Water Resources Management (2023) 37:1947–1963
https://doi.org/10.1007/s11269-023-03464-6

Synergetic Water Demand and Sustainable Supply Strategies in GCC Countries: Data-driven Recommendations

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Received: 9 November 2022 / Accepted: 6 February 2023 / Published online: 27 February 2023

Abstract

The Gulf Cooperation Council (GCC) countries, characterized with limited water resources and high oil/gas revenues, rely heavily on energy-intensive seawater desalination and non-renewable groundwater abstraction. The need to shift solutions to demand-side practices and sustainable supply alternatives has been long advocated; yet this study is the first to "quantify" the impacts of such solutions on the water management system of Qatar – considered a study case of GCC countries. In this research, a scenario-based approach was utilized to predict the impact of water demand control and wastewater reuse (and the resulting synergies) on consumption of desalinated water, extraction of groundwater resources, and development needs of water and wastewater infrastructure. To this effect, country-specific models for Qatar were developed to project annual household water demand, wastewater generation and residential construction growth, up to year 2050. The outcomes showed that tariff reforms and regulated greywater reuse would reduce the annual household demand for desalinated water by up to 27% and 7%, respectively. Also, intensive reuse of Treated Sewage Effluent (TSE) would reduce 40–80% of total groundwater abstraction for irrigation by 2050. Finally, adopting an integrated water strategy, with combined demand and supply management targets, creates synergies that would: (1) limit groundwater abstraction to rates close to the aquifers safe yield; and (2) delay the need for expansion of the water and wastewater infrastructure by more than a decade. Data-driven recommendations were provided accordingly.

Keywords Water management strategies · Water demand models · Water tariff reform · Wastewater reuse

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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). 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, thus the pressure on freshwater resources (Liu et al. 2017; Rosa et al. 2020; Siddiquee and Ahamed 2020). Climate change is also predicted to aggravate the existing challenges of water scarcity by reducing the availability of water resources and arable lands, particularly in arid regions (Meltzer et al. 2014; Sharafatmandrad and Khosravi Mashizi 2021). In regions suffering from physical water scarcity, the state of the economy affects both demand and supply. This is the case of developing wealthy countries, such as the ones in the Gulf Cooperation Council (GCC), where increasing water consumption is expected with higher standards of living coupled with ample capacity by water utility providers to invest in costly water supply infrastructure, such as desalination (DeFelice and MacDonald Gibson 2013; Oki and Quiocho 2020).

One country in the GCC is examined as a case study, Qatar. Qatar is an arid peninsula located in the Arabian Gulf, with a land area of 11,610 km^2. The weather in Qatar is characterized by erratic rainfall averaging between merely 40 and 80 mm/year, and high temperature and humidity (AlMamoon et al. 2014). Due to its geographical location and climatic features, the country suffers from acute freshwater scarcity with an average annual freshwater availability of 20 m^3/capita (2019), which is considerably lower than the absolute water poverty line of 500 m^3/year (Qureshi 2020). On the other hand, the average annual water consumption in Qatar has been one of the highest in the world, varying between 216 and 238 m^3/capita in recent years (PSA 2018).

Having experienced a tremendous increase in national wealth and a rapid population growth in the last three decades (Hussein and Lambert 2020), Qatar currently meets domestic water demand using energy-intensive fossil fuel-powered desalination technologies where consumers receive their water needs at a heavily subsidized cost (Baalousha and Ouda 2017). While plans are underway to further expand the desalination plants supply capacity and meet the future water demand of the growing population for at least the next 50 years (Alhaj et al. 2017), this process is environmentally unsustainable due to the high carbon footprint associated with the currently used desalination technologies. Furthermore, desalination has negative effects on marine ecosystems due to the discharge of concentrated brine into the sea (Rahman and Zaidi 2018; Mannan et al. 2019).

Regarding the agricultural sector, Qatar relies heavily on extensive groundwater abstraction for its supply. This practice has resulted in the lowering of the water table, the deterioration of groundwater quality, and the rising salinity over the years (Alhaj et al. 2017). In effect, groundwater withdrawals contribute to nearly 25% of total water supply in Qatar, equivalent to around 250 million cubic meters (MCM)/year throughout the period of 2008–2016, of which 226–230 MCM/year are used for agricultural irrigation (PSA 2018). Furthermore, Qatar aims to increase its food self-sufficiency to 40% by 2025, which will put added pressure on the dwindling groundwater resources if no other sources are utilized (Hussein and Lambert 2020).

To overcome these challenges, Qatar has embarked on several initiatives:

- The Ministry of Environment imposed regulations to limit groundwater withdrawals and encourage the use of efficient irrigation methods. This resulted in more than 50% reduction in the volume of water used per metric ton of agricultural produce between 1995 and 2013 (Alhaj et al. 2017).
- Qatar General Electricity and Water Corporation 'KAHRAMAA' invested in reducing the leakage of the water distribution network to 4% in 2016 (Kamal et al. 2021).
- KAHRAMAA allocated four billion dollars in 2018 to build the world's largest potable water mega-reservoir (Hussein and Lambert 2020).
- Qatar started incorporating the use of treated sewage effluent (TSE) in different applications, including irrigation of public green spaces (PSA 2018).

Despite these initiatives, desalination continues to be the largest source of water supply in Qatar, contributing to around 60% of the national water needs, and groundwater withdrawals remain many folds higher than the natural recharge rate of aquifers (PSA 2018).

Multiple studies have concluded the need for a more sustainable water management scheme in Qatar, specifically in terms of incorporating non-conventional supply methods, along with efficient demand control policies – beyond only raising public awareness and promoting the use of water conservation devices (Alhaj et al. 2017; Alghool et al. 2019). In this regard, there has been a few studies to model water demand in Qatar for the purpose of informing the decision-making process.

Khalifa et al. (2019) provided a dynamic model to forecast water consumption in Qatar from 2018 to 2030, under different scenarios of population growth and water conservation policies proxied by a reduction of water consumption elasticity to population. The results predicted that under the implementation of stringent water conservation policies, the residential (villa) and commercial demands, accounting for most of the total water consumption in Qatar, can be decreased by up to 27%-46% by 2030, respectively.

Kamal et al. (2021) used multi-linear regression models to estimate future water consumption in various sectors in Qatar as a function of population, gross domestic product (GDP), and average rainfall. The model was applied to assess the long-term impacts of water efficiency policies, under several scenarios including capped groundwater abstraction and reduced water consumption in the household, commercial, and industrial sector.

Alshaikhli et al. (2021) performed a multi-linear regression analysis to evaluate the impact of population density and weather parameters (temperature, humidity, rainfall, daylight, and sunshine) on per capita water consumption in Qatar for the year 2017. They concluded that temperature and population density are the determining factors.

Multiple researchers and national authorities flagged the need to limit the deficiency in the water budget of Qatar. Yet, to the best of the authors' knowledge, this paper is the first attempt to *quantify* the impact of *combining* non-conventional water supply strategies with water demand reduction policies in Qatar, using *realistic* scenarios of: (1) reduced water subsidies, (2) on-site reuse of greywater, (3) improved TSE reuse, and (4) extracted liquid fraction of organic waste.

On the other hand, few studies attempted to model the water demand in Qatar for informed policy-making. Yet, this is the first study to apply population, GDP, rainfall, and temperature projections, through multiple linear regression, to predict future water demand at the sectoral level. In addition, individual models were developed to feed the forecasting scenarios with necessary intermediate results, including wastewater generation, TSE reuse, and greywater reuse in future residential constructions.

After the introduction, Section 2 describes the rationale behind the adopted demand-side and supply-side solutions. It also presents the methods and models used to forecast (up to 2050) water demand, greywater, TSE, and liquid digestate from waste under the different management scenarios. Section 3 discusses: (1) the projected reductions in residential water demand due to tariff reforms and greywater recycling in future households, (2) the impacts of the demand-side management scenarios on the desalination and wastewater treatment infrastructure, and (3) the additional supply of water that could be reclaimed to substitute groundwater abstraction for agricultural irrigation. Finally, Section 4 closes the paper by developing a data-driven recommendation framework to support future adaptive water management plans in Qatar based on the "indicative" water usage figures and patterns generated in this study.

2 Materials and Methods

2.1 Rationale

While water authorities commonly focus on increasing the country's capacity to supply and store more water, recent integrated approaches call for synergetic combinations of sustainable "supply-side" methods along with "demand-side "solutions (Mardani Najafabadi et al. 2022). In this manuscript, the demand-side solutions target reducing the demand for desalinated water for residential use. In comparison, the supply-side scenarios aim to provide additional supply of agriculture irrigation water, with the purpose of limiting groundwater depletion (Fig. S1 in the Supporting Information (SI)).

"**Demand-side**" solutions typically involve strategies and technologies for water conservation and increased water use efficiency, among those:

- *Scenario 1:* Water Tariff Reform – Using water pricing as an economic tool to reduce water consumption
- *Scenario 2:* Regulating Greywater Reuse – Enforcing on-site reuse of greywater in new residential units

In parallel, various countries facing drought and growing water scarcity have made a paradigm shift from traditional sources of water supply (i.e., surface water and groundwater) to more sustainable "non-conventional" resources. Thus, the following "**supply-side**" scenarios were investigated in this study:

- *Scenario 3:* Intensive Reuse of TSE – "Intense" usage of treated wastewater for agricultural irrigation
- *Scenario 4:* Water Recovery from Waste – Recovery of water by anaerobic digestion of organic municipal waste

2.2 Selection of Modelling Methods

The available literature shows multiple approaches to model water demand. The selection of a particular method is based on: (1) the objective of the analysis; (2) the need to identify the impact of time and other parameters (factors of influence), and (3) the type of collected data (e.g., near-real-time data or data collected from water meters). For instance, neural networks, support vector machine methods, metaheuristic or evolutionary algorithms, and hybrid methods require large data sets to provide conclusive outcomes. As to time series analysis methods, which might be run with a limited set of data, they do not allow to establish a relationship between water demand and factors of influence (e.g., socio-economic and climatic parameters). In comparison, multi-linear regression models present the flexibility to work with limited data resources, while accounting for the impact of determining parameters (Niknam et al. 2022).

Given that this study aims at forecasting water demand as a function of several parameters (namely population, GDP, rainfall and temperature), and considering the lack of an exhaustive database, multi-linear regression was found to be the most suitable method.

2.3 Modelling and Forecasting

2.3.1 Water Demand

Water demand models were developed, using a multi-regression analysis approach, as function of population, GDP, mean annual rainfall and temperature (Table 1). The models were validated, using 2006–2016 data (PSA 2018; Kamal et al. 2021; CCKP 2021a), via the adjusted coefficient of determination (R^2) (Miles 2014), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Mean Absolute Percentage Error (MAPE) accuracy measures (Ostertagova and Ostertag 2012). The error analysis results are provided in SI (Figs. S2 to S7).

Next, the models were used to forecast the water consumption volumes by sector up to 2050 and under various scenarios (Table 2). The sectors studied include household, commercial, governmental, industrial, and agricultural. The below presents the data sources and assumptions:

- Future population estimates in Qatar were adopted from the probabilistic world population forecasts by the United Nation's Department of Economic and Social Affairs, which include lower 95%, median, and upper 95% probabilistic projections (UN 2019)
- The demographic constitution of the Qatari population observed in recent years was assumed to continue over the projection period: 88% expatriates and 12% nationals (Baalousha and Ouda 2017).
- Precipitation and temperature in Qatar for the years 2025–2050 were forecasted using the mean annual precipitation and temperature projections of the Coupled Model Intercomparison Project Phase 6 (CMIP6), based on a multi-model ensemble for the following Shared Socioeconomic Pathways: SSP1–1.9, SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5 (Reference Period: 1995–2014) (CCKP 2021b).
- Qatar's GDP growth rate has been projected to average 3.9% for years 2010–2025 and 1.5% for years 2025–2050 (Fouré et al. 2012). According to the International Monetary Fund (IMF 2021), the country's real GDP growth rate fluctuated between -3.6% and 3.1% recently, with an average of 3.8% over the period of 2010–2022. As this value confirms the estimated figure by Fouré et al. (2012), a GDP growth rate of 1.5% was adopted for the forecasts over the period 2025–2050.
- Losses from the desalinated water distribution network were assumed constant at 4% over the projection period.

Table 1 Developed models for water demand (by sector), household count and wastewater generation

Model	Equation	Adjusted R^2	F-Statistic, ρ-Value ($\alpha < 0.05$)
Household water demand	$Hh = -300.542 + 131.725 \times Pop + 0.08202 \times GDP - 0.32277 \times Rnf + 11.7919 \times T$	0.9434	42.673; 0.00015
Commercial water demand	$Cm = 1358.7 + 149.515 \times Pop - 1.024 \times GDP - 0.28632 \times Rnf - 50.3766 \times T$	0.7451	8.3066; 0.01267
Governmental water demand	$Gv = -1685.22 - 1.9347 \times Pop + 0.71359 \times GDP + 1.04664 \times Rnf + 56.332 \times T$	0.7376	8.0285; 0.01376
Industrial water demand	$In = 4.63937 - 0.32591 \times Pop + 0.02608 \times GDP + 0.02805 \times Rnf$	0.6026	6.0535; 0.0234
Total demand met by desalination	$DW = (-30.2445 + 0.9879 \times Hh + 0.8047 \times Cm + 0.9661 \times Gv + 1.3681 \times In) \times 1.04$	0.9994	4472.308; 1.5×10^{-10}
Agricultural water demand	$Ag = 35.0586 + 7.69362 \times Pop + 0.28584 \times GDP + 0.20537 \times Rnf + 5.99174 \times T$	0.7599	8.9141; 0.01066
Household members count	$Hhc = 274{,}983.5457 + 189{,}841.7133 \times Pop + 1258.228298 \times GDP$	0.9064	20.3651; 0.04681
Wastewater generation	$WW = -55.8506 + 0.489865 \times DW$	0.9873	697.7363; 4.53552×10^{-9}

Hh household demand (MCM/year), *Cm* commercial demand (MCM/year), *Gv* governmental demand (MCM/year), *In* industrial demand (MCM/year), *Dw* demand in desalinated water (MCM/year), *Pop* population (million), *GDP* gross domestic product (billion USD), *Rnf* mean annual rainfall (mm), *T* mean annual temperature (°C), *DW* total desalinated water demand (MCM/year), *Hhc* annual household members count (million), *WW* wastewater generation (MCM/year)

Table 2 Projection equations for adopted scenarios

Scenario	Equations	Parameter Definitions
1	$Hh_{new} = \left[-Hh_{exp}\left(\frac{PED_{exp}\times F_{exp}+1}{PED_{exp}\times F_{exp}-1}\right)\right] + \left[-Hh_{nat}\left(\frac{PED_{nat}\times F_{nat}+1}{PED_{nat}\times F_{nat}-1}\right)\right]$ $Hh_{exp} = Hh \times Hh_{exp}$ $Hh_{nat} = Hh \times Hh_{nat}$ $F_{exp} = \left(P_{1,\mathrm{exp}} - P_{0,\mathrm{exp}}\right)/\left(P_{1,\mathrm{exp}} + P_{0,\mathrm{exp}}\right)$ $F_{nat} = \left(P_{1,\mathrm{nat}} - P_{0,\mathrm{nat}}\right)/\left(P_{1,\mathrm{nat}} + P_{0,\mathrm{nat}}\right)$	Hh_{new} is the new household demand after tariffs reform (MCM/year), Hh is the initial household demand (MCM/year) (calculated from Table 1), Hh_{exp} and Hh_{nat} represent the proportions of household demand by expatriates and nationals, respectively, $P_{0,exp}$ and $P_{0,nat}$ are the initial water prices paid by expatriates and nationals, respectively, $P_{1,exp}$ and $P_{1,nat}$ are the new water prices paid by expatriates and nationals, respectively, and PED_{exp} and PED_{nat} are the price elasticity of demand for expatriates and nationals, respectively
2	$Gw = \left[-300.542 + 131.725 \times \left(Hhc_{year} - Hhc_{2025}\right) + 0.08202 \times GDP - -0.32277 \times Rnf + 11.7919 \times T\right] \times S$	Gw is the volume of recycled greywater (MCM/year),Hhc_{2025} and Hhc_{year} are the estimated household members (millions) (calculated from Table 1) for the year 2025 and years post 2025, respectively, S is the percent water savings (20–50%), GDP is the gross domestic product (billion USD), and Rnf is the mean annual rainfall (mm)
3	$WW = -55.8506 + 0.489865 \times DW$ $TSE_{reuse} = \varepsilon \times WW \times Reuse$	WW is the generated wastewater (MCM/year), DW is the total demand met by desalination (MCM/year) (calculated from Table 1), TSE_{reuse} is the volume of TSE reused for irrigation (MCM/year), ε is the wastewater treatment efficiency (99% of WW), and $Reuse$ is the TSE reuse rate (31%, 42%, and 72%)
1 & 3	$WW = -55.8506 + 0.489865 \times DW_{new}$ $TSE_{reuse} = \varepsilon \times WW \times Reuse$	DW_{new} is new total demand met by desalination upon introducing tariff reforms (MCM/year), calculated from Table 1 by replacing Hh with Hh_{new}
2 & 3	$WW = -55.8506 + 0.489865 \times DW_{GW}$ $TSE_{reuse} = \varepsilon \times WW \times Reuse$	DW_{GW} is total demand met by desalination upon regulating greywater (MCM/year), calculated from Table 1 by replacing Hh with $(Hh - Gw)$.
4	$LD = \left[\left(MSW_C \times Pop - MSW_T \times 10^3\right) \times ndays \times OFMSW \times LFD/\rho_d\right] \times 10^{-6}$	LD is the volume of liquid digestate (MCM/year), MSW_C is the per capita MSW generation rate (kg/capita.day), Pop is the population (millions), MSW_T is the proportion of MSW currently treated (tons/day), $ndays$ is the number of days in a year, $OFMSW$ is the organic fraction of MSW, LFD is the liquid fraction of digestate recovered by AD, ρ_d is the density of the digestate (kg/m^3), and 10^{-6} is a conversion factor

2.3.2 Household Members Count

As part of estimating annual water savings by greywater recycling, *a household count model* (Table 1) was developed to forecast the number of new housing units and their occupants. A regression analysis was run as a function of population and GDP, using data from the latest national census of population, housing and establishments for the years 1986 to 2015 (MDPS 2016). The error analysis results are provided in SI (Fig. S8).

2.3.3 Wastewater Generation

To be able to forecast TSE volumes that could potentially replace groundwater resources in irrigation applications, a *wastewater generation model* (Table 1) was developed using linear regression based on the annual wastewater generation figures of the years 2010–2019 (PSA 2018, 2021; KAHRAMAA 2020). The error analysis results are provided in Fig. S9 in SI.

2.4 Demand-side Water Management Strategies

2.4.1 Scenario 1 – Water Tariff Reform

The impact of water tariff reforms on water consumption was projected by applying the principle of price elasticity of demand (PED) (Table 2). PED is a measure that assesses the sensitivity of the water demand slope to the change in water price (Srouji 2017).

One year following water tariffs increase, future household water demand values were estimated using the midpoint method for elasticity (Eq. (1)), which alleviates the discrepancy of a fully subsidized water price (Srouji 2017):

$$PED = \left| \frac{(Q_1 - Q_0)/(Q_1 + Q_0)}{(P_1 - P_0)/(P_1 + P_0)} \right| \tag{1}$$

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.

Global studies of PED used two main categories of water demand data corresponding to bulk and metered water demand. The data provided by Qatar's water utility represent bulk water use divided over the population to obtain the annual per capita water demand, as water metering is not yet fully deployed in the country (Alrefai 2020). Statistical data on the number of water users and water use per tariff block are therefore not available. Consequently, the potential impact of water price increases on demand with respect to the first block of residential water consumption and pricing in Qatar (<20 m^3/capita/month; 1.51 USD/m^3) (KAHRAMAA 2021) was evaluated, since the reported per capita household water use values (PSA 2018) all fall within this block.

As to PED rates, the actual elasticity of residential water demand in Qatar has not been established. Therefore, analogous values in the United Arab Emirates (UAE) were adopted (Srouji 2017). UAE is a GCC country with a similar weather, close socio-economic setup (wealthy GCC country with high gas reserves), demographic constitution (~88% expatriate workers and only 12% nationals), and water management scheme (i.e., high water demand, high water subsidy, heavy dependence on desalination for domestic use and depleting groundwater for agriculture). In 2015, higher water tariffs were introduced in UAE, charging expatriates nearly 4 times more than national who received water at 75% subsidy. Subsequently, median PED values of -0.23 for nationals and -0.33 for non-nationals were established by Srouji (2017) for Abu Dhabi – the largest emirate of UAE.

To estimate the potential reduction in household water demand due to increased tariffs in Qatar, Scenario 1 assumes reforms similar to those recently imposed in UAE, while adopting the same PED figures for nationals and expatriates (-0.23 and -0.33, respectively). The actual water production cost in Qatar (2.74 USD/m^3) was considered as the reference value. Accordingly, the Qatari government could subsidy nationals by 75% (as opposed to the current 100%), who would then pay 0.7 USD/m^3 of residential water use, while non-nationals would pay at least 2.74 USD/m^3.

Finally, this scenario assumed complete enforcement of a tariff payment mechanism – as opposed to the current poor billing and collection system. (Hussein and Lambert 2020).

2.4.2 Scenario 2 – Regulating Greywater Reuse

In Qatar, greywater and black water are diverted collectively into one sewer line and sent to wastewater treatment plants (Alghool et al. 2019). Scenario 2 estimates the impact of home-level separation of greywater, with on-site treatment and reuse for toilet flushing, cleaning, laundry, and outdoor activities (car washing, landscaping, etc.) (Table 2).

Qatari residents have shown willingness to reuse treated greywater for landscaping (85–92%), toilet flushing (72–83%) and car washing (72–83%). Yet, recycling greywater by retrofitting all buildings in Qatar may not be economically sound; but it would be viable for future household units (Lambert and Lee 2018). Therefore, Scenario 2 assumes a *regulation reform* requesting new constructions to utilize a greywater reuse system – as part of the construction permitting procedures.

The minimum achievable water *savings*, due to on-site greywater reuse, was set at 20%, based on the findings of Alghool et al. (2019) for a residential villa in Qatar. Alghool et al. (2019) noted, however, that efficiency improvements in the adopted greywater collection network and treatment systems can be made. Hence, an upper limit of *water savings* of 50% was assumed in Scenario 2. This upper limit was validated against global studies showing that domestic water consumption can be reduced by 30–50% for different greywater reuse systems and residential applications, including those implemented in countries in the arid region (Samayamanthula et al. 2019).

2.5 Supply-side Water Management Strategies

2.5.1 Scenario 3 – Intensive Reuse of TSE

Currently, about 99% of the generated wastewater in Qatar is treated to secondary and tertiary levels (PSA 2018), resulting in a high-quality effluent that can be safe for reuse in crop irrigation, with minimal risks to soil, groundwater, and crops (Darwish et al. 2015). Yet only around 31% of the TSE is reused for agriculture and 28% for green space irrigation. The remainder TSE portion is either injected into aquifers (29%) or discharged into lagoons and the sea (12%) (PSA 2021). Scenario 3 projects the impact of improved TSE reuse for agricultural irrigation purposes (Table 2). It suggests increasing the TSE reuse rate in irrigation from 31% to 43–72% by incorporating the TSE fraction lost to lagoons and the sea (12%) and the portion injected into aquifers (29%). The TSE water supply to the agricultural sector was assessed with respect to the current reuse rate of 31% and improved rates (43–72%) under two cases:

- Case 1: Intense reuse of TSE (43% and 72% rates, successively) without any water-demand strategies in place (i.e., water consumption and wastewater generation remain as usual)
- Case 2: Intense reuse of TSE in tandem with water tariff reforms (i.e., lower water consumption) and regulated greywater reuse (i.e., lower wastewater proportion converted to TSE)

2.5.2 Scenario 4 – Water Recovery from Waste

Qatar has one of the world's highest daily municipal solid waste (MSW) generation rates (1.8 kg/capita). A substantial portion of this waste (60%) is organic, which is about 50–70% water, most of which (> 50%) is sent to landfills (Mariyam et al. 2022). Scenario 4 estimates the water volumes that may be recovered by treating the organic fraction of MSW with anaerobic digestion (AD) methods (Table 2). These methods allow the retention of water in the waste, with subsequent recovery through liquid–solid separation and reuse in agricultural irrigation (Guido et al. 2020). The following assumptions were made:

- Future (up to 2050) MSW generation rate was considered constant (1.8 kg/capita/day) with 60% organic content.
- The proportion of the MSW that is currently treated via biological and thermal methods (2300 tons/day) by Qatar's main waste processing plant (the Domestic Solid Waste Management Centre) (Clarke et al. 2017) was considered unavailable for future technology upgrades.
- Only the remaining waste, which is currently being landfilled, was considered in the following analysis by assuming that the organic fraction will be diverted from the landfill and treated using the AD technology.
- The volume of the liquid digestate produced by AD was assumed to be 50-70% of the organic fraction of MSW (OFMSW), with a density of 990 kg/m^3 (Schiavon et al. 2018).

3 Results and Discussions

3.1 Scenario 1: Tariff Reform

Under business-as-usual (BAU) conditions of water pricing in Qatar, household water demand could reach 524–586 MCM by 2050. A tariff reform is expected to reduce the annual residential water demand by up to 27% (380–425 MCM in 2050) under all population projections (Fig. 1a). Additionally, under BAU, the volume of desalinated water demand is anticipated to surpass the current supply capacity of the desalination plants (830 MCM/year) by: 3% prior to 2045 for the lower 95% population estimates, and 10% to 18% by 2035 and 2040 if the median and upper 95% population projections are reached, respectively. In comparison, upon applying the tariff reforms suggested in this study, total water consumption would decrease by around 17%. As a result, the

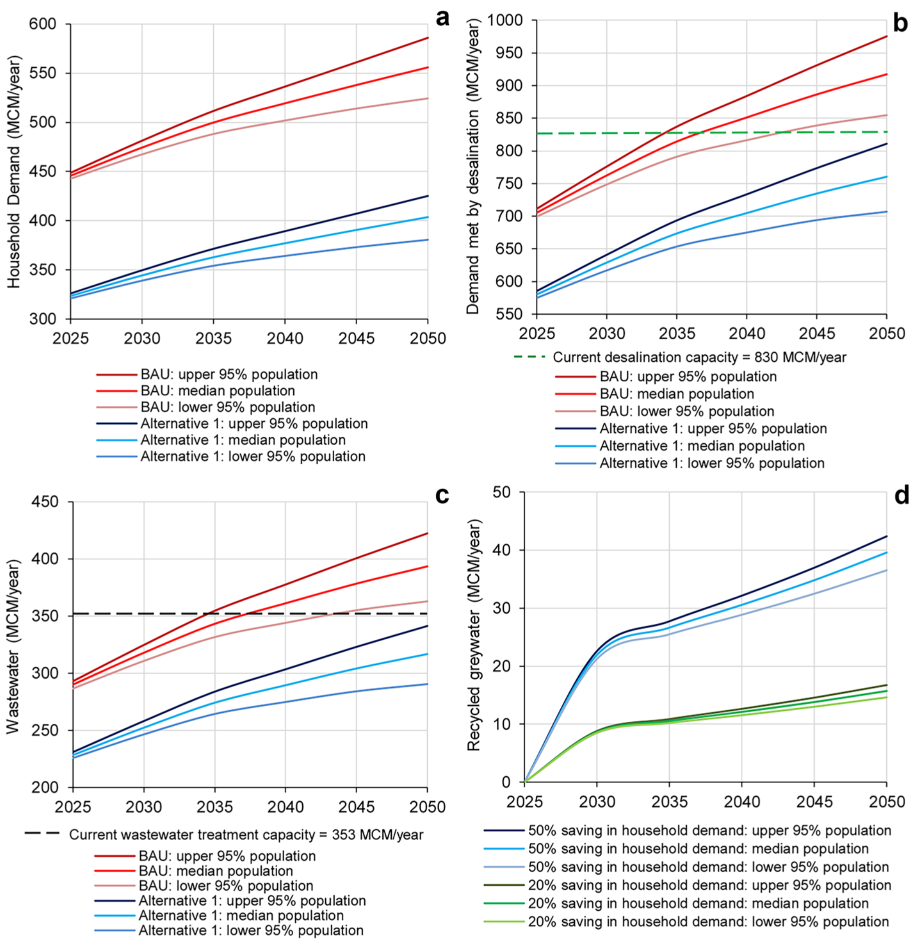

Fig. 1 **a** Household water demand, **b** water demand met by desalination, and **c** wastewater generated, under BAU and tariff reform (Scenario1); **d** recycled greywater volume (Scenario 2) – considering lower 95%, median, and upper 95% population projections.

current supply capacity of the desalination facilities remains satisfactory until 2050, indicating no need for expansion (Fig. 1b).

On the other hand, wastewater generation is also expected to exceed the current wastewater treatment capacity (353 MCM/year) by 19–20% in 2050. Expansion of the wastewater collection and treatment infrastructure would then be needed before the year 2035 for the upper 95% population projections, and before 2045 for the lower 95% population forecasts (Fig. 1c). Conversely, increasing water tariffs (thus reduced water consumption) is expected to cause a drop of 19–20% in the volume of produced wastewater (from 363–422 MCM to 291–341 MCM in 2050). Accordingly, expanding the wastewater treatment infrastructure may be needed past 2050 only if upper 95% population forecasts are reached.

3.2 Scenario 2: On-site Greywater Reuse

The impact of reusing treated greywater in future residential units on household water consumption was studied. Based on the local figure of 20% demand reduction (Alghool et al. 2019), the total volume of recycled greywater could reach 15–17 MCM in 2050 for the different population estimates. However, by achieving a higher reduction of 50%, similar to global rates, the total volume of reclaimed greywater could amount to 37–42 MCM (Fig. 1d). Overall, greywater reuse has the potential to save 3–7% of the country's household water demand.

3.3 Scenario 3: Intensive TSE Reuse

3.3.1 Case 1: Without Any Water-demand Strategies in Place

Agricultural demand is forecasted to reach 317–321 MCM by 2050. Under the current rate of 31% TSE reuse, the reclaimed TSE could supply 35–40% of the total irrigation demand by 2050 – equivalent to 111–130 MCM, while the rest of the demand (191–206 MCM) would still be met by groundwater abstraction at the present stabilized rate of 230 MCM/year.

By making use of the 12% TSE currently disposed in lagoons, the reuse rate increases to 43% TSE, leading to a supply equivalent to 49–56% of the total agricultural water consumption – corresponding to 154–180 MCM in 2050. The remainder fraction of the agricultural demand (141–162 MCM) would be met by groundwater abstraction, implying a 30–39% reduction in aquifer withdrawals compared to the current rate of 230 MCM/year.

Allocating the additional 29% TSE currently injected into deep aquifers, to reach an overall 72% TSE reuse, would allow a total irrigation water supply of 259–301 MCM in 2050, equivalent to 82–94% of the irrigation water needs (Fig. 2a). This would limit aquifer abstraction to only 20–58 MCM in 2050 (75–91% less than the current rate of 230 MCM/year) for the different population projections, which falls within the average groundwater safe yield of 55 MCM/year in Qatar (PSA 2018).

3.3.2 Case 2: With Tariff Reforms and Regulated Greywater Reuse

Implementing water demand reduction strategies (Scenario 1 and Scenario 2) would reduce the volume of produced wastewater, thus the overall amount of TSE available for reuse. Combining increased TSE reuse with tariff reforms (Scenario 1), the potential irrigation supply drops to 28–33% of the agricultural demand for 31% TSE reuse, 39–45% for 43% TSE reuse, and 65–76% if TSE reuse increased to 72% – equivalent to 89–105 MCM, 124–145 MCM, and 207–243 MCM by 2050, respectively (Fig. 2b). These rates remain substantial for 72% TSE reuse, reducing groundwater abstractions to 77–110 MCM (52–67% less than the present withdrawal rate of 230 MCM/year).

Similarly, combining increased TSE reuse with greywater reuse (Scenario 2), the volume of water available for irrigation decreases only marginally to:

1. 109–127 MCM, 151–176 MCM, and 253–295 MCM in 2050 for 31%, 43%, and 72% reuse TSE, respectively, if the minimum (20%) water saving is adopted (Fig. 2c); and

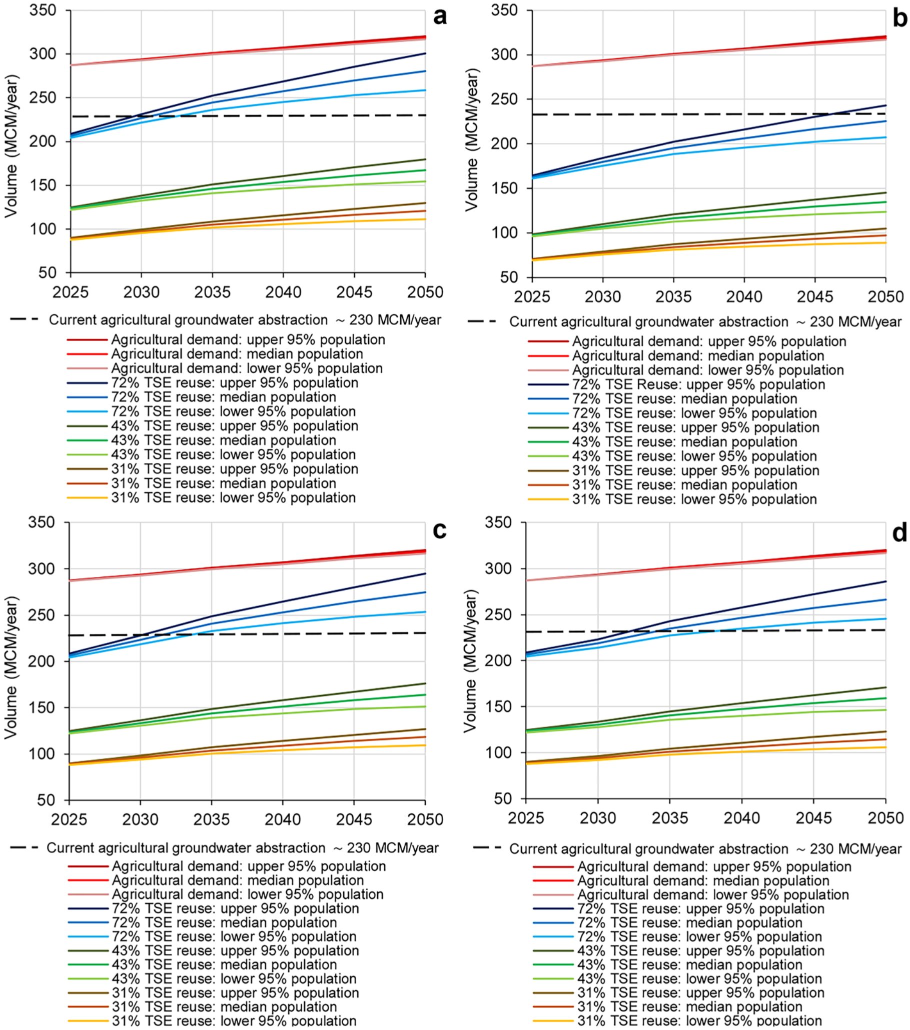

Fig. 2 Agricultural demand and potential TSE volume for irrigation under: **a** BAU, **b** tariff reforms, **c** regulated greywater reuse (at lower limit of 20% savings), and **d** greywater reuse (under upper limit of 50% savings) – considering 31%, 43%, and 72% TSE reuse rates with lower 95%, median, and upper 95% population projections

2. 106–123 MCM, 147–171 MCM, and 246–286 MCM for 31%, 43%, and 72% TSE reuse, respectively, if the upper limit (50%) water saving is adopted (Fig. 2d).

Overall, considering synergies between Scenarios 2 and 3, the volume of TSE for irrigation could amount to 33–55% of the agricultural water needs if 31–43% TSE is reused, and would reach 77–92% of those needs for 72% TSE reuse, limiting groundwater withdrawals to 26–71 MCM by 2050.

3.4 Scenario 4: Recovery of Solid Wastewater

By applying AD to the OFMSW that is currently landfilled, about 0.52–0.74 MCM of water may be recovered in 2050 – adopting the upper 95% population forecasts (Fig. S10 in SI). These results show that AD may not be considered a substantial water source for agricultural irrigation.

4 Conclusions and Recommendations

This study is the first to quantify the impact of the long-advocated shift to demand-side solutions with non-conventional supply on the water system in Qatar – a study case of GCC countries. The forecasts are based on country-specific models that were developed and validated using actual local data. These models were applied into a scenario analysis that allowed the investigation of synergetic effects between demand- and supply-side of the water system components. The outcomes are translated into the following data-driven recommendations:

- *Tariff reforms and enforced billing mechanism could substantially lower residential water consumption (by up to 27%) and delay the need to expand the desalination infrastructure (beyond 2045).* This makes water pricing a major determinant in the country's water budget. Thus, water metering, through smart water distribution networks, should be the starting point to capture water consumption patterns, categories and variables. These factors should be used to generate local PED models that reflect community specificities of the GCC country. Subsequently, water demand should be spatially modelled to allow forecasts based on weather characteristics and socio-economic variables (e.g., water price, location, social status, consumer and property characteristics, etc.). Only then, efficient water pricing strategies may be developed and effectively implemented. The impact of higher water tariffs on water consumption could also be extended to other sectors. Equally important, an efficient billing and collection mechanism need to be enforced.
- *On-site greywater reuse could have a fairly significant impact (3–7% reduction) on residential water demand.* This proves the benefit of future efforts to optimize the impact of regulating greywater reuse. As such, it is recommended to run a detailed socio-technical analysis for the potential of reusing greywater in various residential applications (toilet flushing, garden watering, floor cleaning, car washing, clothes washing, etc.). This allows site-specific estimation of: (1) the citizens willingness to reuse greywater, and (2) the technical constraints and opportunities. Subsequently, strategies should be designed to combine water pricing and greywater reuse for optimum reduction of water demand.
- *From a supply perspective, this study showed that reusing the portion of TSE that is currently disposed or injected into deep aquifers could supply, at least, 40–80% of the total irrigation water demand.* This justifies the urgency to initiate an extensive analysis, both financially and technically, in combination with: (1) agriculture-related drivers and challenges, including climate change adaptation and the use of modern production methods to minimize the use of space, soil, and water; and (2) the health, environmental, social, and cultural concerns associated with TSE reuse. These factors should be properly incorporated in any TSE reuse plans as they may excessively delay, or even hinder, implementation. Other non-conventional water resources that were not

addressed in this paper may be considered for specific applications. Those include the brine generated during the desalination of seawater and the produced water generated during the extraction of natural gas and oil.

- *Combining demand and supply management initiatives has shown to create synergies that can: (1) limit the exploitation of groundwater resources to a range close to their safe yield; and (2) delay the need for expansion of the water and wastewater infrastructures.* This highlights the need for decision-support modelling packages that: (1) merge supply- and demand-side scenarios, (2) incorporate climate change impacts on water resources availability and water demand sectors, (3) favor the resilience of water supply and wastewater collection infrastructure, and (4) consider environmental and socio-economic variability and uncertainties.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11269-023-03464-6.

Authors Contribution S.Ghanimeh is the senior author of this paper. She proposed the objectives of the study and guided the calculations, discussions and write up of the manuscript. I. Al Khoury is the junior (student) author. He reviewed the literature, gathered the data, designed the calculation methods, and developed a preliminary draft of the Manuscript. D. Jawad and M. Atiyeh reviewed the methodology, assisted in the interpretation of results, and reviewed the overall manuscript.

Funding Open Access funding provided by the Qatar National Library.

Availability of Data and Material This manuscript has no associated data available.

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.

Consent to Publish Not applicable.

Competing Interests There is no potential conflict of interest that the authors know about.

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