2020b) and establishing a technical guiding framework for implementing reuse programs are needed to reduce public concerns and guarantee reliability or steadiness of continuous supply of treated wastewater. Moreover, applying economic tools, such as tariffs, on the heavily subsidized current freshwater supplies (i.e., groundwater and desalinated water) would help convince users to accept treated wastewater and in achieving the target of full reuse of wastewater (Qureshi 2020).

5.2 Environmental Health Concerns: Standards and Regulations

While wastewater has numerous positive economic, environmental, and security benefits, and contributes considerably to decreasing the burden on the threatened groundwater, its reuse remains subject to physical, chemical, and biological restrictions and concerns. Risks to human health and environmental quality are a serious bottleneck for reusing wastewater in agriculture (Kehrein et al. 2020). Wastewater treatment is designed to eliminate long-term chemical risks, such as suspended solids, dissolved and particulate organic matter, nutrients (mainly nitrates and phosphates), and heavy metals and immediate microbial risks. Regulating wastewater reuse and discharge depends on microbiological and physical–chemical standards. Poor treatment and inadequate management guidelines can result in pollution with microbial pathogens and toxic chemical components, even if discharged to the environment without reuse affecting marine organisms and mangroves. Therefore, it is critical that wastewater effluents are effectively treated, and then monitored to ensure a safe supply and reuse.

In order to ensure the safe use of wastewater for workers as well as consumers, sanitation standards and health guidelines within the requirements of the WHO must always be followed (WHO 2018). All GCC countries are strictly following national and international low-risk guidelines and quality standards, based on high technology and high-cost approach, (e.g., California and USEPA standards) to eliminate those impacts. The quality of treated wastewater is typically defined in terms of its regulations set (Alkhamisi and Ahmed 2014). Table 3 shows the guidelines for wastewater reuse in agriculture in GCC countries for restricted agriculture. These standards and regulations outline the degree of wastewater treatment levels and the irrigation methods to determine the compatibility of reuse in crop production (Lahrich

Table 3 Standards of reuse of treated wastewater for restricted irrigation in the GCC countries

GCC country	Chemical and Microbial parameters											
	pH	Turbidity	TDS	TSS	BOD	COD	NH_4	NO_3	Phosphate	Fecal Coliforms	*E. coli*	Helminth eggs
		NTU	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	Count/100 ml	Count/100 ml	Egg/L
Bahrain[a]	6.5–9	2	3,500	10	10	40	1	10	1	<1,000	<2.2	<0.1/1000
Kuwait[b]	6.5–8.5	–	1,500	15	20	100	15	–	30	400	20	<1
Oman[c]	6–9	–	2,000	15	15	150	5	50	30	200	70	<1
UAE[d]	6–8	5	2,000	20	10	150	–	–	–	<1,000	–	<1
Qatar[e]	6–9	2	2,000	50	50	150	1	–	30	0	–	<1
Saudi Arabia[f]	6–8	5	2,000	10	10	50	5	10	1	1000	23	1

Data Sources [a](Government of Bahrain, 2020); [b](Abusam and Shahalam 2013); [c](Baawain et al. 2012); [d](Dalahmeh and Baresel 2014) representing Abu Dhabi; [e](Darwish et al. 2015); [f](Al-Jasser 2011) et al. 2021), in order to be free from health hazards. However, inadequate operational experience, high operational and maintenance costs, regulatory control, limited monitoring and evaluation of wastewater quality, and overlapping roles of organizations involved in the collection, treatment, monitoring of quality, and public health protection may have adverse effects and sometimes restrict its use in agriculture in the GCC countries (Qureshi 2020).

In arid and semi-arid zones, salinity can be considered the most significant environmental risk and heavy metals are a potential health risk (Elgallal et al. 2016). In Bahrain, infiltration into the old wastewater collection or distribution infrastructure network by shallow water levels resulted in increased salinity levels of the produced treated water, affecting the suitability of its reuse (Al-Zubari et al. 2017). The risk of heavy metals accumulation in soil could also be critical under the prevailing alkaline soil conditions in the GCC, increasing the probability to be immobilized and exceeding the maximum allowable limits (Al-Zubari 1998). Therefore, it is important that industrial wastewater, as a source of heavy metals, be kept separately and prevented from entering or mixing with domestic wastewater network, affecting the efficiency of treatment and eventually reuse.

The occurrence of diseases, caused by pathogens particularly bacterial (as fecal coliforms and *E. coli*), helminth eggs, protozoa, and viral pathogens can be associated with wastewater. Research conducted in UAE (Khan and Dghaim 2016) examined the risk of contamination from microbial pathogens of four public parks in Dubai irrigated by treated wastewater. Most of the tested samples (total 96 samples) were found contaminated with bacterial indicators and protozoan parasites. The study results indicated that microorganisms are surviving in treated wastewater, soil, and in the irrigation network system, and recommended that further monitoring of treated wastewater at the point of end use is vital to avoid the risk from microbiological contamination. In Bahrain, helminthic infections had posed a great risk that prevented the authorities from distributing treated wastewater to farmers (WHO 2004). Moreover, emerging concerns, of pharmaceuticals, antibiotics, disinfectant by-products, and personal care products in wastewater pose an additional threat (Jasim et al. 2016) and should be studied and considered carefully in the design of WWTPs (Ouda 2016).

Additionally, the COVID-19 pandemic, caused by coronavirus (SARS-CoV-2) spread, has also raised several concerns and revealed the world's under-preparedness to tackle incidents of disease outbreaks. The COVID-19 outbreak, emerged in China, was declared by the World Health Organization (WHO) in March 2020. This pandemic had caused turbulence to the GCC economies and major downfall in oil demand across the globe (Al Rashdi et al. 2020). The pandemic had led to the emergence of a number of previously unexperienced risks, affecting the water supply and wastewater sectors in an exceptional way and highlighting the importance of sufficient safe water supply, proper sanitation, and sound Water, Sanitation, and Hygiene (WASH) services, along with awareness, as necessary issues to reduce the spread of the SARS-CoV-2 virus. To combat the COVID-19 virus and limit its spread, all the GCC countries had implemented partial and/or complete curfews, by closing many sectors including governmental, educational, industrial, and commercial, or at least restricted their operations and to continue their responsibilities from home. These conditions had affected the water supply, the volume of generated wastewater and altered the peak periods of both. To overcome the challenges and mitigating risks associated with the pandemic, the GCC Secretariat General conducted several virtual workshops. Personal attendance of workers in the water supply and sanitation sectors was considered essential, allowing them to go to work during curfew hours. Moreover, shortage of spare parts and chemicals, due to the closures of borders, had a direct impact on the operation and maintenance of water supply stations and wastewater systems in terms of capacity and quality. In response, some GCC countries have begun to increase their dependence on locally produced materials or materials produced in other GCC countries (Al-Zubari and Al-Rashidi 2020). This indicates the significance of localizing the water technologies, wastewater besides the desalination, at least spare parts, in the region.

The virus cannot only affect the respiratory system, but also the gastrointestinal tract. Recently, several studies reported the existence of the genetic material, ribonucleic acid (RNA), of the virus in wastewater treatment plant samples. Research on the removal of coronavirus in municipal and hospital wastewater, by disinfection technologies, is required to reduce the risk associated with the virus. Lack of a standardized protocol for detecting SARS-CoV-2 in wastewater is a crucial challenge because there is limited knowledge on how to do this efficiently. However, no additional measures specific to COVID-19 were recommended by the WHO. Tertiary or advanced treatment with the final disinfection step, such as chlorine, ozone, and ultraviolet light should be used to produce water free of viral pathogens (Lesimple et al. 2020; Lahrich et al. 2021). The only concern in the GCC countries is about the safety of the workers in the WWTPs, since wastewater is treated at the tertiary level before being reused, and this needs precautions that later became standard practices, as wearing appropriate personal protection equipment (PPE); frequent applying hand hygiene; avoiding touching their faces; and practicing social distancing (Al-Zubari and Al-Rashidi 2020).

It is important to mention that the use of wastewater as a tool to detect COVID-19 prevalence, known as wastewater-based epidemiology (WBE), is not widespread, but it is beginning to expand. The presence of SARS-CoV-2 RNA in municipal wastewater may predict the virus occurrence qualitatively and quantitatively. This has the potential to give an alert and an early sign to monitor COVID-19 spread within a community, if the virus rises above the threshold, allowing for quicker action and containing the infection before its spread at an alarming rate (Al Huraimel et al. 2020; Mandal et al. 2020). A few articles reported a correlation of the viral genetic material concentration in wastewater with the number of COVID-19 confirmed cases. The United Arab Emirates was the first Arab country to detect SARS-CoV-2 in wastewater samples (Albastaki et al. 2021; Hasan et al. 2021). A large number of municipal wastewater samples (2940) and aircraft wastewater samples (198) were tested in the Albastaki et al. (2021) study, and the results showed a direct correlation between cases of COVID-19 recorded in Dubai and the viral load. It is important to point out that eleven WWTPs influents in UAE tested positive for SARS-CoV-2 on different dates, however, none of the 11 WWTPs effluents tested positive during the entire sampling period, indicating that wastewater treatment is efficient in removing the virus, and confirming the safety of reusing treated wastewater (Hasan et al. 2021).

These constraints could be minimized by risk assessment where barriers are added to reduce both the possibility and severity of contamination. Treated wastewater should be used for irrigation under controlled conditions after ensuring no health risks arising from potential pathogenic and toxic pollution to the users, agricultural products, soils, surface, and groundwater (Alkhamisi and Ahmed 2014). In addition, developing a framework on wastewater, which highlights the implementation of sanitation safety plans that minimize the risks of reuse and enhance the trust in treated wastewater, is urgently needed and essential, to secure the long-term sustainability of the system.

5.3 Economic Constraints

Although most of the central cities in the GCC have WWTPs generally built near the residential domestic areas to reduce the infrastructure cost of transferring the untreated wastewater to those WWTPs, their established infrastructures do not cover all of the expanding areas, especially in the big areas of Saudi Arabia and Oman. WWTPs are sometimes far away from the agricultural areas and transportation costs of treated wastewater to the crop production areas could be an economic constraint. For example, the Al-Ansab treatment plant, the largest wastewater treatment plant in Muscat, Oman, is about 100 km from Al-Batinah agricultural area where the treated wastewater is needed, and Sulaibiya WWTP in Kuwait is about 120 km far from Al-Abdali agricultural area. Along those distances, treated wastewater is transferred through pipes and may have to be stored (Abdul-Khaliq et al. 2017). In response to the high transportation costs, there has been a growing emphasis on the potential advantages of adopting "decentralization approaches" to sanitation management, which are believed to be appropriate for peri-urban areas (areas with a mix of rural and urban characteristics and land uses). This will offer opportunities for wastewater reuse and also offer increased improvements in the environmental health conditions (Parkinson and Tayler 2003; Capodaglio 2017), and most importantly, has a considerable security effect.

There is a growing trend toward decentralization worldwide and large-scale centralized wastewater treatment systems may no longer be the best option for urban water management. Recently, GCC countries have moved to the decentralized wastewater system (Al-Zubari and AlAjjawi 2020). They allow for the recovery of nutrients and energy, save freshwater, and help secure access to water in times of scarcity (UN WWAP 2017). Internal decentralized treatment facilities in different industries will reduce the pollution load to domestic WWTPs, and then they can use their own treated wastewater, principally in cooling, sand washing, and construction purposes (ACWUA 2010). A study in Saudi Arabia (Kajenthira et al. 2012) indicated that the potential for expanding urban wastewater reuse in high altitudes and/or inland cities is effective, and can result, if applied in only six cities, in financial cost and energy savings of about USD 225 million (2009 dollars) and $4*10^9$ kWh annually.

As indicated earlier, water tariffs are generally very low, heavily subsidized by the governments, and are widely seen in the GCC as an economic right and a basic human need (Economist 2010), but this situation has a negative impact on the full utilization of treated wastewater. Currently, wastewater collection, treatment, and even distribution services are provided free of charge (with literally zero cost recovery) in the majority of the GCC countries (except for Oman, and recently in Saudi Arabia and Qatar), which does not provide an incentive for water savings, especially in the agricultural sector, and lowers the probability of large investments in wastewater projects. This will increase the financial burden on the government budget. Therefore, applying a proper tariff, which is lower than other water resources, on sanitation services linked to domestic water supply bills can reflect the economic value of the service and provide some cost recovery and financial stability. The funds generated could then be used to expand plants' capacities, ensure their adequate maintenance and operation costs, collection and transportation of the water (Abdul-Khaliq et al. 2017). Moreover, adding tariffs as a percentage of the domestic use can also be used as an economic tool to lower water consumption. The National Water Company in Saudi Arabia had completed a comprehensive study to evaluate the willingness and ability to pay for treated wastewater and to identify treated wastewater tariff for various sectors. The industrial and commercial sectors had the highest willingness to pay. Accordingly, a new wastewater tariff was introduced for the government, commercial and industrial sectors in December 2015, raising the potable water cost to USD 1.6/m^3 and introduces a wastewater service cost of USD 0.8/m^3 (Ouda 2016).

5.4 Other Constraints

The wastewater sector has zero control on the driving forces or the direct pressures of the wastewater system inflow and outflow and is considered as a reactive sector to the municipal water supply sector. Hydraulic loadings, which occur on some occasions as a result of rapidly increasing municipal water demands and overwhelming generated wastewater volumes beyond the TWWP capacity, decrease the efficiency of wastewater treatment and increase the carryover volumes, leading to the discharge of untreated or partially treated wastewater into the environment and increasing pollution. The capability to deal with these hydraulic loadings depends mainly on the integrated planning and cooperation between the water supply and wastewater sectors as well as other relevant agencies (Al-Zubari and AlAjjawi 2020). Therefore, institutional arrangement, between the water supply, wastewater, health, agriculture authorities, is needed in all the GCC countries to ensure the coordinated and effective utilization of the treated wastewater. Moreover, many of the GCC countries face fragmentation of legislation that is scattered among agencies, overlapping responsibilities (e.g., water resources authorities and agricultural authority), and weak enforcement of water regulations. Currently, no country, except Saudi Arabia, has a comprehensive "Water Law." Nevertheless, the majority of the GCC countries have a policy for expansion of the reuse and incentivizing farmers, like Bahrain, that provides free delivery of treated wastewater to 92% of all agricultural lands (Al-Zubari and AlAjjawi 2020).

6 Potential Future Contribution of Wastewater

The population of GCC countries is projected to reach 68 million by 2035 (UN 2019), which will increase domestic water consumption and subsequently wastewater generation rates. Dawoud (2017) indicated that the production of wastewater has been increasing by 11% annually in the GCC countries, and by 2030 volumes of treated wastewater would reach about 17 BCM. Future potential for increasing the reuse of treated wastewater is recognized as one intervention strategy for developing unconventional water resources in the GCC countries. Hence, the expansion of the reuse of treated wastewater for irrigation and other activities could contribute greatly to reducing water scarcity in the region. For this to be accomplished, adequate political will, sound laws, policies, strategies, and frameworks, private sector participation, intensive public awareness campaigns, and finance plans are necessary for successful achievement of this goal. Meeting the country's increasing water demands necessitates adopting a national sanitation law or strategic wastewater reuse policy that includes regulations not only for enhancing the treatment efficiency, but also for maximizing the reuse of treated wastewater. Such initiatives can conserve non-renewable oil and gas resources consumed in desalination.

This was clearly reflected in the strategic objectives (SOs) of the Unified Water Strategy (2016–2035) for the GCC countries (GCC-UWS), which has been approved by the GCC Supreme Council in 2016 during their 37th Gulf Summit. Treated wastewater reuse in agriculture has been emphasized in a number of strategic objectives that have been formulated to address this topic (Table 4). SO3 is dedicated to wastewater and targets to increase the collected wastewater to reach at least 60% of the municipal water supply, to maximize wastewater treatment and reuse up to 90% by 2035 in each GCC country. Moreover, it aims to raise the WWTPs capacities, the level of treatment, treated wastewater reliability, decentralization, and privatization, in order to expand the reuse plans and reduce the environmental impacts of wastewater disposed without utilization and/or treatment. In addition, the GCC-UWS aims to protect groundwater resources from depletion and deterioration, increase water efficiency in the water-consuming sectors, localize desalination and water treatment technologies in the region, improve water governance, and increase economic efficiency. Furthermore, the overall strategic objectives are to help guarantee achieving long-term level of water security and sustainability to the water sector in the GCC countries (Al-Zubari et al. 2017).

With the aim of highlighting the numerous benefits of implementing the GCC-UWS targets, three management intervention future scenarios were modeled using

Table 4 Strategic Objectives (SO) of the GCC-UWS (Al-Zubari et al. 2017) related to the wastewater sector

SO1:	**To Acquire Technology Development and Manufacturing of Desalination and Water Treatment Plants and Diversification of Energy Resources**	
	1.1	Establishing joint GCC desalination and water treatment industry
	1.2	Establishing an advanced joint GCC R&D base in desalination and water treatment
	1.3	Developing professional and technical capacity in desalination and water treatment in the GCC
	1.5	Mitigating the impacts of desalination and water treatment practices on the environment
SO3:	**To Maximize Municipal Wastewater Collection, Upgrade Treatment, and Increase Economic and Safe Use of Treated Wastewater and Sludge**	
	3.1	Increasing wastewater collection rates, treatment capacities, and treatment levels
	3.2	Increasing treated wastewater reuse in all appropriate sectors
	3.3	Enforcing legislation related to the protection of health and environment in all stages of collection, treatment, and reuse of domestic wastewater
	3.4	Maximizing the beneficial use of wastewater sludge
SO4:	**To Achieve the Highest International Standards of Water and Wastewater Services**	
	4.1	Ensuring the highest international standards of water supply and sanitation services to all populated areas in the GCC countries
	4.3	Achieving the highest management standards for sanitation utilities
	4.4	Enhancing the capacity and performance of Water Supply and Sanitation personnel
SO6:	**To Establish a Water-Efficient and Rational Agricultural Sector Compatible with the Available Water Resources**	
	6.1	Improving water use efficiency and increasing water productivity in the agricultural sector
	6.2	Increasing the use of treated wastewater in agriculture in conformity with reuse standards
SO8:	**To Improve Governance in the Water Sector to Achieve Effective and Integrated Water Resources Management**	
	8.1	Ensuring integrated planning and coordination among water-related sectors in each GCC country
	8.2	Ensuring water sector regulation
	8.5	Providing water data and information for decision-making support

(continued)

Table 4 (continued)

	8.6	Customizing water-related standards compatible with the GCC countries conditions
SO9:	**To Achieve Water-Oriented Society in the GCC Countries**	
	9.1	Building water importance and value awareness for the future generation
SO10:	**To Minimize Water Supply Economic Costs and Increase Cost Recovery while Maintaining the Quality of Service**	
	10.1	Giving water an economic value in the GCC countries
	10.3	Increasing public–private partnership in the water sector
	10.4	Adopting and implementing "polluters pay" principle in the water sector

WEAP[5] Modeling System (Al-Zubari et al. 2017). These management scenarios were: (1) increasing wastewater collection rate to 60% (currently averaging 57% but varies among the countries), (2) increasing irrigation efficiency to 60% (from the low level of 35–40%), and (3) decreasing per capita water consumption to 250 l/day. The results were then compared with the reference (2012 data) scenario that represents the Business-As-Usual conditions (Fig. 7). The simulation results indicated that the potential of the generated wastewater, if properly treated and fully reused, would completely fulfill all the agricultural water needs in Bahrain, Kuwait, and Qatar (averaged 50% of the total water demands in the GCC countries). These countries would also have a surplus of treated wastewater, which can be used for expanding agriculture or for other purposes. However, for Oman and Saudi Arabia, the generated wastewater will contribute to only about 15% of the requirements of the agricultural sector, because the municipal sector has a small share of their total water demands (12%) while the agriculture sector represents around 84% of the total water consumption. It should be noted that these figures can be achieved taking into consideration the per capita use reduction to 250 l/day, and without this scenario more wastewater will result in more recovery in agriculture. Moreover, these management scenarios are associated with potential savings in financial, economic, and environmental costs. Consequently, the reuse of treated wastewater should be integrated into the water management and security strategies for all the GCC countries, side by side with the water conservation plans (reducing the consumption of water, reducing the water losses, improving the efficiency in the use of water, and raising awareness). It is important to mention that the study projected the increase in the GCC water demands. Under the current (Business-As-Usual) conditions, total municipal water supply requirements in the GCC countries are expected to increase from 5.7 BCM in 2015 to about 11 BCM in 2035 (50% more in 20 years), however, when implementing a management intervention scenario, the increase will reach about 7.3 BCM in 2035 (with 3.7 BCM reduction).

[5] WEAP (Water Evaluation And Planning) dynamic modeling software that takes an integrated approach to all water resources.

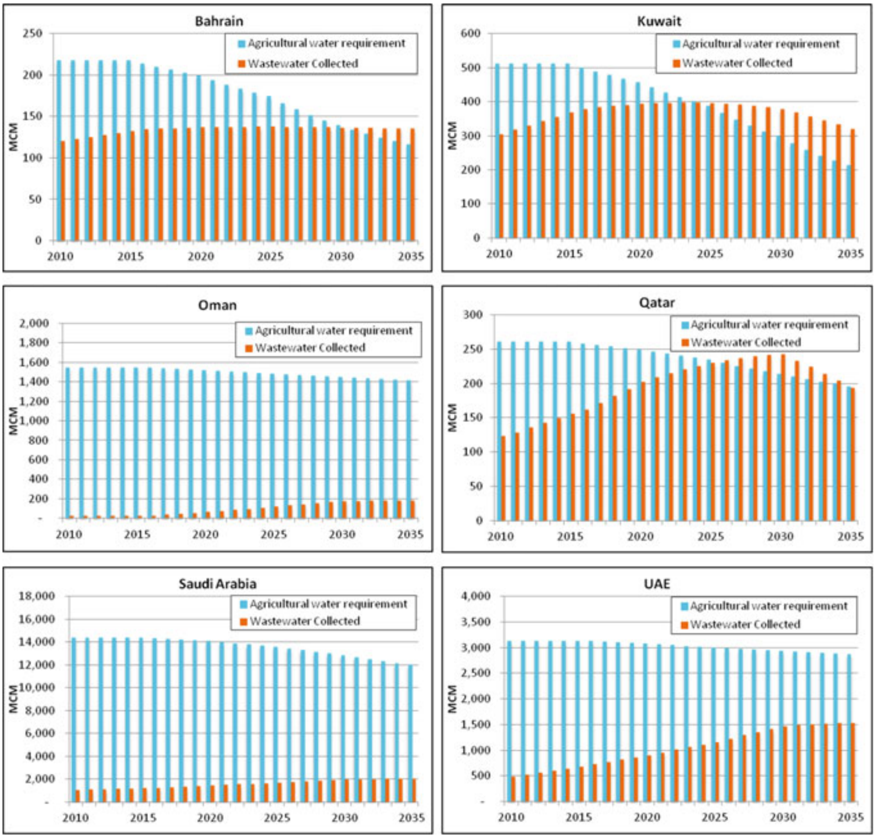

Fig. 7 Potential of wastewater contribution to the agricultural sector in the GCC countries, after implementing three scenarios representing the GCC-UWS targets, i.e., increasing wastewater collection to 60%, increasing irrigation efficiency to 60%, and decreasing per capita water consumption to 250 l/day (Al-Zubari et al. 2017)

7 Conclusion and Recommendations

Currently, the GCC countries' water requirement (around 32 BCM) is met by groundwater abstraction and surface water harvesting (79%), desalination (18%), and very limited reuse of treated wastewater (3%). Water demand in the GCC countries is predicted to rise dramatically and, consequently, municipal wastewater generation will increase steadily. Treated wastewater has been adopted in the GCC countries as a non-traditional alternative water resource among other water resources. Great efforts have been made to provide access to sanitation services, and establish many of modern wastewater treatment plants, with mostly tertiary and advanced treatment capabilities, in all the GCC countries. Although the GCC countries treated about 95% of the collected municipal wastewater in 2018, the reuse of this treated wastewater was only about 35%. Much of this treated wastewater is discharged into the marine and coastal environment without being used, even when treated to a tertiary level. As a result, the potential for reusing this generated wastewater is not fully developed until now and the reuse of treated wastewater is still in its early stages of development, representing a major untapped opportunity under the current water scarcity conditions of the GCC countries. However, many ambitious plans have been announced in all the six countries to increase the reuse share in their total water budget and water supply portfolio, in order to meet their future demands for irrigation water and other purposes. In response, the following should be kept in mind to ensure complete utilization of treated wastewater:

- The produced wastewater will be treated, due to environmental considerations, irrespective of whether it is going to be used or not. Therefore, maximizing the reuse should be addressed as a much better option than discharge, from environmental and economic perspectives to minimize the contamination and reduce the environmental footprint of wastewater treatment.
- The evolving necessity to conserve valuable groundwater and energy resources require policymakers to give more consideration to the potential benefits of wastewater, such as: (1) Reuse will protect groundwater from depletion and from deterioration in water quality. (2) Reuse is a better choice than desalination, at least for non-potable water needs, because it consumes less energy and at the cost is much lower than that of desalting seawater. (3) Reuse can reserve freshwater resources for priority uses and help alleviate water scarcity in the region. (4) Reuse can contribute significantly to cover the water needs of the agricultural sector, the GCC's biggest water consumer. To achieve these benefits tertiary treatment should be increased, and 100% reuse should be accomplished.
- Monitoring and enforcing strict standards and legislation to ensure proper wastewater treatment, avoid health risks and environmental impacts and guarantee wastewater reliability, requires more consideration and should be addressed as a priority.
- Decentralization and privatization policies will marginally guarantee the security and safety of treating and reusing wastewater and will also reduce the financial and environmental costs.
- The reuse potential can be increased if coupled with demand management in the agricultural sector. Therefore, a policy to shift toward demand management by improving water use efficiency, especially in irrigation systems, controlling collection and distribution networks, leakage and rehabilitation are all of interest to the sector.
- Complete utilization of treated wastewater can only succeed with a positive public perception toward reusing. Therefore, there is a necessity to launch awareness programs and campaigns for farmers, as well as for the public, to address the water scarcity problem and water supply costs, and to overcome social and religious concerns regarding the use of treated wastewater in agriculture, landscaping, and other purposes.

- Reducing the large government subsidy of water supplies by revising and restructuring the water tariff is an important step for raising people's perception toward the importance of wastewater. In addition, developing an effective cost recovery mechanism (tariff on wastewater reuse) to fully recover the cost will reduce the burden on governments and ensure the long-term availability of this water resource.
- Institutional arrangement, or at least integration and strengthening institutional cooperation between the water supply, wastewater, health,and agriculture authorities is required in all the GCC countries to avoid fragmentation of legislation, weak enforcement of water regulations, and to ensure effective utilization of the treated wastewater.
- Finally, all the GCC countries are considering the wide-scale expansion in the reuse of treated wastewater as a major part of their Integrated Water Resources Management policies, plans, and investments to overcome the constraints and the main management challenge in the wastewater sector, which is the large mismatch between treated and reused wastewater quantities.

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