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A long-term forecast of water demand for a desalinated dependent city: case of Riyadh City in Saudi Arabia

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ABSTRACT

The forecast of long-term water demand is important for the planning of future requirements for water supply, distribution, and wastewater systems. The forecast is particularly important for arid countries such as Saudi Arabia which rely on costly desalination plants to satisfy the growing water demand. This study develops a model for forecasting water demand for Riyadh city, the capital of the country. The development of a sound forecast model is complicated by the uncertainties associated with key factors, such as the population growth and the economic activity, which is largely dependent on fluctuating oil prices. The forecast is also made difficult by the inefficient management of unaccounted-for-water (UFW). All these factors limit the usefulness of any deterministic forecast model. This paper develops a probabilistic forecast model that incorporates explicitly the uncertainties associated with population growth, household size, household income as well as conservation measures, and UFW management. The methodology makes use of historic time series records of water consumption to forecast the future demand, and applies the Monte Carlo sampling to describe the associated uncertainties. Results show that future water demand in the city is governed equally by socioeconomic factors and weather conditions. The study also illustrates the importance of conservation measures and the need for reduction of UFW.

Keywords: Water demand forecast; Uncertainties; Probabilistic model; Monte Carlo simulations; Saudi Arabia

1. Introduction

The forecast of potable water demand is important to water utilities in fast-growing urban regions for drinking water system planning, design, and water utility asset management. The forecast is particularly important in regions of scarce water supplies where the role of demand management policy becomes increasingly important. Saudi Arabia has no perennial rivers or lakes and its renewable water resources total 95 cubic meters per capita, well below the 1,000 cubic meters per capita benchmark commonly used to denote water scarcity. However, being also an oil-rich country, the authorities have embarked on an ambitious plan to build desalination plants that currently satisfy about half of potable water needs [1,2]. The process of building desalination plants is costly and time consuming. Decisions about investments in this technology depend crucially on how future demands

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for water are to be forecasted. It is, therefore, of importance that policy-makers have a reliable estimate of the long-term water demand in order to implement the appropriate capital expenditures and to avoid any shortage in the domestic water supply.

Although water demand forecasting is important for the country, there is remarkably few work in the literature on developing forecast models. Instead, most of the published work in the literature focuses on the description of available resources [3,6], the need to shift from supply development to demand management [4] and the need to reduce water losses, the enhancement of water conservation, and the increase in water tariffs [5,6]. As pointed out by some authors [7], the mismanagement of the water sector in the country makes it difficult to acquire reliable water consumption data. One primary reason is that water metering is not universally applied.

Regarding forecast studies, Rizaiza [8] was among the first to develop water consumption models for four major cities of the western part of Saudi Arabia. The developed models correlated the residential water usages with a number of parameters including weather temperature, income, family size, and price of water. Albraithen [9] in his study of municipal water management in Riyadh city, highlighted the importance of water losses from the distribution system and the need for public education to rationalize the use of water. Awadalla and AbdulRazzak [10], on the other hand, used the Institute of Water Resources Municipal and Industrial Needs (IWR-MAIN) software to develop a forecast model as well as a strategy to minimize water demand for Jeddah city.

These few works in the literature on water demand forecasting are also outdated. This requires, therefore, the development of rigorous and up-to-date forecast models, which is the aim of this paper.

The attainment of high accuracy in the prediction of water demand is, however, a challenging task because the forecasting model must simultaneously consider a variety of influential factors (i.e. explanatory variables) that affect water demand. These include socioeconomic parameters (population, population density, housing density, income, employment, and water tariff), weather data (temperature and precipitation), conservation measures as well as cultural factors such as consumer preferences and habits. A clear understanding of the drivers of potable water demand is essential if water managers wish to craft effective demand management policies.

Various methodologies are available for water demand forecast [11–16]. The selection of a forecast methodology is driven in part by the data that can be made available through collection efforts. Forecast models can also be classified to deterministic or probabilistic. Deterministic models are widely used for the generation of water forecast. However, in situations where key explanatory variables are uncertain, the usefulness of such deterministic models may be limited. This is particularly the case for countries such as Saudi Arabia. The only variable which holds a good deal of certainty is the temperature, barring dramatic future changes in the weather. Other potential explanatory variables are, on the other hand, characterized by high degree of uncertainties. Both the growths of population and housing units, for instance, cannot be predicted with accuracy, given the fluctuations in the immigration from both inside and outside the country. The immigration from outside the country is, on the other hand, dependent on the levels of economic activity spurred by the oil price, which is itself a fluctuating parameter that introduces a good deal of uncertainty in the income, another explanatory variable. A deterministic forecast is also made difficult by the absence of a rigorous water-pricing policy and the inefficient management of the unaccounted-for-water (UFW). All these factors make that the deterministic approach is not capable of providing a complete assessment of impacts caused by future change in the explanatory variables. One way to consider uncertainty in the forecasting is to use a probabilistic model. We propose in this paper to develop such model for Riyadh, the capital city of Saudi Arabia. The probabilistic forecast model for the city starts by identifying the quantitative nature of uncertainties through assigning probability density functions to each explanatory variable. The point demand model and the specified variable uncertainties are subsequently nested in a Monte Carlo simulation, forming a probabilistic demand model.

A note should be made about the scope of this study. The demand forecasts are generated only for the residential sector for which consumption data are made available by the local water authority. Nonresidential water (i.e. commercial, industrial and institutional), on the other hand, was not included in the study due to lack of reliable consumption data. The water used in the agricultural sector was also not considered.

2. Water demand and supply in the city

Riyadh city, with a population of around five millions, compromises more than a fourth of the total population of Saudi Arabia. Being also the capital and an important administration and industrial center, it is a focal point for local and international immigration with 30% of the population being nonSaudi. The annual population's growth estimated at 3% puts considerable strains on available water resources.

On the demand side, the per capita water consumption in the city was estimated to be 308 liters per day in 2011 [17]. This figure is quite large by international standards and is particularly larger than consumption levels in many developing countries. On the supply side, the city receives around 48% of its resources from local ground water. The other part of water supply comes from desalination plants located on the sea and transported across 450 km of pipelines. The city also encompasses a number of sewage treatment plants. However, the treated water is used exclusively for agricultural needs. The water supply system in the city is also characterized by large UFW, estimated to be 30% of the water supply [17]. As to water tariff, the government is subsidizing heavily the water consumption making the water virtually free in the country. As result, water is currently largely underpriced which makes demand artificially high and this, itself, leads to its inefficient use. Therefore, rather than using water-pricing policy as a tool for demand-management, the authorities have embarked on aggressive campaigns of encouraging consumers to adopt conservation measures.

3. Selection of explanatory variables and assignment of probability distribution functions

A classical way for communicating uncertainty is through the assignment of a probability distribution function for each selected explanatory variable. A variety of functions are available in the literature (e.g. uniform, normal, triangular, etc.). Besides the selection of the probability distribution function, there is the task of choosing suitable parameters that describe the function. These include, for instance, parameters like the mean, standard deviation, minimum and maximum allowed values.

In the following section, we present the selected explanatory variables and the probability distribution function selected for each variable. Before that, a note should be made about the data-collection process. Historical data for the last eight (2004–2011) years were collected from the relevant sources. The water consumption was available from the ministry of water and electricity. The consumption data were reported as average monthly values for the residential sector. The maximum monthly temperature was, on the other hand, made available from the local weather authority. The data pertinent to population number, population growth, median household income, and persons per house were obtained from the central department of statistics, taking the country census data of 1992 and 2004 as reference points. It should be noted that the water tariff, being virtually constant over the last years, was not included in the model. Moreover, ample information was obtained concerning the amplitude of UFW and the conservation plans of the authorities. This information will be used together with the forecast model to predict the effects of conservation and UFW management policies.

3.1. Socioeconomic data

The average household income is the first explanatory variable in the model. For normal goods, demand should increase proportionately with income. In countries where the water price is important, water bills often represent a proportion of household's income [12]. However, in our situation, the income affects the consumption of water indirectly. Since income approximates wealth, income can be used to proxy other normal and luxury goods associated with household water consumption where data may not be as easily obtainable, including swimming pools and dishwashing machines. Moreover, high-income households tend to have large houses which are reflected in the water consumption. The income was assumed to have a normal distribution. In order to predict future values of the income, both the mean and standard deviations were allowed to increase. The mean was assumed to grow annually by a rate of 2.2% while the standard deviation was confined to 10% of the mean. The choice of a normal distribution is in line with similar work in the literature [18]. Also, needed for water forecast are the demographic data pertinent to the population number and growth. The city is an attracting point for both local and international immigration. International immigration, in particular, is characterized by large fluctuations caused by changing economic conditions of this oil-rich country. For these reasons, the incorporation of uncertainties in the population's projections is essential, and a variety of approaches are available in the literature to describe these uncertainties [19,20].

Future projections of population were made on the basis of a set of assumptions, taking the country census data of 1992 and 2004 as reference points. The current annual growth rate for Saudi populations is estimated at 2.95%. However, the planning authority predicts that this high growth rate will decrease over the years due to socioeconomic and cultural factors. Data from the central department of statistics suggest that the growth rate will decrease with a mean of 0.16%, and minimum and maximum values of 0.1 and 0.25%, respectively. As for nonSaudi population, the current annual growth rate is 2.90%. The authorities also forecast a decrease in the international immigration. The growth rate is assumed to decrease with a mean of 0.26% while the minimum and maximum values are 0.2 and 0.3%, respectively. These three parameters pertinent to the change in the growth rate are better described by a triangular probability distribution function which also requires three parameters (mean, minimum, and maximum).

The household size (i.e. average persons per household) is another explanatory variable selected in the water use model. As the number of household members increases, per capita water consumption is expected to change. However, the change could be positive or negative, depending on whether water uses, such as washing and cooking, increase more or less proportional to the increase in the household size [21]. According to the predictions from the central department of statistics, the number of housing units will increase by an annual rate of 2.3%. Since the population growth was assumed to follow a triangular probability distribution, it seems logical that a similar distribution is selected for the household size. The parameters of the distribution were taken from the demographic forecast. The minimum and maximum values of the triangular function were taken to be ±1.5% of the mean, which was assumed to increase by an annual growth rate of 2.4% from the base value of 5.86 in 2011. The use of a triangular continuous distribution instead of a more rigorous discretionary distribution for the household size is justified by previous similar work in the literature [18,22].

3.2. Weather variables

Riyadh city is located in a very arid zone. The city receives on average 94 mm of precipitation annually. The temperature can show variations between 45˚C in the summer and 5˚C in the winter. The temperature is, therefore, expected to affect significantly the water consumption. The monthly mean of maximum daily temperature was the only weather variable selected in the predictive model. It was assumed to have a normal distribution with a standard of deviation of 1˚C.

3.3. Unaccounted-for-water management

The data available from the ministry of water and electricity [17] suggest that UFW in the city is about 30%, which means that the per capita water production is even higher than the recorded consumption of 308 liters per day. The ministry's ambitious plan is to reduce the current total UFW down to 15% by 2031. Moreover, we assume that only half of UFW is real loss that can be affected by UFW management, with a target of 5% real loss by 2031. We can interpolate, therefore, the UFW percent for any year between 2011 and 2031. These assumptions entailed setting the expected UFW to 10% and restricting its possible values between 0 and 20%. A triangular distribution with a mean of 10% and minimum and maximum values of 0 and 20% is suitable to capture the variations of UFW. This is also consistent with previous studies in water forecast [18].

3.4. Water conservation measures

Water conservation measures planned to be implemented by the Ministry of Water include the replacement of a number of fixtures such as toilets, showerheads, faucets, and clothe washers with those consuming less water. Based on the data available from the ministry, the total water production is 30% UFW, 50% residential, and 20% nonresidential. Moreover, 80% of residential sector makes use of these types of fixtures compared to only 20% in nonresidential sector. Finally, we make the assumption that by the year 2031, 90% of the existing fixtures will be replaced. If the replacement program starts in 2011 with a target of 90% new fixtures by 2031, then we can interpolate the percent of fixtures replaced each year in between 2011 and 2031. A number of alternative assumptions were tested. The most likely set of assumptions resulted in a range of 20–25% reduction. Since the potential water savings due to conservation vary between a lower and an upper bound, a uniform distribution is selected for this purpose. This is also consistent with previous studies in water forecast [18]. The upper and lower bounds of the uniform distribution were chosen to be no more than 20% away from the annual average savings of 5%.

4. Model development and validation

Before developing the predictive water demand model, we show in Figs. 1 and 2 samples of variations of temperature and water consumption. Fig. 1 shows a sample of evolution trends of the monthly mean of maximum daily temperature. The figure attests to the severe climate of the city where temperatures can reach 47˚C in the summer. But, while the maximum monthly temperature is seen to change only slightly from year to year, the monthly per capita water consumption (Fig. 2) can be seen to increase each year, confirming the effects of the various explanatory variables. Moreover, the effects of temperature on water consumption are important. For instance, in the year 2010, the lowest consumption rate occurred in the

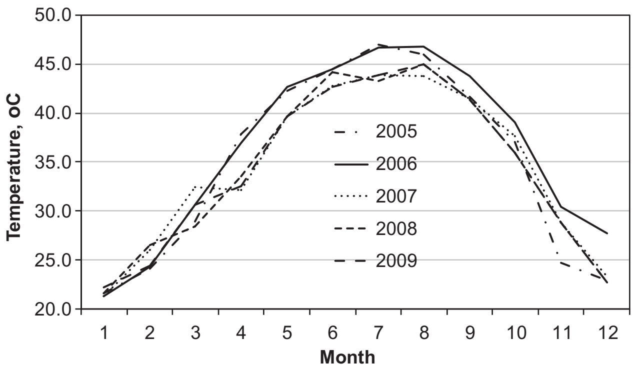

Fig. 1. Historical time series records of monthly mean of maximum daily temperature.

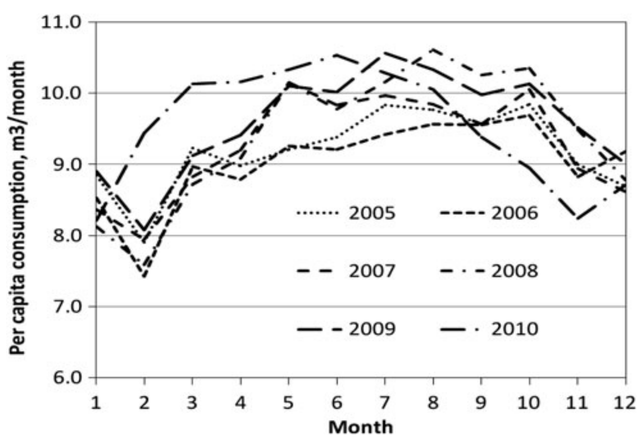

Fig. 2. Historical time series records of water consumption.

month of January (274 l/day) and then increased to 351 l/day in the month of June, an increase of 28%.

The first step in the water demand forecast is the development of the probabilistic model followed by Monte Carlo simulations (MCS) to obtain distribution of total water use. MCS is a well-established method of overall assessment of the uncertainties. The technique generates an estimate of the overall uncertainty in the predictions due to the associated uncertainties in the input parameters [23]. The simulations were carried out using the software package @Risk [24]. The package allows the assignment of various probability distribution functions, random number generation, and assignment of sampling rules as well as graphics and scenario options.

Before the results of simulation are presented, a note should be made about the prediction capabilities of the developed model. Since there are no reference values in the future, no validation study might be plausible. Under these circumstances, we have provided, in an earlier section, some justifications for the assumptions made, especially for the selection of the probability distribution functions. Furthermore, for validation purposes, we have depended on historical data. Fig. 3 shows the results of the validation process. Overall, the predictions of the model are reasonable, keeping in mind that some discrepancies are inevitable given the existence of unavoidable modeling errors.

5. Results and discussion

A long-term water demand forecast was simulated using the methodology defined in the previous section. The forecast was simulated for the 2012–2031 time period in yearly increments. Monthly predictions of demand have been combined into annual forecasts.

One way to display forecast results is to use pairs of the calculated percentile values to delineate particular forecast intervals. The forecast of demand is represented by an interval within which 90% of potential demand would normally fall. In the following discussion, a 90% confidence interval is formed by the values of the 5th and 95th percentiles. Given the specification of the forecast models and the assumptions outlined in the previous section, one may feel confident that 90% of all forecast possibilities will fall within this interval for any forecast year. The expected values (the mean or median) of the forecast distributions are also included and roughly provide the midpoint of the probabilistic forecast.

The resulting projected forecast of the water demand is shown in Figs. 4 and 5. Fig. 4 shows the 90% forecast interval for the daily per capita water demand as forecast over the 2012–2031 periods. The figure shows that the interval expands only slightly from the base year of 2011 until 2020. Beyond the 2020 year, the interval width increases steadily and by

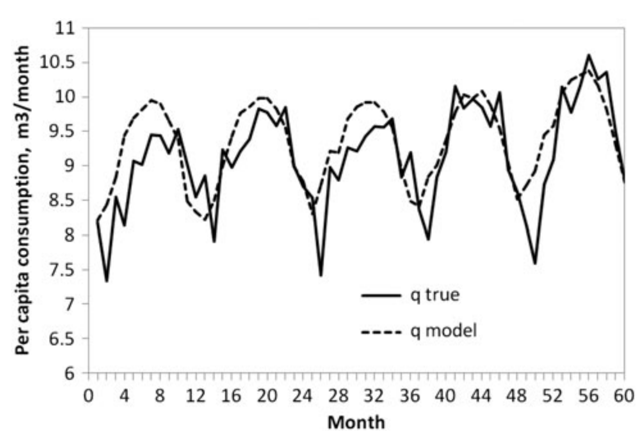

Fig. 3. Validation with historical data (Data from 2004 to 2008).

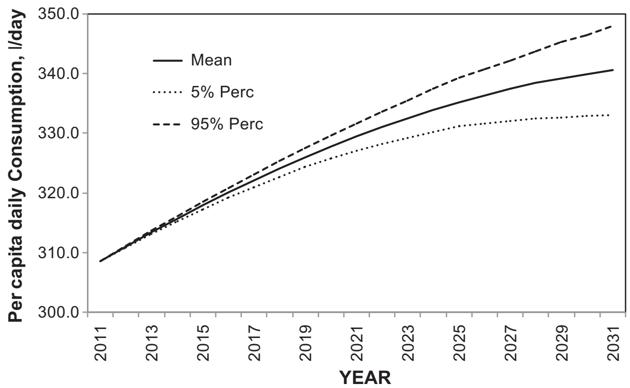

Fig. 4. Ninety percent confidence interval for the per capita water demand.

the end of the projected period of 2031, the demand interval ranges from 333 to 348 l/day. Another way to interpret this finding is that 5% of the simulated 2031 per capita water demands would exceed 348 l/day and 5% would be below 333 l/day.

The evolution of the total water demand is shown in Fig. 5. Using the mean as the expected value, the 2031 expected total water demand of $2,610 \times 10^3\,m^3$/day lies nearly halfway between the bounds of $2,451 \times 10^3$ and $2,766 \times 10^3\,m^3$/day, which serve as the 90% confidence interval for total demand in 2031.

The effect of combined management of UFW and conservation measures is shown in Figs. 6 and 7. Since the control of UFW affects more the production, it is more natural to show the projected water production rather than consumption. Fig. 6 shows that the dual effect of UFW control and conservation measures is rather important. As result of these measures, the average per capita water production can be seen to

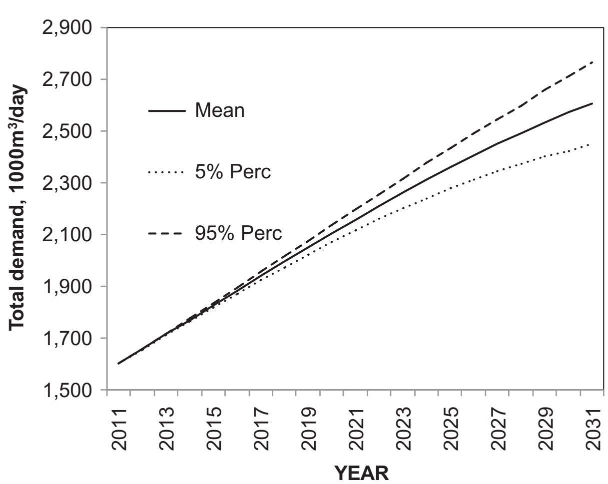

Fig. 5. Ninety percent confidence interval for the total water demand.

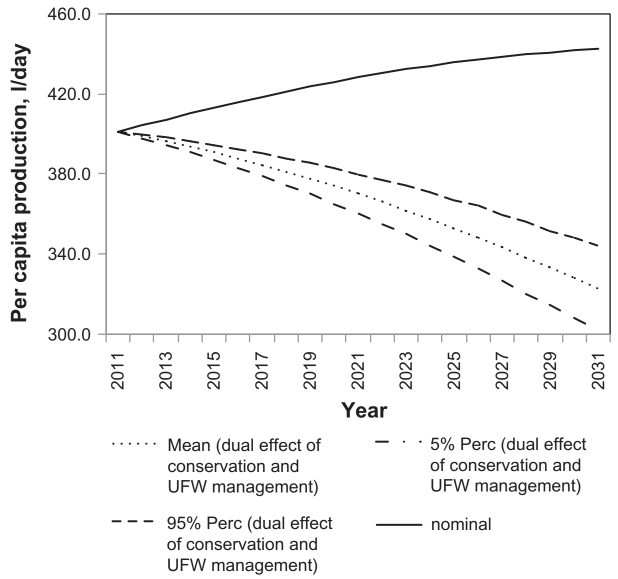

Fig. 6. Ninety percent confidence interval for the per capita water production under the dual impact of conservation measures and UFW management.

decrease from 402 to 322 l/day by the end of the projected period which would represent a decrease of 20% in water supply. The width for the 90% confidence interval can be seen to increase steadily, and by the year 2031, the lower and upper bound for the interval are 310 and 344 l/day, respectively. Moreover, Fig. 6 shows that without UFW management and conservation measures (i.e. the nominal case), the per capita production would increase from 400.4 to 440 l/day by the end of the projected period. Therefore, the savings in water supply as result of UFW control and conservation will be around 36.7% (from 440 to 322 l/day).

The corresponding effect on the total production is shown in Fig. 7. As result of the combined effect of UFW management and conservation measures, the average production would increase much slower than in the nominal case. By the end of the projected period, the production would reach $2,410 \times 10^3\,m^3$/day. The width of the 90% confidence interval is seen to increase through the years, and by the end of the projected period, the lower and upper bound for the interval are $2,270 \times 10^3\,m^3$/day and $2,695 \times 10^3\,m^3$/day, respectively. Fig. 7 also shows that in the nominal case, the production would increase to reach $3,400 \times 10^3\,m^3$/day. Therefore, by the end of the projected period, and provided the combined UFW management and conservation measures are implemented, the savings in water supply will be around 41% (from 3,400 to $2,410 \times 10^3\,m^3$/day).

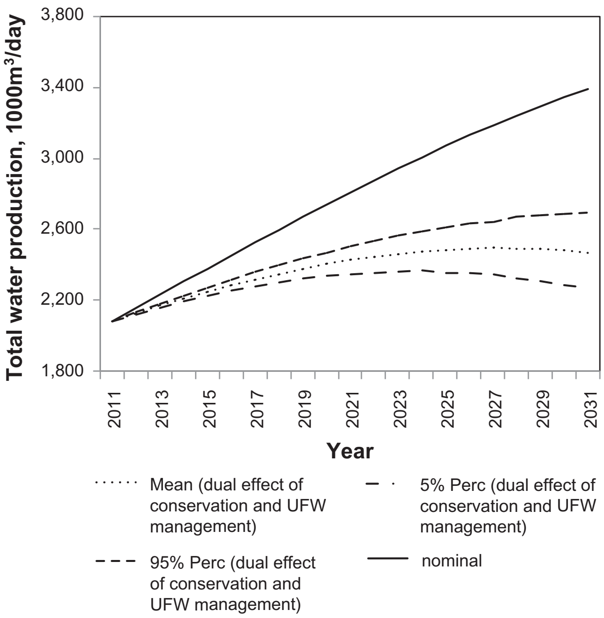

Fig. 7. Ninety percent confidence interval for the total water production under the dual impact of conservation measures and UFW management.

6. Conclusions

This paper has presented the development of a probabilistic model that quantifies uncertainties in the long-term water demand forecast for the city of Riyadh, the capital of Saudi Arabia. The work was also an opportunity to shed some light on the peculiarities and the challenges for forecasting water demand in an arid and oil-rich country, where the water sector lacks efficient management policies. The absence of a rigorous water-pricing policy and the high levels of UFW make the water demand both artificially high and inefficiently used.

Past and current experiences in the city (and in the country as whole) have demonstrated that the supply-driven approach for water management is unable to deliver substantial degree of water sustainability to the water-stressed country. Despite the strenuous efforts made in augmenting and maximizing its water supplies, the city still faces serious water deficits due to the continuously increasing water demands beyond the limits of their available water resources.

The model developed in this study could help in water demand forecasting for planning infrastructure (i.e. desalination plants and pipelines), infrastructure management (i.e. reduction of leaks), and future need for conservation efforts. In this regard, the forecast model predicted an increase of water consumption due to both climate conditions and socioeconomic changes (population, household size, and income). The predictive model also showed that substantial savings in water demand could be achieved by a combination of UFW management and conservation policies. In each numerical simulation, bounds were established that set the mean, minimum, and maximum values of changes in future water demand.

The other potential tool for demand management is the retail price which is low and has been unchanged, and, therefore, was not included as an explanatory variable in the predictive model. There is no current study on the potential effects a price increase can have on water demand. However, a recent study for Kuwait [11], where the water sector has similar features, suggested that water price can be a very effective tool for remand management.

Practically, therefore, in the absence of polices to reduce the government subsidies of water, it seems that the only realistic option for the reduction of consumption of water is a good policy for control of UFW and long-term conservation measures. This can be achieved through a strong program of leakage inspection of water distribution systems, rehabilitation, and the introduction of advanced automatic pressure adjustment systems combined with program of retrofitting household water use systems and appliances with water efficient technologies [25].

On a final note, the model could be further refined by completing the picture as far as defining other sources of uncertainty. This study has considered only those potential errors associated with explanatory variables. In addition to these errors, there are random and sampling errors that lie at the heart of the forecast. Incorporating these factors would, however, widen the forecast intervals which would limit the practicability of such predictive models.

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