TOWARDS A MORE SUSTAINABLE WATER MANAGEMENT SCHEME FOR QATAR

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Ibrahim G. Al Khoury

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Nomenclature

AD: Anaerobic Digestion

DSWMC: Domestic Solid Waste Management Centre

GCC: Gulf Cooperation Council

GHG: Greenhouse Gases

LCD: Litres per Capita per Day

MCM: Million Cubic Meters

MED: Multi-effect Distillation (MED)

MIGD: Million Imperial Gallons per Day

MSF: Multi-Stage Flash distillation (MSF)

MSW: Municipal Solid Waste

OFMSW: Organic Fraction of Municipal Solid Waste

PED: Price Elasticity of Demand

RO: Reverse Osmosis

TSE: Treated sewage effluent

Abstract

Qatar is an arid country with limited natural freshwater resources due to low rainfall and high evapotranspiration. The country, having the third largest natural gas reserve in the world, relies primarily on fossil fuel-powered seawater desalination to meet domestic water demand, estimated at around 600 liters per capita per day. Additionally, groundwater is being depleted to supply the agricultural sector, which consumes about 230 million cubic meters of freshwater each year. Hence, this paper aimed at improving the sustainability of the water management scheme of Qatar by developing a combination of water demand and water supply management strategies. On the demand side, the impacts of higher water tariffs and greywater reuse on domestic water demand were studied independently relative to the current conditions in which the increase in domestic water demand is met by a similar level of growth in desalination capacity. On the supply side, this study proposed increasing the reuse of treated wastewater effluent in irrigation and looked into the possibility of recovering a liquid fraction by anaerobic digestion of municipal solid waste for use in irrigation. Results revealed that maintaining the current approach to water demand management could result in domestic water demand exceeding supply by 12-51% in 2100, with a need to expand the desalination and water supply infrastructure capacity starting 2030-2040. Increasing water tariffs could reduce national demand by 24%, which would keep domestic water demand below the current supply capacity up to the year 2100 or delay the need for further expansion of the desalination and water supply infrastructure by several decades in comparison to the current conditions, depending on the projected population. The reuse of treated greywater in future residential units, however, could only save up to 1.7-8.4% of the national demand, assuming a 100% response rate and a 20-50%

reduction in domestic water use by recycling greywater. In terms of irrigation water supply, reusing 30-45% of the treated wastewater effluent can cover 32-56% of the agricultural sector water needs by 2100. Results also showed that the liquid fraction that can be potentially generated by anaerobic digestion of organic waste in Qatar covers merely 0.2% of the groundwater abstraction and therefore is not a promising source of water for use in irrigation.

Chapter 1

1. Research justification and objectives

1.1. Introduction

In the past few decades, freshwater scarcity has become a global threat to the sustainable development of societies, with half of the global population living under conditions of severe water scarcity at least one month of the year (An et al., 2021; Mekonnen & Hoekstra, 2016). The increasing world population, economic development, changing consumption patterns, and expansion of irrigated agriculture are the main driving factors of the rising global demand for water, and thus the pressure on freshwater resources (Liu et al, 2017; Rosa et al., 2021). In regions suffering from physical water scarcity, the state of the economy affects both demand and supply. It is the case of developing resource-rich countries, such as the ones in the Gulf Cooperation Council (GCC), where increasing water consumption is expected with higher standards of living, and water utility providers have the capacity to invest in costly water supply infrastructure (i.e. groundwater abstraction, seawater desalination) (DeFelice & Gibson, 2013; Oki & Quiocho, 2020).

Qatar (the case studied here) is an arid country located in the Arabian Peninsula, with a land area of 11,610 km^2, and is characterized by erratic rainfall averaging between 40 and 80 mm/year, high temperatures, and high relative humidity (AlMamoon et al., 2014). Due to its geographical position and climatic features, the country suffers from acute freshwater scarcity with renewable freshwater resources of 29 m^3/capita/year (2015), which is far below the worldwide average of 6000 m^3 and the water poverty threshold of 1000 m^3 (Alhaj et al., 2017; Alsheyab & Kusch-Brandt, 2018). Qatar, however, has the third largest natural gas reserve in the world and exports more than 20% of the world's liquefied natural gas

(Kim et al., 2020). Having experienced a tremendous increase in national wealth and a rapid population growth in the last three decades (Hussein & Lambert, 2020), Qatar currently meets domestic water demand using energy-intensive fossil fuel-powered desalination technologies, and consumers receive their water needs at a heavily subsidized cost (Baalousha & Ouda, 2017; Ibrahim & Shirazi, 2021). While desalination may alleviate the pressure on freshwater resources, it is accompanied by adverse impacts on the marine environment and significant greenhouse gases (GHG) emissions (Liu at al., 2015). In fact, the energy sector is the leading catalyst of air pollution in Qatar, contributing to 96% of the country's aggregate GHG emissions (Ibrahim & Shirazi, 2021), and nearly 13% of these emissions (109 Mt CO_2 eq.) was attributed to desalination in 2015 (Sahin et al., 2019). In addition, Qatar's agricultural sector relies heavily on groundwater abstraction for its supply, which resulted in lowering of the water table, deterioration of groundwater quality, and rising salinity over the years (Mohammed & Darwish, 2017).

With increasing water demand and limited freshwater supplies, water demand management has been applied as a tool in the integrated management of water resources to balance demand and supply either by developing new resources (supply-side management) or by managing water consumption before increasing available water supply (demand-side management) (Arfanuzzaman & Atiq Rahman, 2017; Thivet & Fernandez, 2012; Xiao, 2017). Consequently, water-scarce countries have developed strategies and technologies for water conservation and increased water use efficiency (Liu et al., 2020). Several studies have addressed the potential of water conservation in households using water-saving plumbing fixtures, greywater, and rainwater harvesting. Replacing conventional plumbing fixtures with water saving ones was shown to reduce domestic water consumption by nearly 30%, while greywater reuse and rainwater harvesting can save water by up to 20% and 30%, respectively (Cureau & Ghisi, 2019). Also, the role of water price increase as an economic tool for improved efficiency of water use has been investigated globally (e.g., Huang et al., 2010; Rinaudo et al., 2012; Rivers & Groves, 2013; Smith & Al-Maskat, 2007; Srouji, 2017). With the increased demand for food and agricultural products, water allocation and physical irrigation efficiency improvements were achieved using policies and innovative technologies to conserve water and increase agricultural production per unit of water (Dionisio et al., 2020; Koech & Langat, 2018; Mojid & Mainuddin, 2021). Furthermore, numerous countries facing drought and growing water scarcity have made a paradigm shift from traditional sources of water supply, such a surface water and groundwater, to non-conventional resources such as treated wastewater (Chojnacka et al., 2020; IWA, 2018), which became commonly reused in agricultural irrigation (e.g. Belhaj et al., 2016; Gatto D'Andrea et al., 2015; Helmecke, 2020; Jaramillo & Restrepo, 2017; Jeong et al, 2016). More recently, by-products generated from the anaerobic digestion of organic waste in the form of solid residues and liquid digestate from composting reactors and maturation fields are being applied for irrigation and also transferred to external wastewater treatment plants for proper management (Guido et al, 2020; Seruga et al., 2020).

In Qatar, projects that have been implemented to reduce domestic water consumption were limited to changing plumbing fixtures and promoting water saving and efficient use through conservation programs and awareness campaigns (Alghool et al., 2019). Qatar General Electricity and Water Corporation "Kahramaa" reduced the leakage of the water distribution network from 35% to 4% by 2016 (Kahramaa, 2017) and deployed

17,000 water meters in households, with plans to make them smart by 2024. These newly installed devices, however, are unlikely to monitor and bill more than 7.3% of households in 2020 (Hussein & Lambert, 2020). In terms of water supply for the agricultural sector, the Ministry of Environment imposed regulations to limit groundwater withdrawals and use efficient irrigation methods, which resulted in more than 50% reduction in the volume of water used per ton of agricultural produce between 1995 and 2013 (Alhaj et al., 2017; Mohammed & Darwish, 2017). Qatar also started incorporating the use of treated wastewater effluent in different applications, including irrigation (Planning and Statistics Authority, 2018a). Although substantial research evidence has shown that treated wastewater can be suitable for crop irrigation and growing food, its reuse remains restricted to landscaping among other sectors, with small amounts reclaimed to grow nonedible crops and fodder, due to health, social, and environmental concerns (Qureshi, 2020). Despite these initiatives, withdrawals remained many folds higher than the natural recharge rate of groundwater resources, which prompted future projects that will rely on desalinated water to artificially recharge the aquifers (Alhaj et al., 2017; Baalousha et al., 2017). Overall, desalination provides about 61% of the national water supply, while groundwater accounts to 25% and treated sewage effluent to 14% (Planning and Statistics Authority, 2018a). The combination of growing population and high consumption rates will put more pressure on desalination and groundwater, contributing to higher levels of energy consumption, GHG emissions, and aquifers depletion. Climate change is also predicted to aggravate the existing challenges of water scarcity by reducing the availability of water resources and arable lands (Meltzer et al., 2013). Qatar's mean annual rainfall has already fallen below its long-term average value of 84.9 mm/year and mean annual temperature has already increased by 0.3°C over the past four decades, with climatic projections predicting a further increase in temperature of 2.3–5.9°C by 2100 (Planning and Statistics Authority, 2018a; Planning and Statistics Authority, 2018b; Sowers et al., 2011).

This paper first reviews the status of water demands and supply resources in Qatar. National domestic water demand is then forecasted up to the year 2100 with respect to three governmental approaches to water demand management. The first approach considers that growing demand is met by continuous supply of desalinated water and no reduction in the consumer water use (current conditions), whereas the other two approaches incorporate the impacts of higher water tariffs and greywater reuse in future residential units on demand. The study also projects the volume of treated sewage effluent (TSE) that can be used to cover irrigation demand, either by keeping the same fraction of TSE currently utilized for agricultural irrigation and by adding the portion of TSE lost to evaporation lagoons to the existing reuse system. Moreover, it examines whether a substantial liquid fraction can be recovered by anaerobic digestion of municipal organic waste in Qatar so that it can be considered for further treatment and reclamation in irrigation. The outcomes of this research work may be used to develop future water management policies that can improve the sustainability of the water demand and supply scheme in Qatar.

1.2. Research objectives

The overall objective of this proposed research is to render Qatar's demand and supply management scheme more sustainable. To do so, this research will:

1- Forecast domestic water demand using different water demand values and population forecasts under the following demand management scenario: (a) maintaining the same approach to water demand management whereby increasing demand is met with continuous supply of desalinated water (b) increasing water tariffs (c) implementing in-house greywater treatment and reuse

2- Propose alternatives to conserve groundwater resources by: (a) managing the reuse of treated sewage effluent in irrigation and aquifer injection (b) seeking new non-conventional water resources for agriculture irrigation to limit groundwater withdrawals

1.3. Research questions

Several questions may be answered when carrying out this research, which are:

1- To what extent water tariff increase and greywater recycling in households can reduce domestic water demand for desalinated water?

2- To what extent the reuse of treated sewage effluent in agricultural irrigation can alleviate the pressure on depleting groundwater resources?

3- Can the liquid fraction generated by anaerobic digestion of municipal organic waste be a substantial source of water supply for agricultural irrigation?

1.4. Research hypotheses

The above questions will be examined under the following hypotheses:

Hypothesis #1: Meeting the increasing water demand can be partially achieved by managing consumptive demand trends in order to postpone or avoid the need to develop new resources. In Qatar, there exists a large gap between the price of water paid by consumers and the cost of water relatively to the producers. An increase in water price can induce an increase in the expected water savings and thus a reduction in desalinated water consumption and wastewater generation. Reducing water demand can also be met from existing resources such as greywater. Greywater is generally produced from showers, washing machines, swimming, pools, AC units, and lavatory sinks. It is less polluted than black water, which comes from toilets, kitchen sinks, and dishwashers. Consequently, greywater requires little to no treatment and can be safely used for several purposes, thereby replacing more expensive water resources such as desalinated water.

Hypothesis #2: Governmental water statistics show that Qatar withdraws nearly four to five times as much water from its aquifers than is replenished by rainfall each year. A small fraction of the treated wastewater is injected to help replenish the aquifers. It makes up about 26% of the water abstracted by the agricultural sector and is insufficient to balance extraction rates. More wastewater is expected to be generated due to population growth, and the increased use of treated wastewater in aquifer injection or in agriculture will have direct consequences on the groundwater balance.

Hypothesis #3: Different treatment methods (i.e. ammonia stripping, anaerobic ammonium oxidation, direct contact membrane distillation process, constructed wetlands, air stripping…) have been examined to recover the liquid fraction of AD effluent and remove nutrients prior to sending this liquid fraction to a conventional wastewater treatment plant. As municipal solid waste generation is expected to increase in Qatar due to population growth, the AD of the organic fraction of municipal solid waste (OFMSW) might be an attractive option to convert waste into renewable energy with a potential to recover a new water resource that should be considered in future research.

1.5. Research innovation

The sustainability of the water demand and supply management scheme in Qatar is at risk with population growth exerting more pressure on desalination and groundwater resources. Different studies have assessed water demand and supply resources in Qatar and provided recommendations for future water saving initiatives. Baalousha et al. (2017) reviewed the status of water resources and demands in Qatar (with data up to the year 2015) and discussed three different scenarios (optimistic, moderate, and pessimistic) of domestic water demand until the year 2040. In forecasting domestic water demand, the optimistic scenario used a population growth rate of 2.5%, the moderate scenario considered a growth rate of 5%, while the pessimistic scenario applied the average growth rate of 7.4% observed for the years 1955-2016. In more recent years, however, the Qatari population growth rate has been lower than these suggested figures. In fact, it reached 1.81% in 2019 and current estimates predict that the construction activity will be curtailed by 2022 when Qatar hosts the FIFA world cup, leading to a decline in the migrant worker's population and thus the overall future population (Karanisa et al., 2021). The scenarios were also based on different trends of domestic water demand; the optimistic and moderate scenarios assumed annual decreases of 2% and 0.5% in consumer water demand, while the pessimistic scenario considered no change in water demand for the forecast period. Although the results of this study highlighted the importance of reducing domestic water demand relative to the past desalination and water supply infrastructure capacity, the yearly reductions in demand of 2% and 0.5% used in the optimistic and moderate scenarios, respectively, were not derived with respect to specific water demand management strategies that would be implemented in the future but served to suggest initiatives and measures that can improve the sustainability of water resources development in Qatar. Moreover, Alhaj et al. (2017) conducted an in-depth review of Qatar's available renewable water resources, water consumption sources and patterns, water desalination plants, as well as Qatar's water footprint by calculating the virtual water flow for the country (with data up to the year

2014). The study also served to suggest water conservation policies and strategies that could improve the sustainability of the water management scheme in Qatar, underlining the need for an integrated approach that not only accounts for the demand but also the supply side management. In line with achieving this goal, the following research work provides an overview of the water management scheme in Qatar, using the latest data that could be found in literature (2017-2019), with the aim to improve its sustainability on the demand and supply sides. To do so, this study attempts to quantify the future trends in domestic water demand using probabilistic population projections up to the year 2100, with respect to the current domestic demand management approach. It then investigates the potential impacts of viable water saving strategies, mainly increased water tariffs and greywater reuse in future households, on domestic water demand. These strategies were developed based on local data, studies from the Arabian Peninsula, and global observations. This research work also looks into developing the water supplies of the agricultural sector by increasing the reuse of treated wastewater in irrigation and seeking a new non-conventional water source that may replace groundwater, which is the liquid by-product generated by anaerobic digestion of municipal organic waste. Reducing the consumption from modern non-renewable resources (i.e. fossil-fuel powered desalination) and reusing treated wastewater and other recovered resources in different applications fall under the circular economy lens and align with Qatar's National Development Strategy, which aims toward achieving the Sustainable Development Goals of the 2030 Agenda for Sustainable Development of the United Nations.

Chapter 2

2. Methodology

2.1. Rationale

Desalination is the main source of domestic water supply in Qatar, contributing to more than 60% of the country's total water demand (Planning and Statistics Authority, 2018a). The average per capita water demand in Qatar has been one of the highest in the world, varying between 216 and 242 m^3/capita/year for the period of 2015-2019 (Kahramaa, 2020). Anticipating the increase in national water demand with rising population, the country constructed two additional desalination plants, with a combined capacity of 172 MIGD, bringing the total supply capacity of desalination units from 328 MIGD (540 MCM) in 2014 to 500 MIGD (830 MCM) in 2017 (Rahman H & Javaid Z, 2018). To enhance water savings, Kahramaa invested in reducing the leakage of the water distribution network from 29% to 6% by 2016 (Planning and Statistics Authority, 2018a). It also spent 4 billion dollars in 2018 on the world's largest potable water mega-reservoir. The reservoir has been designed to provide seven days of reserve water supply in case of desalination shut-off, and is part of a project of 15 concrete reservoirs connected to the country's main desalination plants, each with a capacity to hold 100 million gallons of water (Hussein, & Lambert, 2020).

Qatar now relies on three desalination technologies for freshwater supply: the multi-stage flash distillation (MSF), the multi-effect distillation (MED), and reverse osmosis (RO). In order to reduce the environmental impacts associated with thermal desalination, there has been a shift of trend in desalination in Qatar to rely on using RO technologies to a greater extent, and the distribution of the overall capacity of desalination plants changed from MSF

(75%), MED (24%), and RO (1%) in 2010 to MSF (22%), MED (31%), and RO (47%) since 2016 (Rahman H & Javaid Z, 2018).

While plans are underway to expand the desalination plants supply capacity and meet the future water demand of the growing population for at least the next 50 years, this process is environmentally unsustainable (Alhaj et al. 2017). The thermal-based MSF and MED facilities are energy-intensive, consuming more than 20 kWh/m^3 of desalinated water, while membrane-based RO systems require an energy supply of 4-5 kWh/m^3 of desalinated water for operation (Darwish et al. 2016). Substantial GHG emissions result from burning fossil fuels in desalination processes. The carbon footprint associated with desalination ranges from 0.3 to 26.94 kg CO_2 eq/m^3 of water produced using MED and reaches up to 34.7 kg CO_2 eq/m^3 of water produced using MSF. For RO technologies, it is significantly lower and falls between 0.08 and 4.3 kg CO_2 eq/m^3 of desalinated water (Cornejo et al., 2014; Jiahong et al., 2015). Desalination also has negative effects on marine ecosystems due to the discharge of concentrated brine at high temperature into the sea (Darwish et al., 2013). Additionally, the country's future financial ability to maintain the same approach to water management could be compromised given the fluctuating fossil-fuel prices, which represent 70-80% of all desalination costs (Alhaj et al. 2017; Darwish et al., 2016). Qatari nationals are still granted desalinated water for domestic use free of charge, and non-nationals pay for water depending on the volume of water consumed past a given threshold (increasing block structure) at a highly subsidized cost: it starts at 1.21 USD/m^3 for the first 20 m^3 of monthly water use (55.84% subsidization rate) and rises to 2.58 USD/m^3 past 250 m^3 of monthly water use, while to the true cost of production and distribution of desalinated water is valued at 2.74 USD/m^3 (Mackey H et al., 2018; Srouji, 2017). In addition, although

Qatar has broad network system for the collection and treatment of domestic wastewater, greywater and black water are currently diverted into one sewer line before being sent for treatment through the main sewage network (Alghool et al., 2019).

Thus, two water demand management strategies were considered in this study to lower domestic water demand and desalinated water production: increasing water tariffs (Alternative 1) and the implementation of in-house greywater treatment and reuse (Alternative 2).

On the other hand, groundwater withdrawals contribute to nearly 25% of total water supply in Qatar and have been estimated at around 250 MCM/year throughout the period of 2008-2016. The decrease in groundwater storage is primarily attributed to water abstraction for agricultural irrigation which amounted to 226-230 MCM/year during the same period. (Alhaj et al., 2017; Planning and Statistics Authority, 2018a). In recent years, local farmers started adopting modern cultivation techniques such as greenhouse structures and efficient water-conserving irrigation methods in order to improve their agricultural production while consuming less water. As a result, water use per unit of agricultural produce dropped from 940 m^3 to 437 m^3 between 1995 and 2013 (Alhaj et al., 2017; Karanisa et al., 2021). Treated wastewater also started being used to grow some nonedible crops and fodder. However, because of Qatar's limited water resources and arid climate, agriculture remains an emerging activity in the country, which imports more than 90% of its food requirements. The total virtual water flow of agrifood products into Qatar amounted to 24,470 MCM for the period of 1998–2015, with an average virtual water flow of 1,350 MCM/year (Alhaj et al., 2017; Mohammed & Darwish, 2017). The growth in population and per capita income contribute substantially to the increase of agrifood demand and virtual water trade of Qatar, whereby every 100,000 increase in population could result in a need for an additional 127 MCM of virtual water (Mohammed & Darwish, 2017). With the start of political rift between Qatar and some of its GCC neighbors in 2017, the country no longer imported food from Saudi Arabia (KSA) and the United Arab Emirates (UAE), its largest food trade partners (Embassy of the Kingdom of the Netherlands in Doha, 2019), and Qatar's self-sufficiency ratio in agrifood decreased from 13.5% in 2014 to 11.5% the same year of the blockade (Alhaj et al., 2017; Karanisa el al., 2021). Meanwhile, Qatar still aims to increase its self-sufficiency of agrifood needs to 40% by 2025, which will likely put additional pressure on dwindling groundwater resources if no other water resources are utilized (Hussein & Lambert, 2020). Remaining groundwater withdrawals for use by different sectors have been stabilized by 2016 as follows: 0.18 MCM/year for the industrial and construction sectors, 9.7 MCM/year for domestic wells, and 10.4 MCM/year for municipal wells (Alhaj et al., 2017; Planning and Statistics Authority, 2018a).

Overall, groundwater withdrawals have been exceeding the rate of replenishment and annual deficits in groundwater reserves in the range of 97-158 MCM were observed in the past decade due to irrigation water needs (Planning and Statistics Authority, 2018a). Therefore, to improve the sustainability of the water management scheme at the level of the agricultural sector, two approaches were considered to increase the available water supply for irrigation. The first looked into the impact of increasing the fraction of treated wastewater reuse in irrigation relative to groundwater abstraction, while the second investigated the possibility of developing a new water resource by recovery of the liquid fraction generated by anaerobic digestion of municipal organic waste.

2.2. Demand-side water management strategies

The impacts of higher water tariffs (Alternative 1) and greywater reuse (Alternative 2) on domestic water demand were evaluated relative to the current governmental approach to water demand management, whereby the increase in domestic water demand is met by a similar level of growth in desalination capacity (current conditions). For this analysis, domestic water demand was estimated up to the year 2100 using probabilistic population forecasts established by the United Nation's Department of Economic and Social Affairs, which include lower 95%, median, and upper 95% projections (United Nations, 2019), and using the per capita water demand figures reported by Kahramaa between 2015 and 2019, with a minimum value of 216 m^3/c/year (592 LCD), an average of 227 m^3/c/year (623 LCD), and a maximum of 242 m^3/c/year (663 LCD) (Kahramaa, 2020).

2.2.1. Impact of water tariffs

The impact of water tariff reforms on water consumption was projected by applying the principles of price elasticity of demand (PED). PED is a measure that assesses the sensitivity of the water demand slope to the change in water price. A studied commodity is said to be price inelastic when the change in price has little effect on the quantity demanded ($-1 < PED < 0$), whereas it is elastic when it is strongly affected by price changes (PED greater than -1) (Srouji, 2017). Recent studies on domestic water demand price elasticity from the Arabian Peninsula have covered the United Arab Emirates (UAE) (DeFelice and Gibson, 2013; Srouji, 2017). The UAE is a neighboring country to Qatar and is characterized by a high water demand (544 LCD), historically linked to the country's wealth, subsidized utilities, and the government continuous investment in desalination infrastructure. The government has had a fully subsidy for water supplied to UAE nationals and about 71% for non-nationals until 2014. It then restructured water tariffs, starting January 2015, to subsidy nationals by around of 75% compared to 21.7% for expatriates. Previous estimates of PED for Abu Dhabi, capital and largest emirate of the federation, were established by DeFelice and Gibson (2013) in the range of -0.37 and -0.27 based on global findings. Srouji (2017), however, studied the impact of water price increases on elasticity of demand in Abu Dhabi between 2014 and 2015 (full year comparisons). It was found that the average PED is -0.23 for all nationals and -0.33 for all non-nationals, indicating that water consumption is rather price inelastic. Since the actual elasticity of water demand in Qatar is unknown due to the lack of data on water consumption changes with respect to water price variation, PED values of the UAE were used in this study (-0.23 for all nationals and -0.33 for all non-nationals), as both countries are members of the CCG with tremendous natural gas reserves, share a similar economy and demography (~ 88% expatriate workers and only 12% nationals), and have had comparable consumption habits linked to the incessant supply of desalinated water at heavily subsidized costs (Baalousha & Ouda, 2017; Srouji, 2017).

Global studies of PED used two main categories of water demand data: bulk water demand and metered water demand. The data provided by Qatar’s water utility correspond to bulk water use divided over the population to obtain the yearly per capita water demand, as metered water data are not yet fully introduced (Alrefai, 2020). Statistical data on the number of water users and water use per tariff block are therefore not available. The average per water capita demand values reported by Kahramaa for the years 2015-2019 fall within the first block of the water pricing system in Qatar (< 20 m^3/c/month; 1.21 USD/m^3). Consequently, water price increases were applied with respect to the first block, considering it should be representative of the reduction in average per capita water demand due to tariff reform. Given that the real value of desalinated water in Qatar amounts to 2.74 USD/m^3 of water produced and in accordance with the pricing reforms adapted by UAE, Alternative 1 considered that the Qatari government will subsidy nationals by 75% as opposed to 100% and that nationals will pay 0.69 USD/m^3 of used water, whereas subsidy will be reduced from 55.84% to 6.5% for non-nationals by increasing water price to 2.63 USD/m^3. Water consumers' response to increased tariffs is also linked to the number of users who receive or pay a bill. A national phone survey conducted by researchers at Qatar University in 2015, revealed that the water billing system in Qatar is inefficient, as only 8% of nationals and 51% of expatriates ever received a bill. Among the expatriates, only 45% pay their own bill, while for over half of them, it is paid by their employers (Hussein & Lambert, 2018). Hence, Alternative 1 considered that water use should be fully metered by 2024 and that 100% of water consumers will receive and have to pay their water bill.

The final domestic water demand values after a full year following water price increases were estimated using two PED models.

The following model was used by DeFelice and Gibson (2013) to estimate water demand changes with price:

$$\mathrm{w} = \alpha \mathrm{p}^{\mathrm{e}}$$

Where w = demand, p = price, e = demand elasticity and α = constant determined by dividing current demand by current price raised to a power equal to the elasticity (determined using the initial water demand and price information). The above function can estimate water demand changes with pricing reforms at the level of non-nationals but will yield invalid results for nationals who receive water at no charge. Consequently, the midpoint method for elasticity was employed to alleviate the discrepancy of fully subsidized water price and estimate water demand changes for nationals (Srouji, 2017):

$$\mathrm{PED} = \left|\frac{(Q_1 - Q_0)/(Q_1 + Q_0)}{(P_1 - P_0)/(P_1 + P_0)}\right|$$

Where P_0 is the initial marginal water price, P_1 is the new marginal price, Q_0 is the initial water demand value, and Q_1 is the new water demand value.

2.2.2. Impact of greywater reuse

Greywater recycling has been previously tested by Alghool el al. (2019) for a residential villa in Qatar, where greywater was separated from black water by retrofitting at different end points and reused to replace a fraction of the consumed desalinated water. A prototype dual-purpose GSM-based smart water/power nano-grid was implemented in this residential unit and was coupled with on-site treatment and recycling of greywater using a RO unit, providing users with information about their water consumption as well as quality of the recycled greywater. As a result, a 20% reduction in freshwater consumption was reached by reusing treated greywater for cleaning, flushing, laundry, and gardening. The study noted, however, that efficiency improvements in the adopted greywater collection network and treatment systems can be made to increase the volume of reusable greywater. In this context, global studies have shown that domestic water consumption can be reduced by up to 30-59% for different greywater reuse systems and domestic applications (Byrne et al., 2020; Samayamanthula et al., 2019).

The implementation of greywater reuse is also dependent on the level of awareness of the public on the problem of water shortage, the advantages of greywater reuse and water conservation, their desire to apply in-house greywater reuse, and their opinion about its quality (Al-Jasser, 2011). In a recent survey on the Qatari's public perception of treated wastewater reuse, Lambert & Lee (2018) established that Qataris are very likely to accept the use of greywater to replace desalinated water in various residential applications. A wide majority of the respondents said they would use treated greywater in garden irrigation (85-92%), toilet flushing (72-83%), or car washing (71-76%), with particularly 82% of Qataris and 91% of expatriates in favor of using greywater in landscaping. However, the consumption of fully treated greywater for drinking was not accepted, due to health concerns, psychological repugnance, and religious norms. Lambert & Lee (2018) also emphasized that the high level of acceptance of greywater use stems mainly from the fact that retrofitting costs associated with the separation of grey and black waters will be fully covered by the government, being the primary stakeholder with the greater interest in introducing water efficiency measures, since most Qatari residents do not own their houses.

Recycling greywater by retrofitting all buildings in Qatar is not economically sound and should be applied only where enough water resources are available and minimal engineering costs are required (i.e. future household units) (Lee & Lambert, 2018). Therefore, Alternative 2 estimated the potential savings in domestic demand for desalinated water by integrating greywater reuse in new residential units, assuming the growth in the number of households is based on population. According to the General Census of Population, Housing and Establishments (2015), the number of built and occupied residential units in Qatar increased from 146,707 to 201,432 between 2010 and 2015, at an annual rate of 6.55%, which strongly correlates with the average annual population growth rate (6.78%) for the same period. Nearly 40% of the population (955,769 members) occupied those residential units (Ministry of Development Planning and Statistics, 2016). For Alternative 2, it was considered that new houses under construction will be required to build a greywater reuse system by including designs in the plans and making the construction permit conditional on incorporating a greywater reuse system, starting 2024. This would ensure a 100% response rate to greywater recycling in the future. It was also considered that the implementation of greywater reuse systems in new households is optional and will be promoted through awareness campaigns and water conservation programs, with an anticipated response rate of 70-90% based on the survey by Lee & Lambert (2018). A probable 20% reduction of the domestic water consumption by using treated greywater was first used in accordance with the findings of the system tested by Alghool et al. (2019), and then increased to 50% by minimizing the losses induced during the collection, treatment, and recycling processes of greywater, based on global observations.

2.3. Supply-side water management strategies

2.3.1. Impact of improved wastewater reuse

Darwish et al. (2015) showed that the quality of treated wastewater effluent in Qatar is safe for reuse in crop irrigation, with minimal risks to soil, groundwater, and crops. By 2017, a total of 24 urban wastewater treatment facilities were in operation across the country, with a total design capacity of 302.17 MCM/year. The volume of wastewater generated was 233.91 MCM in 2017, of which 231.47 MCM were collected (98.95% wastewater collection rate) and 228.668 MCM actually treated (98.8% wastewater treatment rate). All wastewater treatment facilities were equipped with at least a secondary level of treatment to remove organic pollutants and nitrogen using anaerobic–anoxic–aerobic methods (Alhaj et al, 2017). Five of these facilities used biological treatment only and received less than 0.19% of the collected wastewater stream, while tertiary level treatment was implemented in the remaining facilities with around 30% of the wastewater passing through disinfection and 70% of the wastewater being treated by removal of nitrogen and phosphorous (Alsheyab & Kusch Brandt, 2018; Planning and Statistics Authority, 2018a). Collectively, the treatment efficiency of wastewater treatment plants in Qatar reached 95% in terms of BOD_5 and 90% in terms of COD in most of the years during the period 2004-2017, and nitrogen and phosphorous removal rates of 78-80% and 52%-85% were achieved by Qatar's three largest wastewater treatment facilities in 2017 (Planning and Statistics Authority, 2018a). In the same year, around 57% of the TSE was reused for agriculture (29.93%) and green space irrigation (26.94%), 27.93% of the TSE was injected into aquifers, and the excess TSE was directly discharged into lagoons (14.96%) and the sea (0.24%) due to the lack of infrastructure to divert the water for use in different applications (Planning and Statistics Authority, 2018a). These figures suggest that around 15% of the treated wastewater may be recovered towards reuse in irrigation. The current wastewater collection and conveyance networks can therefore be expanded to allow additional TSE reuse in irrigation.

Therefore, to evaluate the impact of improved wastewater reuse in agriculture, the volume of treated wastewater that can be used to cover irrigation demand without the need for groundwater abstraction was evaluated up to the year 2100 by: (1) maintaining the same approach to TSE reuse applications, whereby 30% TSE is reclaimed for irrigation and 15% TSE is sent to lagoons due to the lack of infrastructure that supports the reuse of the total TSE generated-(2) increasing TSE reuse in irrigation to 45% by incorporating the fraction of TSE lost to lagoons and the sea in the expansion of the wastewater reuse infrastructure.

The volume of treated wastewater available for reuse in irrigation was also assessed with respect to the current conditions, Alternative 1, and Alternative 2.

2.3.2. Impact of recovering water from solid waste

Municipal solid waste (MSW) management continues to be a serious challenge faced by Qatar, and is fueled by its fast growing population, urbanization, industry, and economy. The country already generated more than 2 million tons of MSW in 2011 (Al-Maaded, 2012) and has had one of the world's highest per capita waste generation rates at 1.37 kg/capita/day (2008-2014) (Embassy of the Kingdom of the Netherlands in Doha, 2019). Around 57% of the generated MSW in Qatar is comprised of organic materials, while the remaining fraction is made up of recyclables: plastics (13%), paper (17%), metals (5%), construction and demolition waste (5%), and glass (3%) (Al-Maaded, 2012; Qatar Development Bank, 2017). MSW is managed by Doha’s main waste processing plant, the Domestic Solid Waste Management Centre (DSWMC). Established in 2011, it treats around 2,300 tons/day of comingled solid waste by sorting and recycling (26%), composting (35%), waste-to-energy applications (38%), and landfilling of non-renewable materials (Clarke et al., 2016). Overall, more than 95% of the waste managed by DSWMC is reclaimed or converted to energy, with 30 MW of electricity produced by incineration of non-organic waste and 8 MW generated by anaerobic digestion combined composting. (Embassy of the Kingdom of the Netherlands in Doha, 2019). With the anaerobic digestion combined composting process adopted by DSWMC, the generated biogas is exhausted as fuel in a combined heat and power unit. The electricity produced from biogas is used to handle the digestate and aerate the composters. For the aerobic digestion stage, the digestate and effluent from AD are fed into the composter with the addition of leaves and yard waste, producing 300 kg of compost/ton of waste processed (Al-Rumaihi et al., 2020). In 2013-2014, a total of 2,700 tons/day of domestic solid waste was produced in Qatar, of which 2,300 tons were treated and the remaining 400 tons sent to the Mesaieed landfill (Farah, 2016). Because of DSWMC limited treatment capacity, the current waste management system is unable to cope with the amount of MSW produced by the growing population and is already stretched beyond its capacity following the closure of one of the country's three main landfills (Umm Al-Afai) in 2012 (Bello, 2018). The Qatari government should thus consider other sustainable waste disposal methods such as AD to replace landfilling in Qatar, where land availability is limited.

Effective management and treatment of MSW by incorporation of AD reduces the environmental impacts associated with other disposal methods, with an 18% to 40% lower carbon footprint than landfilling and combined sorting-composting-incineration process (Kang J, & Yuan, 2017). AD of the OFMSW is usually followed by a mechanical separation of raw digestate (the end product of the AD) into a liquid and a solid fraction (Akhiar, 2017; Akhiar el al., 2019). A digestate of 60-70% liquid content is generally produced when the OFMSW undergoes a dry AD process (Mohanakrishnan & Visvanathan, 2019). After solid–liquid separation, the liquid fraction retains some nutrients and suspended solids. Digestate can then be processed into sustainable bio-fertilizers for crop production (e.g. Guido et al, 2020; Ronga et al., 2020; Sigurnjak et al., 2017), or may undergo a treatment similar to that of wastewater in order to remove nutrients and organic matter before it can be safely discharged into a receiving water body (Mohanakrishnan & Visvanathan, 2019).

In this study, the volume of liquid that can be recovered by anaerobic digestion in Qatar was estimated considering the total fraction of MSW that exceeds the current capacity of the DSWMC and is being diverted to landfills, while assuming no expansion of the DSWMC capacity during the study period. The mass of MSW was first determined on a yearly basis using the population forecasts and the average MSW generation rate of 1.37 kg/capita/day. Then, the volume of liquid digestate produced by AD of OFMSW was projected by considering that 57% of the comingled domestic waste is organic and that 50-70% of the OFMSW mass is generated as a liquid by-product.

Chapter 3

3. Results and discussions

3.1. Impact of increased water tariffs on domestic water demand

The water subsidy reduction range considered in this study, results in an increase of water tariffs to 0.69 USD/m^3 for nationals and from 1.21-2.58 USD/m^3 to 2.63-5.6 USD/m^3 for expats. Within the sensitivity range of 592-663 LCD, the tariffs increase is expected to reduce the total domestic water demand by up to 24% (average = 393 ± 22 LCD for expats and 488 ± 27 LCD for expats) under lower 95%, median, and upper 95% population projections.

Under the current conditions of water pricing in Qatar, and within the sensitivity range of 592-663 LCD, the domestic water demand is anticipated to surpass the current supply capacity of the desalination plants (830 MCM/year) during 2030-2040 (by 39.5 to 51%) under upper 95% population projections, during 2035-2050 (by 12 to 21.4%) under median population projections, and only in year 2035 (by 6%) for the highest demand (663 LCD) under lower 95% population projections (Figures 1.a to 1. b).

In comparison, domestic water demand is not likely to exceed the present-day supply capacity of the desalination facilities, within the sensitivity range of 592-663 LCD, for lower 95%, and median population forecasts (Figures 1.a and 1.b). However, under upper 95% population forecasts, domestic water demand could exceed the desalination supply capacity between 2070 and 2090 (by 2.5 to 16.4%).

Hence, higher water tariffs have the potential to reduce the pressure on desalination plants either by stabilizing domestic water demand below the current supply capacity of the desalination units (the case of the median and lower 95% population projections) or by delaying the need to expand the desalination and water supply infrastructure by several decades in comparison to the current conditions (the case of the upper 95% population projections).

Similarly, reducing water demand will limit the need for expansion of wastewater treatment facilities. Under current conditions, the results suggest that wastewater generation could become 15% to 62% higher than the current wastewater treatment capacity (302 MCM/year). Expansion of the wastewater collection and treatment infrastructure is needed around the years 2027-2040, if the median and upper 95% population projections are reached (Figures 2.a and 2.b).

By increasing water tariffs on domestic water consumption, the volume of produced wastewater is expected to drop to 202-300 MCM for the lower 95% and median population projections (Figure 2.a and 2.b). The capacity of the wastewater treatment plants is only exceeded when considering the upper 95% population forecasts, starting 2055. In this case, wastewater generation could reach 328-373 MCM by 2100, which is 9-24% higher than the present capacity of the wastewater treatment facilities (Figure 2.c).

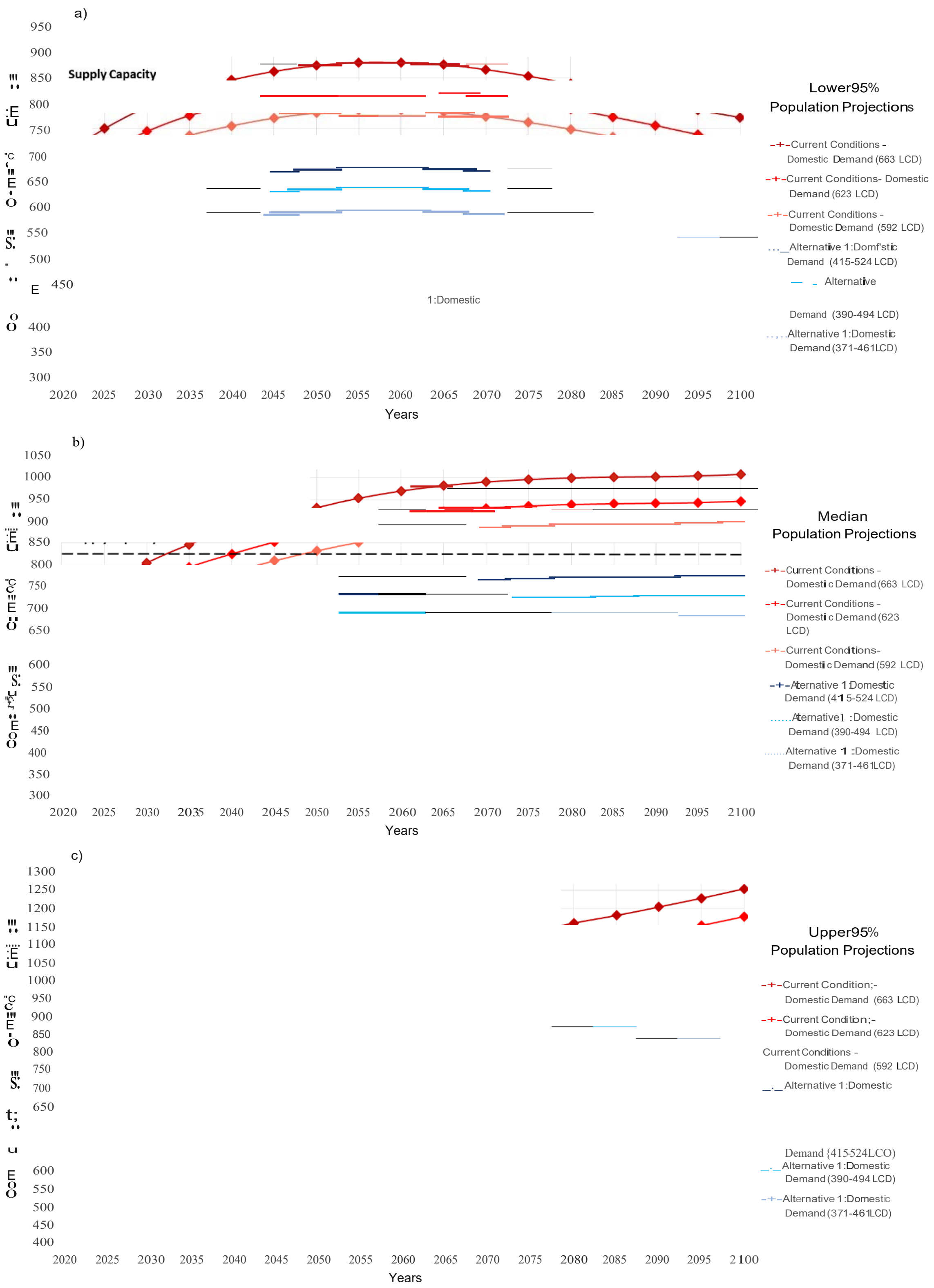

Figure 1. Domestic water demand forecasts under the Current Conditions and Alternative 1, considering (a) upper 95%, (b) median, and (c) lower 95% probabilistic population projections.

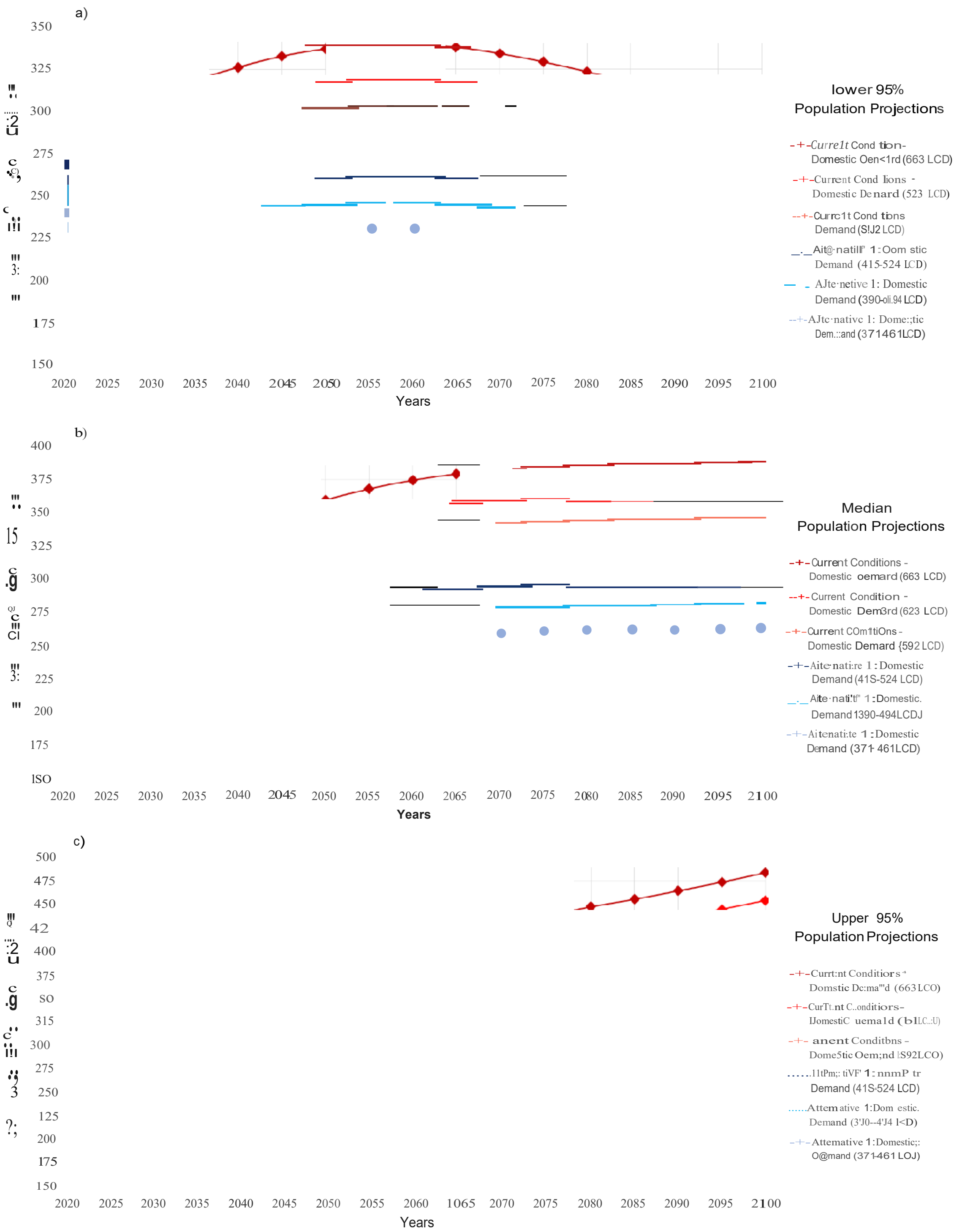

Figure 2. Domestic wastewater generation forecasts under the Current Conditions and Altematrive 1, considering (a) upper 95%, (b) median, and (c) lower 95% probabilistic population projections

3.2. Impact of greywater reuse on domestic water demand

The impact of reusing treated greywater in new residential units on future domestic water consumption was studied, assuming 100% response, within the sensitivity range of 592-663 LCD. Based on the local figure of 20% reduction (Alghool et al., 2019), the total volume of recycled greywater could reach 12-13 MCM in 2100 for the lower 95% population projections, 20-23 MCM for the median population estimates, and 37-42 MCM for the upper 95% population forecasts (Figure 3-a). However, by reaching a higher reduction of 50%, similar to global rates (Byrne et al., 2020; Samayamanthula et al., 2019), the total volume of reclaimed greywater could amount to 29-33 MCM for the lower 95% population projections, compared to 51-57 MCM and 93-105 MCM for median and upper 95% population forecasts, respectively (Figure 3-b). Thus, greywater reuse has the potential to save 1.7-3.4% of the country's domestic water demand that can go up to 4.2-8.4%.

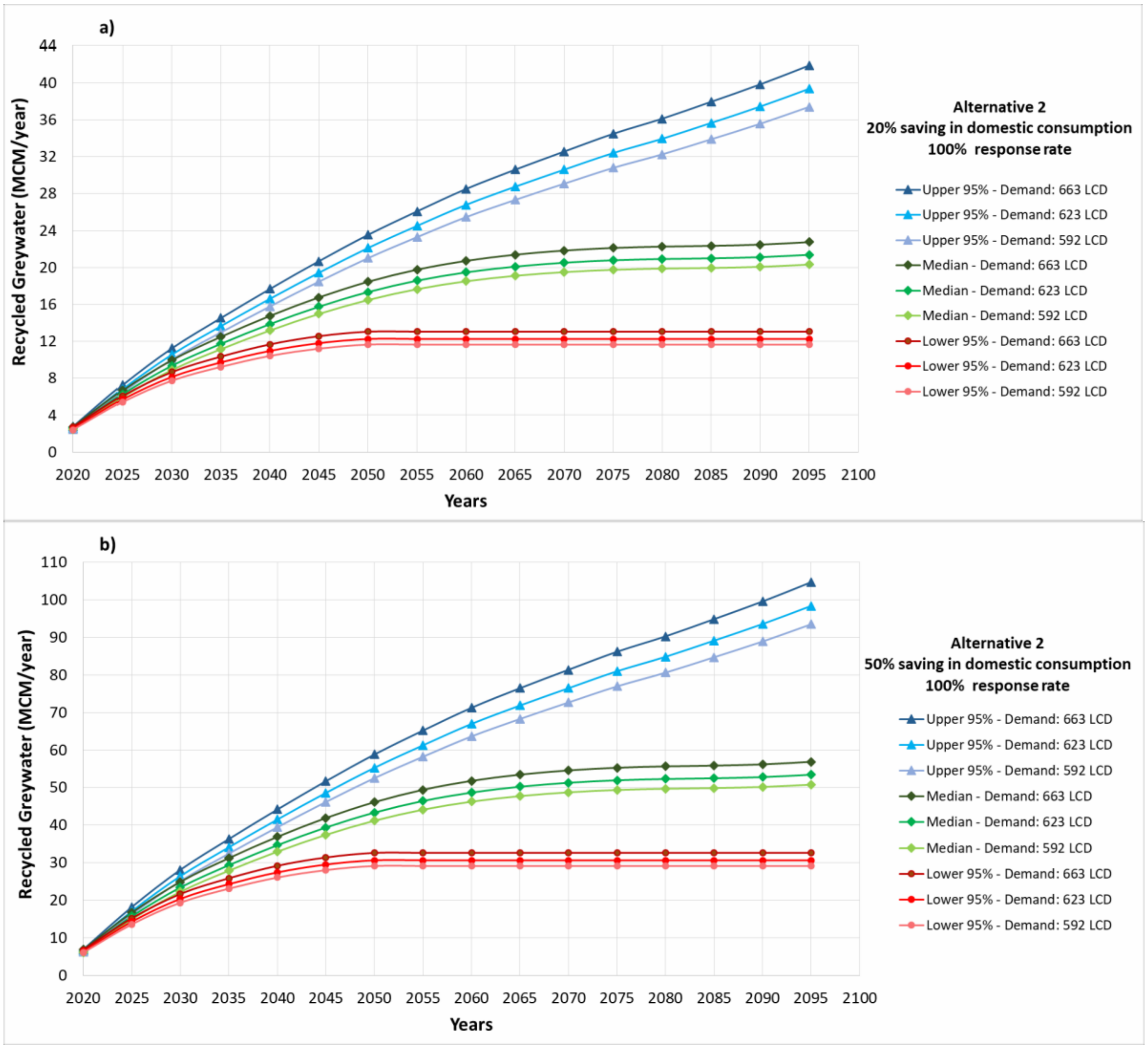

Figure 3. Volume of reused greywater, for the upper 95%, median, and lower 95% probabilistic population projections with: (a) 20% reduction and (b) 50% reduction in domestic consumption

3.3. Impact of increasing treated wastewater reuse on water supply for irrigation

Under the current rate of 30% TSE reuse, adopting median population projections within the sensitivity range of 592-663 LCD, the reclaimed water can supply 34% to 38% of the total agricultural irrigation demand – equivalent to 102-114 MCM by year 2100 (Figure 4). However, by making use of the 15% TSE currently disposed in lagoons, the reuse rate increases to 45%, leading to a supply equivalent to 51%-56% of the total irrigation water supply – equivalent to 153-171 MCM by year 2100 (Figure 4.a).

It should be noted that implementing water demand reduction strategies (Alternative 1 and Alternative 2) would reduce the volume of produced wastewater, thus the overall amount of TSE available for reuse. Combining increased TSE reuse with higher water tariffs (Alternative 1), under median population projections, the potential irrigation supply drops to 26%-29% for 30% TSE reuse and may reach 39%-44% if TSE reuse increased to 45% - equivalent to 77-88 MCM and 116-132 MCM by 2100, respectively (Figure 4.b). These rates remain substantial.

Similarly, combining increased TSE reuse with greywater reuse (Alternative 2), under median population projections, the volume of water available for irrigation decreases only marginally to: (a) 99-111 MCM and 150-168 MCM in 2100 using 30% and 45% TSE reuse, respectively, in case of 20% saving in domestic water use (Figure 5.a); and (b) 96-107 MCM and 144-162 MCM for 30% and 45% TSE reuse, respectively, in case of 50% saving in domestic water (Figure 5.b). Overall, the volume of TSE that can be allocated to the agricultural sector amounts to 32%-56% of the aggregate irrigation water needs.

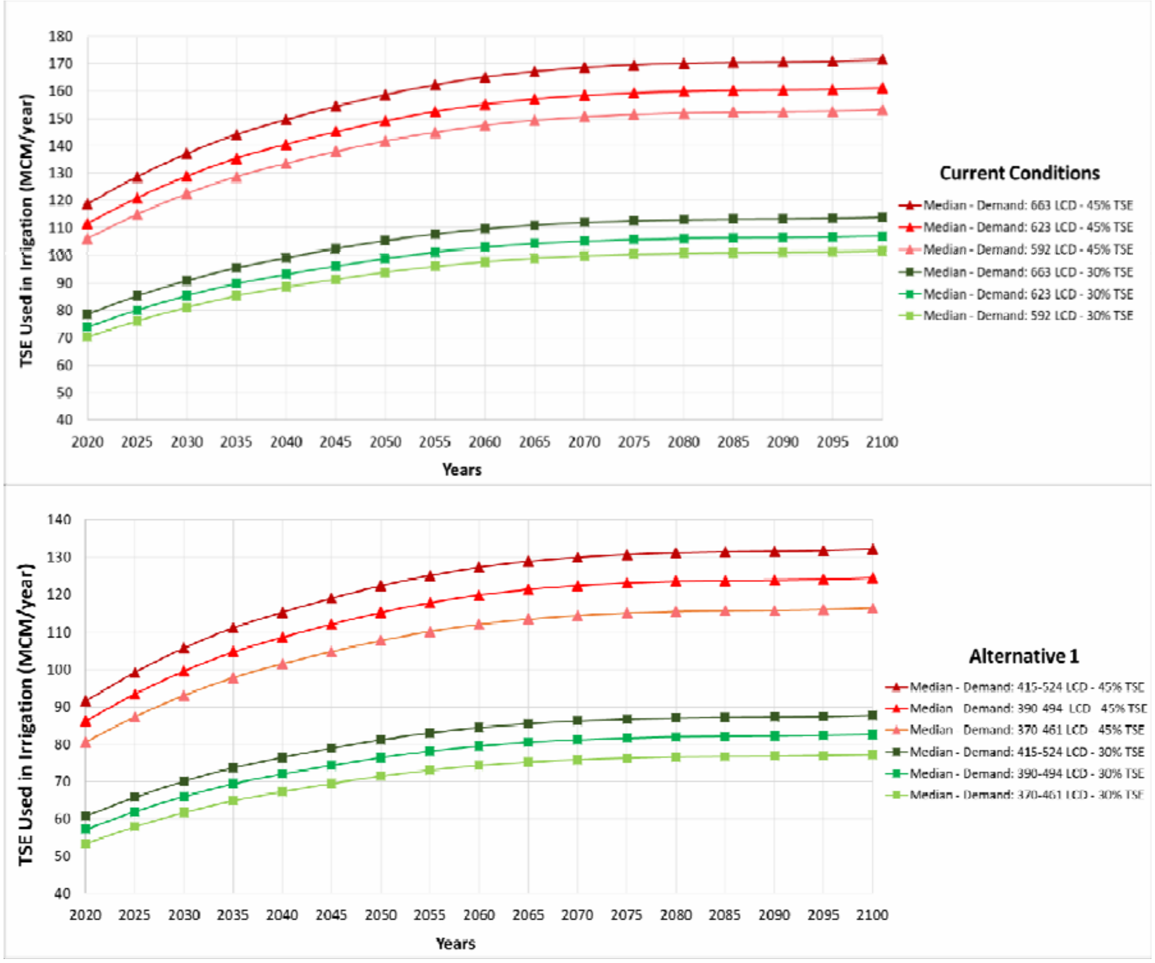

Figure 4. Volume of TSE that can be used in irrigation for 30% and 45% TSE reuse rate, adopting median population projections, under: (a) current conditions, and (b) increased water tariffs

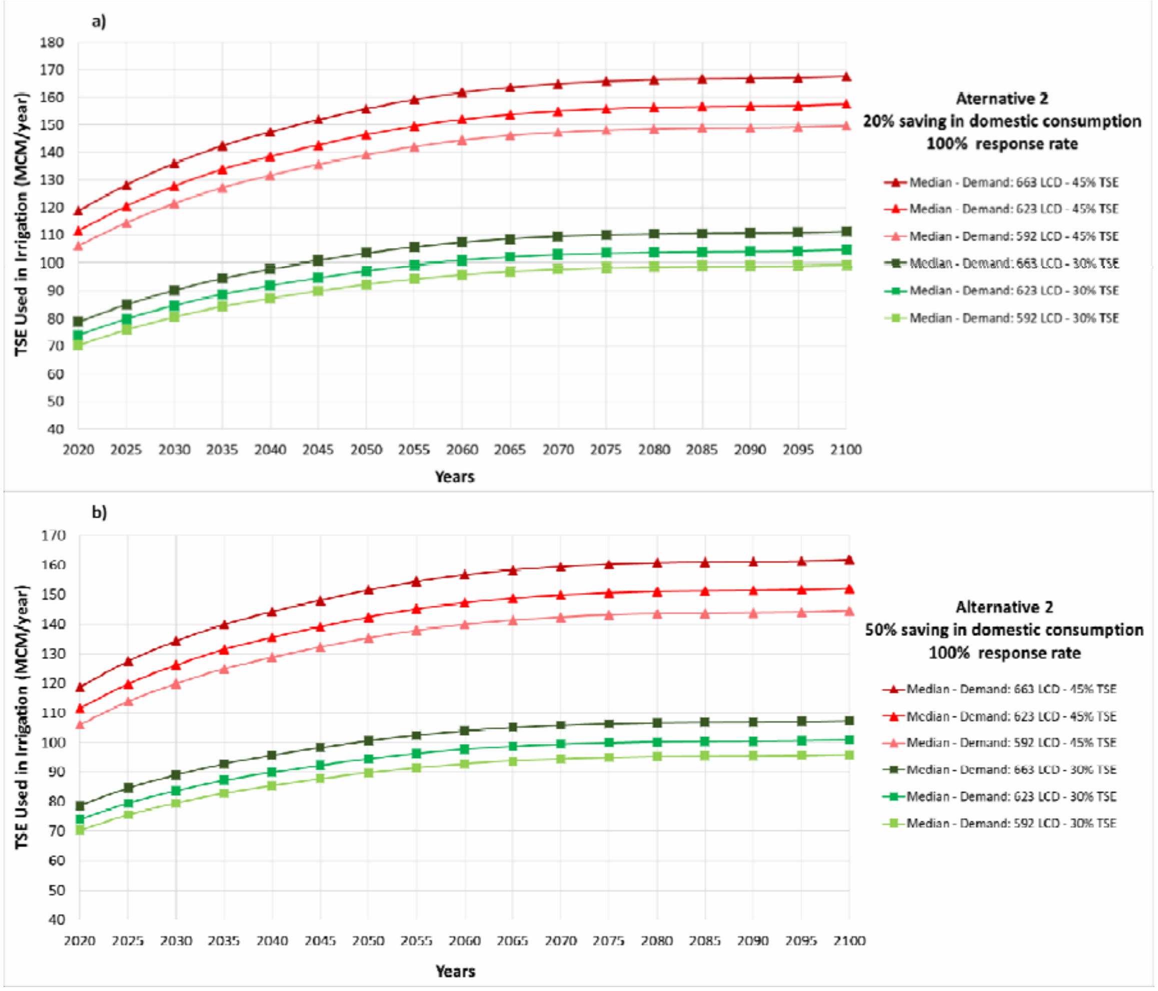

Figure 5. Volume of TSE that can be used in irrigation for: (a) 30% and (b) 45% TSE reuse rate, combined with greywater reuse

3.4. Liquid fraction of the AD of OFMSW

The water in the OFMSW that is currently landfilled, ends as leachate that is usually treated and evaporated in lagoons. Alternatively, this water may be recovered through anaerobic digestion. In this case, about 0.5 MCM may be recovered in 2100, assuming 50% of the OFMSW is recovered as liquid digestate (Figure 6-a). This value may reach 0.7 MCM if the recovered liquid is 70% of OFMSW (Figure 6-b) – adopting the upper 95%

population forecasts. These results show that AD may not be considered a substantial water source for the agricultural sector.

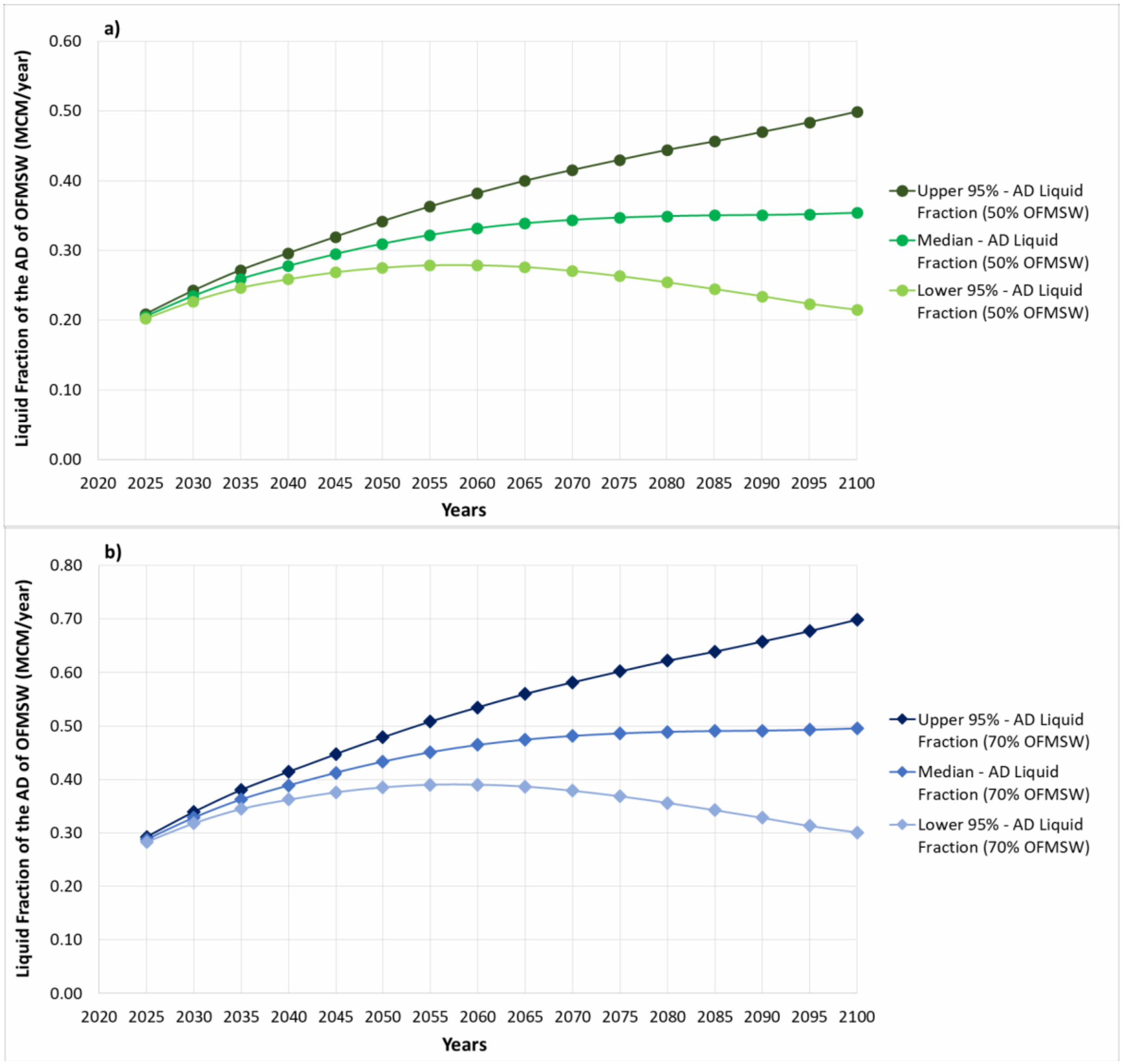

Figure 6. Water recovered by AD of OFMSW, for the upper 95%, median, and lower 95% probabilistic population projections with: (a) 50% of OFMSW (b) 70% of OFMSW as liquid digestate

Chapter 4

4. Recommendations and conclusions

4.1. Recommendations and future research

This study showed that water pricing is a major determinant in reducing domestic water demand. Yet, accurate water metering should be the starting point to capture water consumption patterns, categories and variables. Those are needed to calculate accurate and location-specific PED values, followed by water demand modeling and forecasting based on socio-economic variables (e.g. water price, location, social status, consumer and property characteristics, etc.), and weather characteristics. Only then, efficient water pricing strategies may be developed and effectively implemented (Alrefai, 2020).

Also, a detailed analysis is needed for the potential of reusing greywater in various residential applications (toilet flushing, garden watering, floor cleaning, car washing, clothes washing, etc.). This allows a practically accurate estimation of the impacts of greywater reuse, and allows informed decision making for the reduction of water demand, combining water pricing and greywater reuse. The studied demand and supply management initiatives can then be merged in a single scenario by considering the interrelations between the various demand and supply sectors, in order to perform a scenario-based optimization and find the configuration of strategies that would best improve the water management scheme in Qatar.

From a supply perspective, this study showed that reusing all the TSE, currently disposed in evaporation lagoons, has a considerable impact on agricultural water supply – thus reducing the extraction of fossil water. Yet, financial and technical analyses are needed to assess the feasibility of this alternative. This has to be combined with agriculture-related issues and solutions, including climate change adaptation and the use of modern production methods (e.g. greenhouses and hydroponics, among others) to minimize the use of space, soil, and water (Karanisa el al., 2021).

Other non-conventional water resources need to be considered and for specific applications. Those include the 2 m^3 of brine generated for every 1 m^3 of desalinated freshwater produced and discharged into the Arabian Gulf (Sezer et al., 2017). Several technologies may be investigated, such as membrane distillation, reverse osmosis, nanofiltration, and ultrafiltration (Adham et al., 2013). Another possible source is the wastewater generated during the extraction of natural gas and oil in Qatar, which is currently being injected into deep wells (Shaikh et al., 2020). A water-to-oil ratio of 3:1 was previously estimated for Qatar, implying that 3 barrels of wastewater is produced for every barrel of extracted oil (Echchelh et al., 2018). Various technologies have been proposed such as membrane bioreactors (Jason et al., 2014), sand filtration, activated carbon filtration, and modified activated carbon filtration (Al-Kaabi et al., 2016), adsorption using natural and synthetic adsorbents (Yousef et al., 2020), bioelectrochemical treatment (Mohanakrishnan et al., 2019), and finally combined chemical precipitation and filtration units (Ersahin et al., 2018).

Finally, studies on the impacts of climate change on water security, with plans to increase the resilience of water supply infrastructure are lacking in Qatar (Al-Saidi & Saliba, 2019). Future research should therefore incorporate the climate change impacts on water resources availability and water demand sectors. Decision-support modeling packages can aid in simulating climate change scenarios and developing a combination of water demand and water supply management strategies under various environmental and associated uncertainties (Wang et al, 2016).

4.2. Conclusions

Qatar is a water scarce country relying mainly on desalination and extraction of non-renewable water to provide the country’s water demand. This calls for creative approaches to improve the sustainability of the water management scheme, through reduced water demand and new non-conventional supply methods. For the demand-side management, this study revealed that increasing water tariffs could substantially lower water consumption by up to 24%, and delay the need to expand the desalination infrastructure past the year 2060. On the other hand, integrating greywater treatment and reuse in new constructions could save up to 1.7-8.4% of domestic water demand. As for the supply-side management, the study showed that upgrading the wastewater reuse network, to convey the 15% of TSE currently discharged in lagoons, could supply up to 39-56% of the total irrigation water demand. Recovering water from the OFMSW by anaerobic digestion cannot supply a considerable amount of water.

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