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Kuwait household water demand in 2050: Spatial microsimulation and impact appraisal

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Abstract

Household water demand has increased dramatically in Kuwait over the last few decades, due to rapid population growth and changing lifestyles. Avoiding a water deficit through a supply-side approach has been the default strategy in Kuwait, yet this approach is unsustainable, associated with declining groundwater levels, and reliance on desalination that results in major carbon emission and environmental impact and that takes a large and growing share of oil revenues. In this study, we forecast household water demand in Kuwait to 2050 under a Business-As-Usual (BAU) scenario and evaluate the economic and environmental impacts. A spatial microsimulation, constrained by the national population projection of the Kuwait Institute of Scientific Research (KISR), was developed to overcome data limitations in forecasting household demand. Results show a 45% increase in water demand by 2050, to 664.1 million cubic metres (MCM), relative to the 2019 base year. Annual production costs increase from 1.39 billion USD in 2019 to 1.99 billion USD by 2050, whilst carbon emissions increase from 10.85 to 15.54 million tonnes/year. These results should alert policymakers to the potential impacts of the growing water demand and provide further support for water conservation action to reduce demand.

KEYWORDS

BAU forecast, household water demand, impact appraisal, intervention measures, population projection, spatial microsimulation

Highlights

- Kuwait's household water demand forecast under the current situation is an indicator to inform policymakers of the urgent application of water conservation measures.
- A behavioural spatial microsimulation model has been applied to forecast household water demand at a disaggregate household-level.
- Forecast output has shown that water demand will increase by 45% by 2050, to 664.1 million cubic metres (MCM), relative to the 2019 base year.

1 | INTRODUCTION

Kuwait is located in the northeast of the Gulf Cooperation Council (GCC) region, one of the driest regions in the world, characterized by an extremely poor endowment of freshwater resources, low precipitation and high temperatures and evaporation (Al-Zubari et al., 2017). There is therefore a very high soil moisture deficit, so only a small percentage of rainfall infiltrates into aquifers. There is no surface source of usable water, such as rivers or lakes (Mukhopadhyay & Akaber, 2018). Kuwait is amongst the most highly water-stressed countries in the world, with the lowest availability of renewable freshwater per capita (World Bank, 2005). The renewable resource is below 2 m^3 per capita per year, which judged by the Falkenmark water stress index places Kuwait in 'absolute water scarcity', making it one of the least water secure countries (Rijsberman, 2006).

The severity of freshwater shortage began at the turn of the 1970s when Kuwait oil wealth led to exceptional economic and social transformation. Population grew rapidly, at 4.2% a year (Al-Zubari, 2002; Dawoud, 2005), accompanied by acceleration in agricultural development, industrialization and urbanization and changing consumer lifestyles (Abderrahman, 2000; Kotilaine, 2010). This transition led to a substantial increase in water demand, met initially by significant exploitation of groundwater aquifers, the only natural source of freshwater in the region (Dawoud, 2017). Population growth and a declining groundwater resulted in a dramatic drop in renewable freshwater per capita (Figure 1), which led Kuwait to construct desalination plants and draw down fossil groundwater (El Sayed & Ayoub, 2014; Saif, Mezher, & Arafat, 2014). Unconstrained by supply, water demand increased sharply. Whilst some conservation measures were introduced to protect the strategic fossil aquifers, demand and water stress continued to increase, in an unsustainable manner.

This growing water stress led the state to invest a share of its oil wealth in desalination (Al-Hashemi et al., 2014; Shomar & Hawari, 2017), which overcame the immediate water scarcity (Dawoud, 2012; Mohamed, 2009). Today, desalination meets more than 90% of household and industrial needs (Aliewi and Alayyadhi, 2018; UN, 2019), such that Kuwait ranks sixth in the world for desalination capacity, amounting to 4% of global daily desalination (ADNEC, 2018; ESCWA, 2006). Growth in Kuwait's desalination capacity has followed growth in water demand and population. The state increased desalination capacity from 30 million cubic metres (MCM) in 1970 to 716 MCM in 2016, an increase of 2287%; over the same period population increased 498% (Al-Humoud & Al-Ghusain, 2003; MEW, 2017). This supply-side policy led to a rapid increase in per capita consumption (PCC). PCC in the household sector is the highest in the world and far above that of most other countries (Qureshi, 2020). Average household PCC is about 500 L per day (L/d)

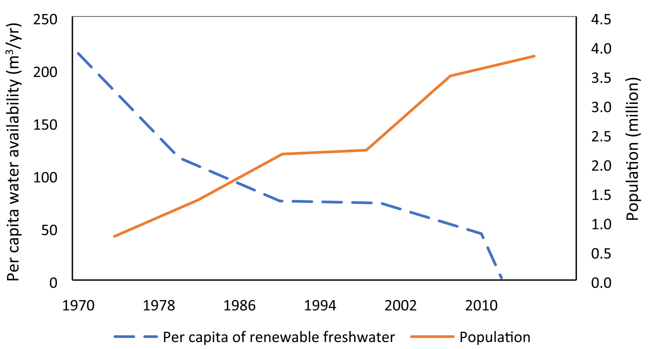

FIGURE 1 Population and renewable freshwater per capita in Kuwait since 1970. *Source*: World Bank (2005); Al-Zubari et al. (2017).

(Al-Ansari, 2013; Al-Zubari et al., 2017). In comparison, average household PCC in Germany and France is about 120 L/d, 156 L/d in England, 128 L/d in the EU and 310 L/d in the United States (Abu-Bakar, Williams, & Hallett, 2023; DiCarlo & Berglund, 2022; McCarton, O'Hogain, & Nasr, 2022; Parmigiani, 2015).

Urban land use in Kuwait accounts for 2.9% of the country by area, of which 2.5% is residential and commercial (Figure 2). The residential/household sector has the highest water demand share (>60% of all demand) compared with other sectors and has the highest demand increase, of about 4.1% per annum (MEW, 2018). The dramatic increase in the household sector is attributed to (i) population growth and urbanization; (ii) tariff structures that do not cover water production costs and encourage wasteful consumption; and (iii) lifestyle changes, such as a greater focus on personal hygiene (e.g., more frequent showering). Under the Kuwait government classification, the commercial sector also includes some residential units (largely high-rise buildings), so commercial areas also includes some household water demand that has been added in forecasting household demand. Household demand is expected to grow further as the government has a National Masterplan 'New Kuwait' that includes 13 new residential areas. These developments will comprise 1086 km^2, which constitutes 6.1% of the total area of the country, more than twice the current residential area. These developments are due for completion by 2045 and will add further pressure on water resources.

Dependence on desalination to satisfy the increasing demand has adverse environmental and economic impacts. Routine discharge of hypersaline effluent harms the marine ecosystem (Jones et al., 2019; Von Medeazza, 2005) by raising sea water salinity 5–10 parts per thousand (Lattemann & Höpner, 2008), raising temperature 7–8°C and lowering dissolved oxygen (Mohamed, 2009), and by polluting with chlorine and un-ionized ammonia. Kuwait's Desalination has to date been fuelled by hydrocarbons and so contributes greenhouse gases (Al-Hashemi et al., 2014). Kuwait is ranked amongst the world's 14 worst countries in terms of carbon footprint with per capita emissions much higher than EU (Reiche, 2010) and OECD countries (Doukas et al., 2006). CO_2 emission are 25.2 t per capita/year, compared with 9.5 t per capita/year for the OECD and 8.9 t per capita/year for the EU (OECD, 2021). Generous subsidies have given rise to a huge gap between water system revenues and operating expenses in Kuwait (El Sayed & Ayoub, 2014). The net revenue covers only 6% of total production costs, far below full cost recovery. If this situation continues under current demand trajectories, subsidies will place an even heavier burden on the fiscal budget (Darwish, Al-Najem, & Lior, 2009). Kuwait already uses around 12% of its oil production to fuel desalination plants, a share predicted to rise to a staggering 50% by 2050 (Al-Rashed & Akber, 2015), which, in turn, will have a high opportunity cost. This strategy of turning non-renewable fuel into water is unsustainable. Despite these problems, Kuwait is expected to invest further in desalination plant construction and expansion to meet growing water demand.

Currently, Kuwait has the lowest per capita freshwater availability in the GCC (and indeed in the world) yet its PCC is amongst the highest in the GCC (and world). Within the GCC, it has the highest share

FIGURE 2 Urban land use in Kuwait.

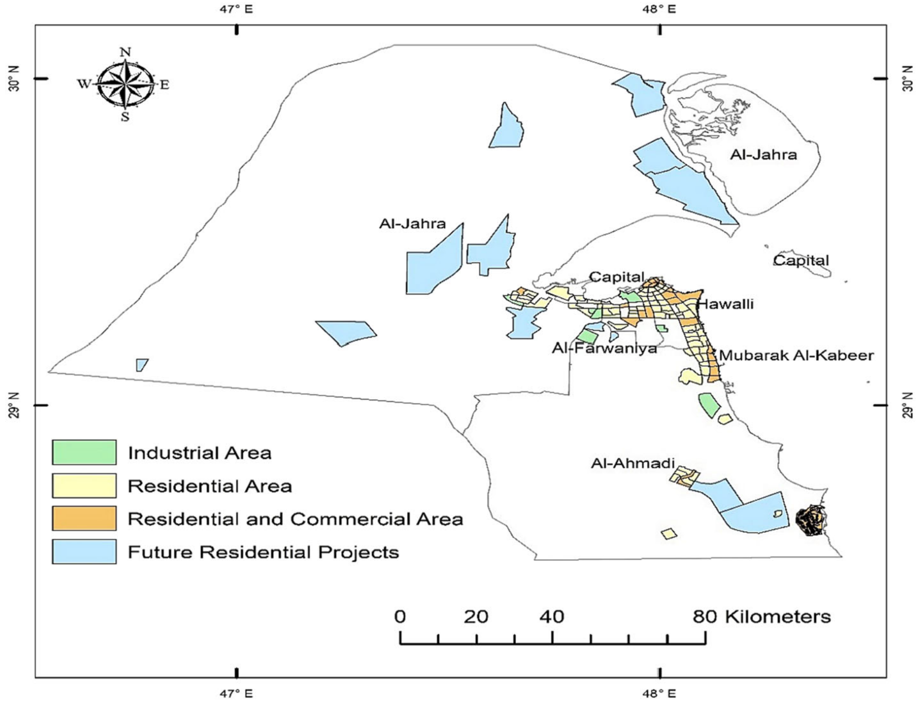

TABLE 1 Methods for forecasting future household demand used in the study.

Objectives	Data type	Data/variables	Method
To assume the missing PHC values (household sizes/ dwelling types not addressed in the PHC demand matrix). Assumption process uses a regression fitting function. To apply this matrix with the aggregate household population to generate the baseline year and forecast water demand 2050.	*Household water demand*	Household size, type of dwelling, PHC demand and nationality (Kuwaiti and non-Kuwaiti). Data sourced from CSB sample for 2013 (only).	a) Omitted households that have zero demand (missing records) and/or households of no specified dwelling type. b) Created tables to classify households based on: (i) nationality; (ii) household size; (iii) dwelling type. c) Reclassified household size ranges from 2 to 33 persons to 2 to ≥12 persons, which covers 95% of all households.
To produce aggregate water demand for observed population years (2013–2018) in association with the CSB dataset—using spatial microsimulation.	*Aggregate household population in the household sector*	Household size, distribution over the country's governorates and nationality (Kuwaiti and non-Kuwaiti) from 2013 to 2018. Source: PACI, Population Census.	a) Omitted households that have no specified size, nationality and/or governorate distribution in the country. b) Checking of the aggregate population in each governorate and aggregate population in the country in each year.
To use population projection to forecast aggregate household demand—developing a behavioural model	*Population projection of Kuwait*	Total population by nationality (Kuwaiti and non-Kuwaiti) until 2050. Source: TED/KISR[a].	a) For the TED/KISR dataset, prepared a table that disaggregated population (Kuwaiti and non-Kuwaiti) of aggregate population (only a single scenario); b) Applied enhancement procedures to TED/KISR projection to fit the observed population (Table 2)

Abbreviations: CSB, Central Statistical Bureau; PHC, per household consumption.
[a]The population projection of the Techno-Division at Kuwait Institute for Scientific Research (TED/KISR) is discussed in Section 2.3.

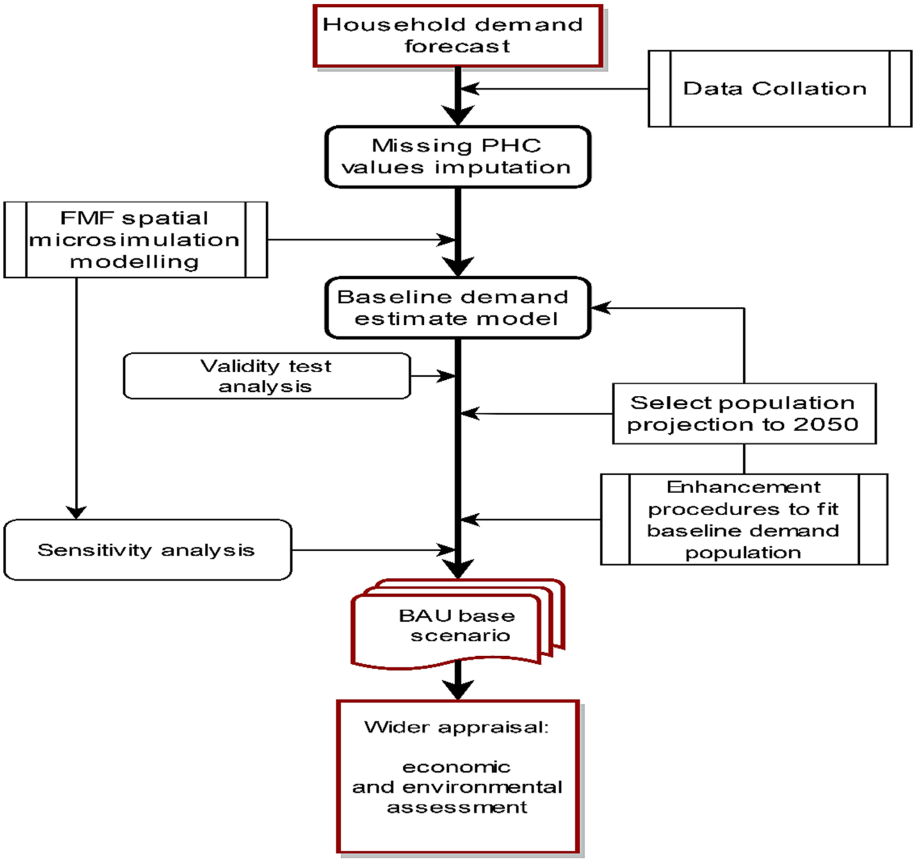

FIGURE 3 Overview of the modelling framework developed for the study.

of demand from the household sector (>60%), yet despite strong annual growth in demand (>4.1%) water demand in Kuwait remains little studied. Against this background, this study assesses future household water demand in Kuwait under current demographic trajectories and then assesses the environmental and economic consequences of this changing demand. By understanding demand futures under current development trends, we hope to support officials and policymakers in Kuwait in taking appropriate conservation actions to avert a future water crisis. Our findings are of relevance to other countries in the GCC region, which share a similar range of scarcity and growth pressures.

2 | METHODS

In this research, several methods (Table 1) have been used to develop the Business-As-Usual (BAU) forecast for household water demand to 2050. A model building process (Figure 3) is used in which demographic forecasts are applied in conjunction with household water use coefficients, with both disaggregated to reflect household characteristics, and techniques used to overcome missing data. The main steps, detailed further below, are (i) demographic disaggregation of per household consumption (PHC) with trendline fitting imputation to complete the set of PHC coefficients by household type/size; (ii) generation of aggregate water demand for the base period (2013–2018); and (iii) projection of the household BAU demand forecast to 2050.

2.1 | Disaggregate PHC trendline imputation

No forecast of water demand in the household sector exists for Kuwait; there are only forecasts for the entire population for all country's sectors. We produced a forecast using spatial microsimulation (Birkin & Clarke, 2011), a method not previously used in water sector in the GCC, that allows observed aggregate PHC demand to be disaggregated by household characteristics (and which in later work enabled scenario modelling with representation of micro-components). This decomposed demand was constrained by an official population projection to generate the BAU household forecast. To develop the baseline demand estimate, two datasets were used: first, a survey of household water demand conducted in 2013 by the Central Statistical Bureau (CSB). The survey is based on probability sampling—a combination of cluster and stratified techniques, involving 2961 households comprising Kuwaiti and non-Kuwaiti households (the household status), household size and dwelling type for each household distributed over the country's governorates, with demand recorded as PHC (hereafter the 'PHC demand matrix'). The dwelling type is recorded as a villa, floor or apartment in a villa, an apartment, a traditional house or an annex.[1]

The second dataset is the household census (2007–2018), provided by the Public Authority and Civil Information (PACI), and

[1]The annex dwelling is only assigned for non-Kuwaiti households.

referred to hereafter as the 'household population matrix'. This matrix includes household status and household size distributed over the country's governorates but lacks the dwelling type variable of the water demand survey, which is an important influence on demand. Both matrices identify non-Kuwaiti inhabitants (domestic workers), which are a large part of the population and play a major role in Kuwaiti households' demand. These demographic variables are further discussed below (Sections 2.2 and 2.3).

To develop the disaggregated PHC demands, a process was applied to the PHC demand matrix (see Table 1) to impute PHC missing values (for dwelling type/household size classes), using non-linear power functions (see Section 3.1).

2.2 | Household baseline demand estimate

The imputed PHC demand matrix must be scaled to the national population using the household population matrix to give total national household water demand. This process is hindered by a lack of dwelling type data in the Kuwait national population census, preventing simple estimation of household size by dwelling type. This problem was addressed using a synthetic population microsimulation that constructs an artificial population with a distribution of characteristics that matches that in the observed population and that enables estimation of variable combinations that do not exist in the census data (Hermes & Poulsen, 2012). In effect, a good synthetic population simulation can reproduce the characteristics of a population allowing extension from a sample to an entire population, thus overcoming data limitations (Whitworth et al., 2017). It is common, for confidentiality reasons, for a census to have fewer details (variables) for individuals and/or households compared with sample surveys, but microsimulation allows these missing data to be imputed at the population level from the more detailed sample (Smith, Clarke, & Harland, 2009; Whitworth et al., 2017).

A Small Area Estimation (SAE) approach using a static spatial microsimulation method was used, considered amongst the most reliable of SAE methods (Ballas, Clarke, & Turton, 2003; Hynes et al., 2009; Tanton, 2014). The static spatial microsimulation linked the household population matrix (census 'macro data') with the PHC demand matrix (sample population 'microdata') through shared benchmarks to produce a synthetic population using Flexible Modelling Framework (FMF) software (Harland, 2013). The PHC demand matrix was then applied to the resulting synthesized population to estimate total national household water demand for the years 2013–2018[2] for which observed aggregate demand is known, allowing the BAU model to be validated.

[2]The estimation starts with 2013 as the base year since the CSB survey is conducted in 2013.

2.3 | Forecasting BAU demand

The BAU forecast demand is driven by demography; hence, a population projection to 2050 for Kuwait is required. We used the projection of the Techno-Economic Division (TED) of the Kuwait Institute for Scientific Research (KISR) in preference to that from the United Nations (UN),[3] as the latter underestimates population with respect to observed data. The TED/KISR projection employs a cohort component method that ages the population with annual representation of births, deaths and migration. This is considered preferable to other forecasts for Kuwait that use mathematical (arithmetic, geometric, logistic) trend projection as these are less successful at representing underlying demographic processes (Gawatre, Kandgule, & Kharat, 2016). Furthermore, the TED/KISR projection builds on the same PACI data structure as the 2013–2018 observed base period described above and differentiates national (Kuwaiti) from expatriate populations. This helps in forecasting as these groups differ very significantly in their household water demand (as evidenced by the CSB, 2013[4] water use survey). The TED/KISR projection was subject to further work (Table 2) to closely fit the projection to the requirements of the demand forecasting. Because TED/KISR produced only a single-variant projection, a deterministic sensitivity test was applied using several population coefficients based on historical observations.

Sensitivity of forecast demand to changes in input parameters, in the range of ±15% (a value suggested by Billings & Jones, 2011), was assessed to identify the relative influence of input variables on demand. In this way, the three most important independent variables for sensitivity testing were identified as domestic worker share, non-Kuwaiti population share and household size variability, which we define here as 'household size distribution'. These variables were manipulated and combined to produce 12 possible population variants, which fed into 12 BAU demand forecasts.

For the domestic workers and non-Kuwaiti population share, parameter values were derived from historical observations (2007–2018) using a naïve[5] value (A) and a weighted moving average value (B). For domestic workers, parameters values are 60.08% (A) and 55.59% (B) reflecting the share of the Kuwaiti population that are domestic workers. Domestic workers are individuals employed by a householder and resident in a household and include maids, cooks and gardeners. We address them as a separate group in the model because the rate of growth of this population group, which now represents a large proportion of households, is considerably higher than for Kuwaitis. These domestic workers are assigned to the Kuwaiti household population in the study's demography matrices. The non-Kuwaiti household population share is similarly represented by the parameters (A) 48.64% and (B) 45.48%. In Kuwait, a significant share of the non-Kuwaiti population is not associated with

[3]The UN projection also uses the cohort component method and is applied to provide multi-variant population projections. *Source*: https://population.un.org/wpp/Graphs/.

[4]Household water expenditure averages 58 USD/month for Kuwaiti households, 30 USD/month for non-Kuwaiti's.

[5]Naïve is the value of the last observation of a historical dataset.

TABLE 2 Enhancement of TED/KISR population forecast to support water demand forecasting.

Objective/reason	Dataset	Method
Procedure I: Kuwaiti population uplift (bias correction)		
To overcome underestimation of the TED/KISR projection compared with the observed population (2013–2018).	*A. Observed Kuwaiti population 2018;* *B. TED/KISR projection of Kuwaiti population 2018*	Developed a constant coefficient to be applied to the period of projection.
Procedure II: define the domestic worker proportions in Kuwaiti population		
To maintain consistency of Kuwaiti population projection compared with observed population. The domestic worker proportions will be added to the Kuwaiti projection.	*Observed Kuwaiti population (2007–2018).*	Three constant coefficients were developed from the historical trends: (i) average of 2007–2018; (ii) average of 2014–2018, as a relative demographic change occurred; (iii) proportion of 2018 as it is the recent observed year. The developed coefficients were applied to the non-Kuwaiti population, then the obtained number will be subtracted from this population and added to the Kuwaiti population.
Procedure III: define non-Kuwaiti household population		
To find the non-Kuwaiti population in the household sector, as the research targeted those inhabitants in the relevant sector.	*Observed non-Kuwaiti population (2007–2018).*	Three constant coefficients were developed from the historical trend: (i) average of 2007–2018; (ii) average of 2014–2018, as a relative demographic change occurred; (iii) proportion of 2018 as it is the recent observed year; The developed coefficients were applied to the total non-Kuwaiti population, then the obtained number will be representative to non-Kuwaiti in the household sector.
Procedure IV: determine population distribution by household size and the country's governorates		
(i) To set PHC demand for each household. (ii) To allow spatial analysis amongst the country's governorates.	*Observed household size distribution for total population (2007–2018).*	Percentile distribution of observed household size distribution was projected onto the forecast population after satisfying previous procedures; this method is derived from the scaling-up method.
Procedure V: define households by dwelling type		
To specify a household's dwelling type, as dwelling type is a determinant of PHC demand.	*A. PHC household demand matrix, as a sample population table;* *B. A certain year of population projection* (e.g., *2019 after modification as constraint table).*	SAE, static spatial microsimulation method, combinatorial optimization–simulated annealing technique, using FMF software.

Abbreviations: PHC, per household consumption; SAE, Small Area Estimation; TED/KISR, Techno-Division at Kuwait Institute for Scientific Research.

household water demand, as they work within the agricultural (or other commercial) sector, and their personal water use is thus recorded as an agricultural (or other commercial) demand. Thus, we need to understand the share of non-Kuwaiti population that are resident in households for which we are forecasting demand.

The household size distribution parameter represents variability in the observed household size distribution, which has changed relatively quickly in Kuwait. The 'High' variant represents the observed household size distribution, averaged over an observed historic period (2007–2018). In this period, the earlier years have a higher proportion of larger household sizes (>7 persons), and conversely, more recent years have a higher share of smaller household sizes (<7 persons). In averaging over the historical period, more weight is given to larger household sizes than is consistent with current, smaller household sizes, which will act to elevate forecast water demand (hence the 'high' variant label). A 'Medium' variant represents the percentile distribution of household sizes where a weighted moving average technique has been used. In this variant, the more recent years (smaller household size proportions) have more weight; that is, more recent years are considered more representative than the earlier ones. A 'Low' variant represents the household size distribution of 2018, the latest year for which observed household size distribution data are available. This variant gives the most weight to the smaller household size distribution, thus implies a lower household water demand.

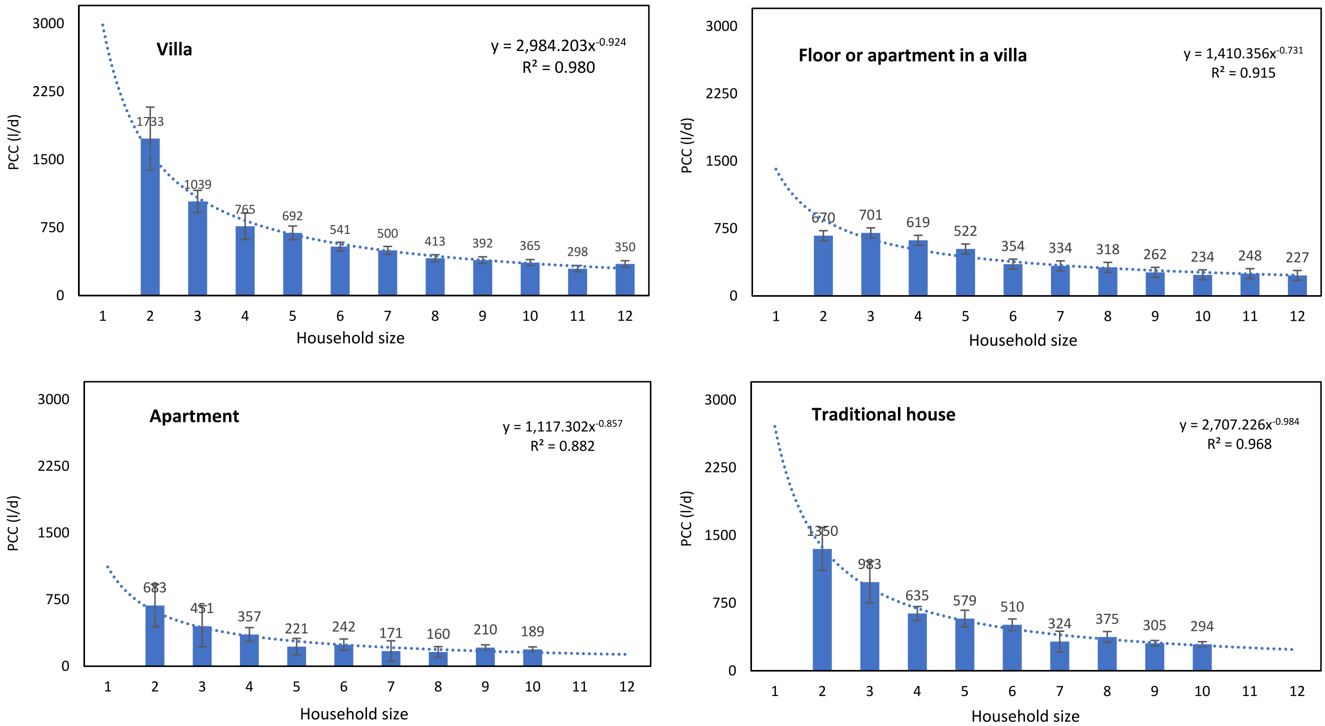

FIGURE 4 Function fitting to derive missing values for the Kuwaiti household dwelling categories.

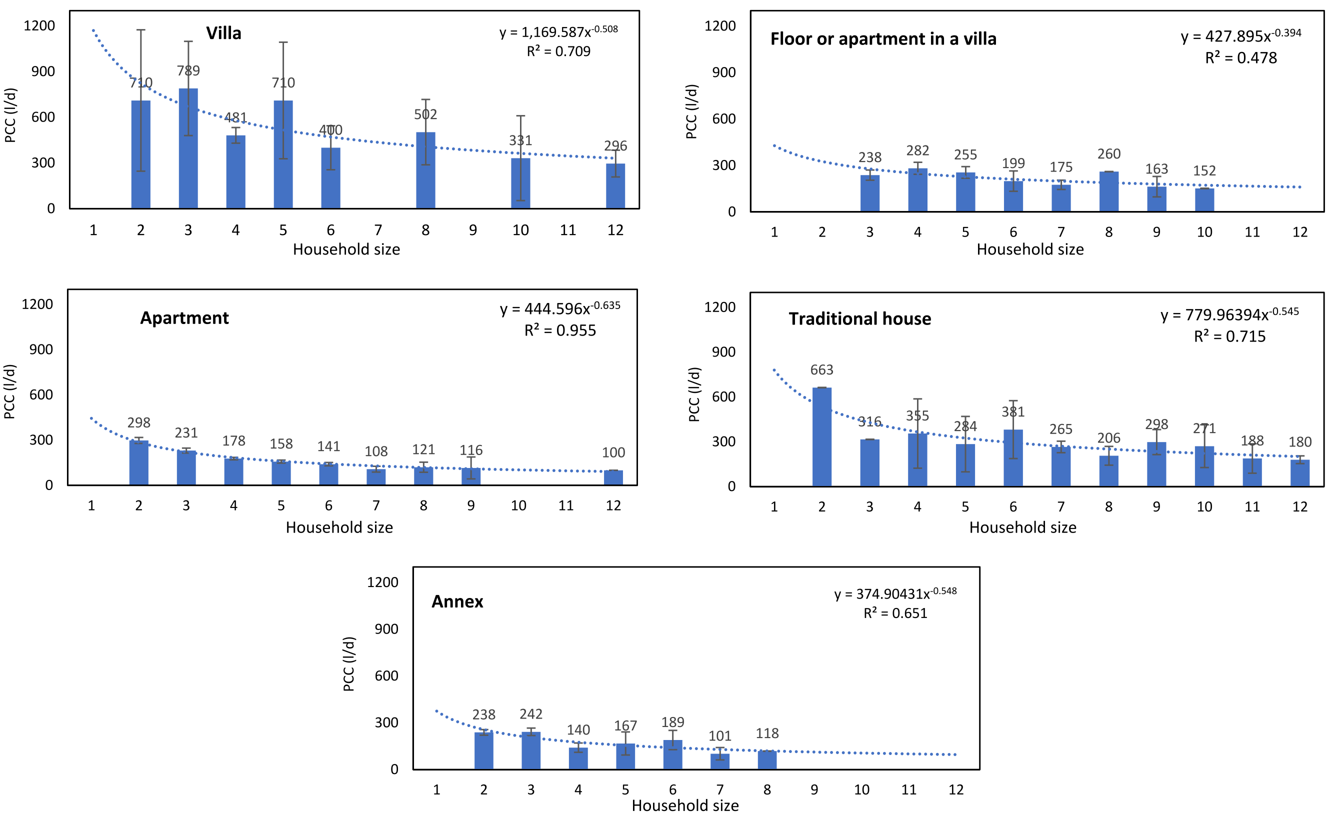

FIGURE 5 Function fitting to derive missing values for the non-Kuwaiti household dwelling categories.

TABLE 3 The leverage and influential outlier points in the PHC demand matrix.

Dwelling type	Household size	Household status	PCC	Leverage	Influential
Villa	9	Non-Kuwaiti	158	✓	
Floor or flat in a villa	11	Non-Kuwaiti	344	✓	✓
Floor or flat in a villa	12	Non-Kuwaiti	361	✓	✓
Flat	10	Non-Kuwaiti	69	✓	
Flat	12	Kuwaiti	55	✓	

Abbreviations: PCC, per capita consumption; PHC, per household consumption.

3 | RESULTS AND DISCUSSION

3.1 | Missing PHC values imputation

Missing values in the PHC demand matrix were assumed by fitting power functions to the observed data (Figures 4 and 5). This process uses PCC values in preference to PHC values as they display a better fit; household size is then used to derive the missing PHC values. Assumed values in the Kuwaiti household dwelling categories fit well ($r^2 > 0.90$) in most categories, whereas non-Kuwaiti household categories have a fair fit in most categories.

The imputation of missing values was satisfactory after application of the influential and leverage points detection tests in the PHC demand matrix. Tests to detect influential and leverage points are used in trendline curve fitting where different trendline functions are applied (over several iterations) with and without extreme observations (outliers) to see how these observations affect the trendline orientation. By applying this test, influential and leverage outlier points in the PHC matrix were detected, and the best fit trendline function (power) selected. Outlier points affect the orientation of the slope and drag the trendline towards its location in whatever trendline is being performed. Five outlier points were detected across the PHC matrix (Table 3) with the influential outliers affecting the trendline and biassing the missing value assumption. Uncertainty exists as to whether these outliers occur because of measurement error in the water demand survey or if they represent actual variability in observed demands. However, due to the high influence of the outlier points in the slope and assumption process, these points were omitted and replaced by values derived by applying a regression fitting function (also used to derive any missing values—e.g., where there is no PHC for a given dwelling type/household size).

3.2 | Baseline demand estimate

To establish a base period that reflects the 'current' situation of water demand in Kuwait, water use coefficients from the PHC demand matrix are used to represent the primary driver of water demand and linked to associated population data[6]; this is represented by

$$BLDE = \sum_{t=i}\left(\left\{cgj_{(h)}^{-d} + egj_{(h)}^{-d}\right\}/10^{-9} * yr^{-1}\right), \quad (1)$$

where *BLDE* refers to the baseline demand estimate; *cgj* is the Kuwaiti demand (PHC – l/d) by spatial distribution *g* and dwelling type *j* for each household size *h* on a daily basis *d*; *egj* is the non-Kuwaiti demand (PHC – l/d) by spatial distribution *g* and dwelling type *j*, divided by a billion (litres per MCM), then, multiplied by days per year *t* (e.g., 2015) to get the aggregate demand for year *t*.

Equation 1 was applied for each year in the 2013–2018 baseline demand estimate period, where the results show an expected increase in demand with household population increase. Figure 6 shows the observed aggregate household demand (2014–2017) and estimated aggregate household demand against observed household population. This base period estimation was compared with observed demands using the mean absolute percentage error (MAPE) statistic to validate the estimation. The MAPE of 2.36% indicates a good a model estimate; hence, we take this baseline period model forward into the demand projection under BAU to 2050.

3.3 | Household demand: BAU forecast 2050

Sensitivity analysis has been applied to the enhanced TED/KISR population projection in which 12 BAU demand variants have been developed. The two population parameters (domestic worker population, non-Kuwaiti household population) are applied to the three household size distributions (High-Medium-Low), to give 12 population variants (Table 4) These are denoted by, for example, AB-High, where A refers to the share of domestic workers parameter (60.08%), B refers to the share of non-Kuwaiti household population parameter (45.48%) and High denotes the household size distribution. PHC water demand coefficients are then applied to the decomposed demographic classes to forecast BAU water demand under each of the 12 demographic variants. Water demand forecasts for the variants, including the base variant (the central population projection segments, Figure 7) are shown in Table 4. It is important to note that these are BAU forecasts, driven by Kuwait's demography, and do not account for any change to PHC demands that might arise in future (e.g., due to water conservation measures or further behavioural change).

The range in forecast water demand in the BAU scenarios increases through the forecast. The difference is 33.4 MCM in 2020, rising to 46.6 MCM in 2050, with the base scenario falling in between.

[6]The synthesized population from the household population matrix by using FMF spatial microsimulation model.

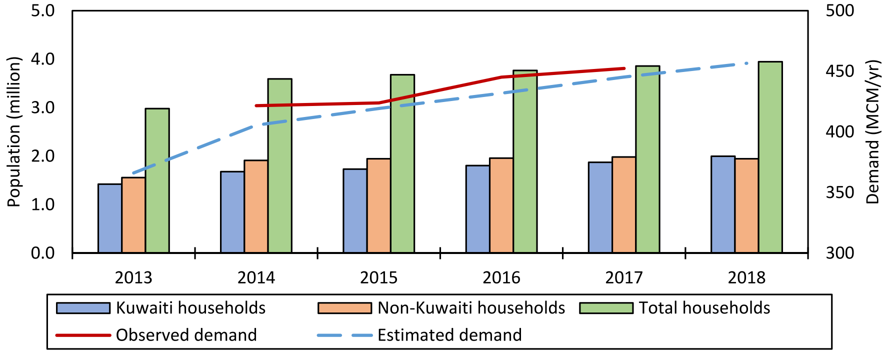

FIGURE 6 Estimated household water demand.

TABLE 4 Kuwait water demand forecasts under different population projections (MCM/year).

Scale	Parameter	2020	2025	2030	2035	2040	2045	2050
Low	AA	474 184	512 506	547 909	583 980	617 828	645 766	666 472
	AB	466 619	504 441	539 353	575 035	608 466	635 806	657 164
	BA	464 309	502 035	536 357	571 936	604 934	632 120	652 500
	BB	456 978	493 882	528 025	563 325	595 369	622 747	643 121
Medium	AA	479 351	518 150	553 504	590 054	624 565	652 129	674 080
	AB[a]	471 922	509 895	545 158	581 409	614 887	642 645	664 079
	BA	469 256	507 138	542 367	578 316	611 241	639 390	660 015
	BB	462 205	499 272	533 679	569 368	601 546	628 772	649 993
High	AA	490 396	530 043	566 596	603 760	639 195	667 698	689 774
	AB	482 903	522 036	557 947	595 015	629 574	658 225	680 059
	BA	480 305	519 526	554 659	591 578	625 605	653 919	675 157
	BB	472 983	511 238	546 293	582 570	616 414	644 036	665 790

[a]AB-Medium is the base BAU forecast for the study.

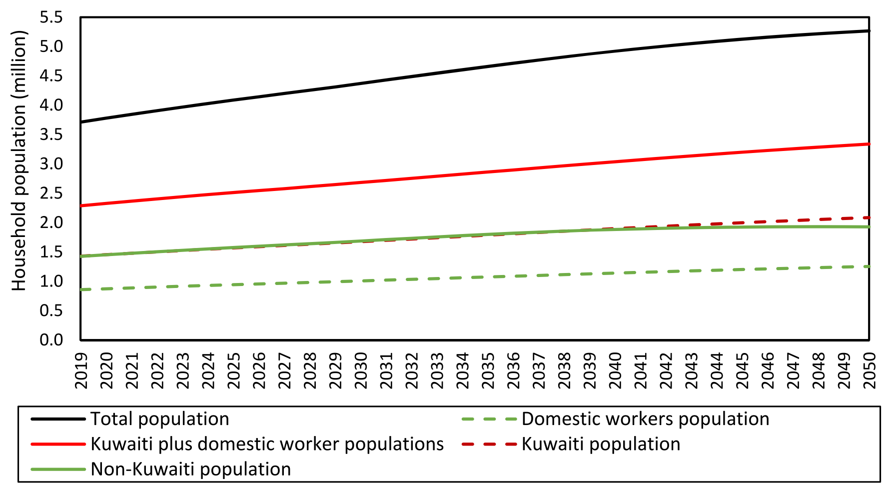

FIGURE 7 Segments of the base household population projection.

The difference between Low-BB and the base scenario is 14.3 MCM in 2020, and between High-AA and the base scenarios is 18.5 MCM. The household size distribution (scale parameter) has a major influence on forecast total demand but is a minor influence in terms of the demand proportion distribution for Kuwaiti and non-Kuwaiti. When applied to high, medium and low scales, considerable variation in total demand (Kuwaiti and non-Kuwaiti) is evident, but little variation arises due to the demand proportions between Kuwaiti and non-Kuwaiti. Furthermore, the domestic workers' parameter has more influence on demand than the non-Kuwaiti parameter.

Base scenario demand (Figure 8) increases from 463.5 MCM in 2019 to 664.1 MCM in 2050, an increase of 30.21%, with highest

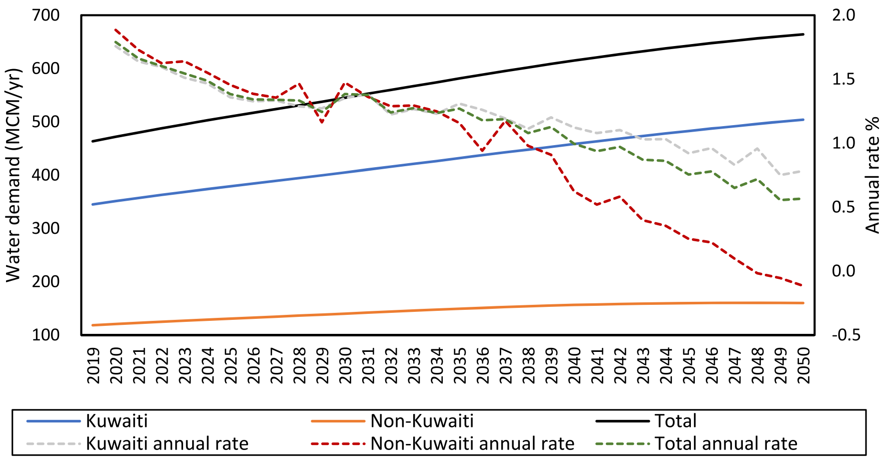

FIGURE 8 Difference between Kuwaiti and non-Kuwaiti demand.

annual increase of 1.8% in 2020, and lowest increase of 0.6% in 2050; the average increase rate of the forecast horizon is 1.15% year^{-1}. For Kuwaiti households, demand increases from 345.0 MCM in 2019 to reach 504.0 MCM in 2050, an increase of 31.5%. The annual increase rate peaks at 1.75% in 2020 and is at a minima of 0.75% in 2050, with an average of 1.2% annually. For non-Kuwaiti households, demand increases from 118.4 MCM in 2019 to peak at 160.4 MCM in 2048 followed by a small decline to 160.1 MCM in 2050. Non-Kuwaiti demand increases 26% overall, with an annual increase of 0.97% (peaking at 1.88% in 2020 and at a minima of 0.12% in 2050).

Demand is broadly proportional to the distribution of households by status, with Kuwaiti households representing over 74% of total demand, and non-Kuwaiti about 25%. Non-Kuwaitis account for c. 70% of the total population but not a similar share of household demand—this is because Kuwaitis have a higher per capita demand, whilst domestic demand for many non-Kuwaitis is not considered household demand but accounted for under agricultural and industrial consumption. The annual proportional demand of Kuwaiti households decreases fractionally for a time (2020 = 74.42% of total demand, 2034 = 74.26%) but increases to peak in 2050 at 75.89%. Correspondingly, the annual proportion demand of non-Kuwaiti households rises from 25.57% in 2020 to peak at 25.73% in 2034, then drops to 24.1% in 2050.

3.4 | Wider economic and environmental appraisal

3.4.1 | Economic impact assessment

To assess the economic implications of the forecast BAU demand, water cost is calculated as production cost per m^3 (2 USD), plus the cost of delivery to end-user (1 USD), giving 3 USD per m^3 of end-use consumption (Al-Damkhi, Abdul-Wahab, & Al-Nafisi, 2009; Al-Humoud & Jasem, 2008; Aliewi et al., 2017; Fadlelmawla, 2009). These costs are in common use in the Kuwait desalination industry, and no more recent data are currently available. The aggregate water cost can be calculated from

$$APC_t = p_t * q_t, \quad (2)$$

where *APC* is the aggregate water cost at time *t*; *p* the price per unit[7] (m^3); and *q* the quantity of water billed and collected at time *t*. For water revenue (benefits), a change in *q* represents the cost costumers pay per unit[8] (0.58 US$). To calculate the PHC cost/revenue per unit, the following has been used:

$$PCRPHC_t = \frac{h_t}{p_t}, \quad (3)$$

where *PCRPHC* is the cost/revenue per PHC at time *t*; *h* is the total household population (or Kuwaiti/non-Kuwaiti households); and *p* is the total cost/revenue at time *t*.

Figure 9 illustrates that the total cost to produce and deliver water increases from 1.390 billion USD in 2019 to 1.99 billion USD by 2050 (nominal prices unadjusted for inflation). This is an increase of 601.80 million USD and an average annual increase of 19.4 million USD. Costs increase most in 2020 (1.82% per year) and least in 2050 (0.57% per year) with an aggregate cost increase of 43.28% over the forecast period. Total revenue from water sales is 276.55 million USD in 2019, rising to 389.15 million USD in 2050, an average annual increase of 4.8 million USD. Water supply to an average Kuwaiti household costs 3314 USD year^{-1} against revenue of 647 USD year^{-1}, whereas for a non-Kuwaiti household, cost is 748 USD year^{-1} against a revenue of 146 USD year^{-1}. Overall, the average household cost is 1814 USD year^{-1} against a revenue of 350 USD year^{-1}, far below full cost recovery.

3.4.2 | Environmental impact assessment: Carbon dioxide emission

Kuwait operates thermal seawater desalination plants (membrane plants are used for wastewater treatment). A CO_2 emission per unit

[7]The price per unit comprises the production and delivery costs.
[8]The tariff structure in Kuwait is uniform volumetric.

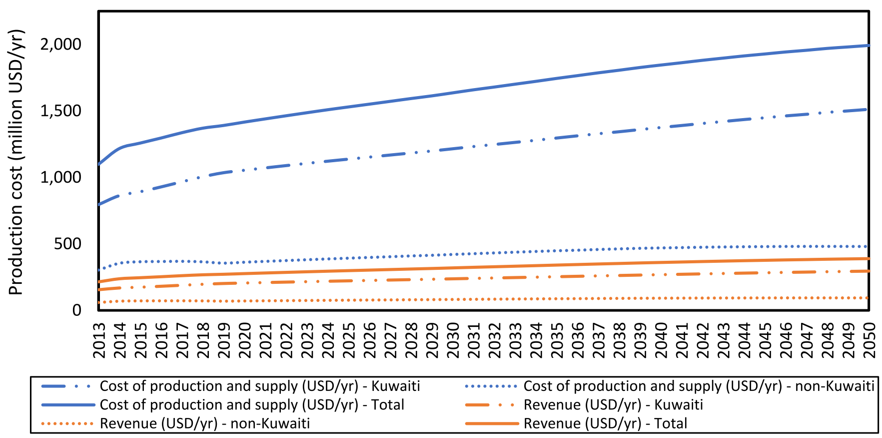

FIGURE 9 The cost of production and revenue in Business-As-Usual (BAU) scenario.

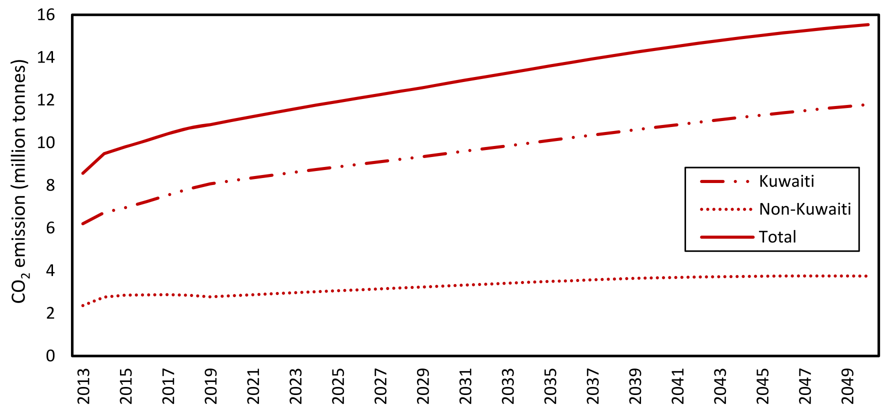

FIGURE 10 CO_2 emissions under Business-As-Usual (BAU) scenario.

thermal desalination[9] of 23.4 kg/m^3 of water produced has been drawn from literature (Darwish, Al-Najem, & Lior, 2009; Dawoud, 2012; Fath, Sadik, & Mezher, 2013; Raluy, Serra, & Uche, 2004). CO_2 emission from desalination was estimated from

$$CE_t = \frac{d_t}{e_t}, \tag{4}$$

where CE_t is the carbon dioxide emission at time t; d_t refers to water produced (applied to the grand total and also total Kuwaiti and non-Kuwaiti demands); and e_t is carbon dioxide emission per unit production at time t. The PHC's CO_2 footprint was calculated from

$$HCF_t = \frac{p_t}{e_t}, \tag{5}$$

where HCF_t is the household carbon dioxide footprint at time t; p is the household population (grand aggregate and aggregate Kuwaiti and non-Kuwaiti); and e is the CO_2 emission to equivalent household population (e.g., Kuwaiti) at time t.

The average annual household carbon footprint is 13.8 t in 2019, rising to 14.1 t in 2050. The average Kuwaiti household emits 25.8 t 2019, and 25.9 t by 2050; for the average non-Kuwaiti household, emission is stable at 5.8 t/year throughout the BAU forecast. However, due to population growth, the results (Figure 10) show, unsurprisingly, that total household CO_2 emission increases substantially with rising demand, from 10.85 million tonnes in 2019 to 15.54 million tonnes in 2050, an annual average increase of 1.02%, equivalent to 151 434 thousand tonnes. For Kuwaiti households, CO_2 emission increases from 8.1 million tonnes in 2019 to 11.8 million tonnes in 2050; whilst non-Kuwaiti households emission increases from 2.8 million tonnes in 2019 to 3.6 million tonnes in 2050.

4 | CONCLUSION

GCC countries are witnessing continued growth in water demand, whilst the availability of freshwater resources, already amongst the lowest of any world region, is declining. Increasing demand is exacerbating the extreme water stress the region already faces. Supply side desalination has been the conventional approach to overcome water shortage, but this is becoming hugely costly to operate. Kuwait already uses around 12% of its oil production to fuel desalination plants, and this share is predicted to rise to a staggering 50% by 2050 (Al-Rashed & Akber, 2015). Our model appraisal shows that the gap between water desalination cost production and revenues is −1.61

[9]Kuwait operates dual plants that desalinate water and generate electricity; thus, the coefficient used is an estimate from previous studies.

billion USD in 2050, which represents a very high opportunity cost if it uses around 50% of its daily oil production. This situation would lead to an economic dilemma as Kuwait's economy is a rentier economy (oil production represents over 90% of the government's income).

This strategy of turning non-renewable fuel into water, with the added environmental impacts of carbon emission and marine discharge from desalination, is wholly unsustainable. Perversely, whilst the GCC countries have the lowest freshwater resource per capita in the world, desalination coupled with very low rates of cost recovery has led to the highest per capita water use in the world (typically 3–4 times those in much wetter Europe).

Despite this immense challenge, there are clearly opportunities to transition to a more sustainable water future, through a range of intervention measures. First is the need to introduce full cost water pricing, with attention given to development of appropriate social tariffs (Barberán & Arbués, 2009). Second, whilst all households are currently fitted with 'dumb' (mechanical) water meters, introducing smart metering technology should increase consumer's awareness and in conjunction with pricing measures lead to behaviour change and water conservation (Koech, Cardell-Oliver, & Syme, 2021). Third is consumer education on water, with awareness raising campaigns to encourage consumers to save water through behaviour change and technology measures (e.g., upgrading water appliances to more efficient ones). Collectively, implementation of such conservation measures in less water stressed regions has shown demand reductions of 40–60% are possible (Abu-Bakar, Williams, & Hallett, 2021; Syme, Nancarrow, & Seligman, 2000). Such savings should then be readily achievable in Kuwait, but the government needs to grow the water conservation industry, so households can access appropriate guidance, buy water efficient appliances and fittings and have access to suitably qualified installers and advisers. Finally, whilst Kuwait's estimated network distribution leakage remains below that observed in many European countries, losses in the range of 7–15% (Akber & Mukhopadhyay, 2021) remain significant; hence, a leakage reduction programme is important. This can be further supported through phasing in of smart water metering. These conservation measures need to be introduced as part of a wider water conservation strategy, recognizing their mutually reinforcing nature. Historically, such measures have been ignored or at best marginalized in Kuwait's water management, where like the wider GCC region, the transition to a sustainable water future lies in embracing demand side management.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon request.

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