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Full Length Research Paper

Determinants of residential water demand in an arid and oil rich country: A case study of Riyadh city in Saudi Arabia

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The accurate forecast of residential water demand is critically important for arid and oil rich countries such as Saudi Arabia which depend on costly desalination plants to satisfy the growing water demand. Achieving the desired prediction accuracy is a challenging task since the forecast model should take into consideration a variety of factors such as economic development, climate conditions and population growth. The task is further complicated given that the water sector in the country is characterized by high levels of unaccounted-for-water and heavy government subsidies, which lead to an artificially high water demand. This study presents a model for forecasting the long term water demand for Riyadh city, the capital of Saudi Arabia. The proposed model used historic records of water consumption to calibrate an econometric predictive model for per capita water use. The explanatory variables included household income, persons per household and maximum monthly temperature. Both the effects of unaccounted-for-water and conservation measures were also included. The calibration results indicate that socio-economic factors and weather temperature are equally important for water demand. The results also predict considerable savings if a comprehensive policy for water conservation and unaccounted-for-water management is implemented.

Key words: Water demand forecast, predictive model, water demand management, Saudi Arabia.

INTRODUCTION

The forecast of future needs in potable water is important for the planning and management of water resources. The projections of urban water use are required for planning future requirements in water supply, distribution and wastewater systems. In this regard, short-term forecasting is useful for the operation and management of existing water supply systems within a specific time period, whereas long-term forecasting is important for system planning, design, and asset management (Bougadis et al., 2005; Davis, 2003). The forecast of water demand is particularly important in regions of limited natural water resources. The county of Saudi Arabia, for instance, is an arid country characterized by a scarcity of its water resources. The country has no perennial rivers or lakes, and its renewable water resources total 95 m^3 per capita, below the 1,000 m^3 per capita benchmark commonly used to denote water scarcity. In order to satisfy the needs for a growing population, the kingdom is currently relying on desalination plants to satisfy around half of the water demand. Building desalination plants is, however, a costly and time consuming process. 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 in the development plans and to avoid any shortage in the domestic water supply.

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Water demand forecasting depends on a number of factors (that is, drivers or explanatory variables) that affect the demand. These include socio-economic parameters (population, population density, housing density, income, employment and water tariff, etc), weather data (temperature and precipitation, etc), conservation measures as well as cultural factors such as consumer preferences and habits. Various methodologies are available in the literature for water demand forecast. The selection of the forecast methodology is driven in part by the data that can be made available through collection efforts.The methodologies for the forecast include end-use forecasting, econometric forecasting and time series forecasting (Davis, 2003). End use prediction bases the forecast on the prediction of water uses, which requires a considerable amount of data and assumptions. The econometric approach is based on statistically estimating historical relationships between the independent explanatory variables and water consumption, assuming that these relationships will persist into the future. Time series approach, on the other hand, forecasts water consumption directly without having to predict other factors on which water consumption depends (Zhou et al., 2000).

We therefore, propose in this paper to develop an econometric model to predict the long term water demand for the city of Riyadh, the capital of Saudi Arabia. The objectives of this study are two-fold. The first objective is to develop the mathematical forecast model for residential water use. The second objective is to analyze the long term water demand (up to year 2031) and to simulate the effects of conservation measures and unaccounted-for-water (UFW) control.

Water demand and supply in the city

Riyadh city, with a population of around five millions, comprises more than a forth of the total population of Saudi Arabia. Being also the capital and an important administration and industrial centre, it is a focal point for local and international immigration with 30% of the population being non-Saudi. The annual population's growth estimated at 3% puts considerable strains on available water resources. On the demand side, the typical household in the city uses about 47% of its total water use in the bathroom. The toilet makes up 27%, while the shower and sink use 20%. Laundry makes up 21%, faucets 16% while the leaks are estimated to be around 17% (Mowe, 2011). The residential per capita water consumption in the city was estimated in 2010 to be 308 L per day (Mowe, 2011). This figure is larger than the consumption levels in many developing countries. However, this figure is comparable to levels of consumption in other oil producing countries of the Middle East. On the supply side, the city receives around 48% of its resources from local ground water, after being treated by reverse osmosis plants.

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 mainly for agricultural needs. The water supply system in the city is also characterized by large levels of unaccounted-for-water estimated to be 30% of the water supply (Mowe, 2011). This is mainly due to leaks in the distribution systems in parts of the old city. As to water pricing, the cost of operating the country's desalination plants and pumping the water to end users is estimated at $6 per cubic meters, and is considered extremely high. As to water tariff, its structure is made up of two parts: a fixed charge and a volumetric charge. Tariff rates are progressive; for example, the volumetric charge increases as consumption increases.

However, the government is subsidizing heavily the water consumption making the water virtually free in the country. Consumers pay only 1% of the cost of water: a little less than $0.03 per cubic meter. As a 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. The ministry of water distributes free conservation devices such as faucets and showerheads to reduce daily water consumption. The authorities also rely on media campaigns to promote conservation of water, citing ethical and religious values.

WATER DEMAND MODEL

The following standard functional population model is adopted to estimate the total water use:

$$Q_y = Nq \tag{1}$$

Q is the total water use, *N* the population number and q is the water use per capita. The water use *(q)* is assumed to depend on a number of explanatory variables (X_i). The projected values for each explanatory variable are required to develop the model. Projected values for the populations *(N)* are also required. A variety of econometric models can be used to express the per capita use *(q)*. Overviews on estimations of residential water demand were provided by a number of authors (Arbués et al., 2003; Dalhuisen et al., 2003; Davis, 2003; Espey et al., 1997; Klein et al., 2007; Worthington and Hoffman, 2008). The log–log model, where all variables enter the regression equation in a logarithmic form is selected in this work. This model was used extensively in the literature (Mazzanti and Montini, 2006; Musolesi and Nosvelli, 2007; Nauges and Thomas, 2003; Schleicha and Hillenbrand, 2009). The model relates *(q)* to the explanatory variables (X_i) using the following equation:

$$\ln q = \alpha + \beta_1 \ln(X_1) + \beta_2 \ln(X_2) + \ldots + \beta_n \ln(X_n) \tag{2}$$

Conveniently, the log–log model allows the parameter estimate β_i to be directly interpreted as the elasticity of demand associated with

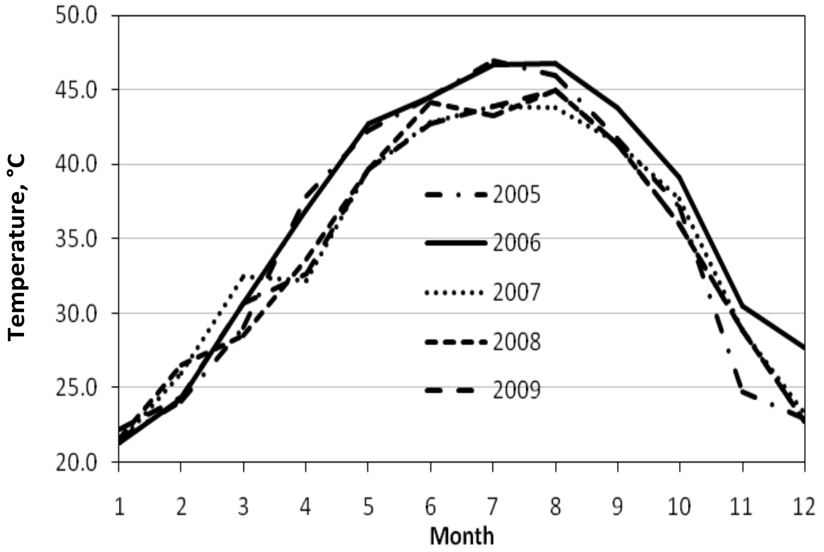

Figure 1. Samples of historical time series records of monthly mean of maximum daily temperature.

the explanatory variable X_i.

The following explanatory variables were selected in this study. These include the household median income (X_1), the household size (that is, persons per house) (X_2) and the maximum monthly temperature (X_3). The selection of these explanatory variables was conditioned by the availability of historical data and also by the anticipated importance of the variables. Median household income was the first explanatory variable in the model. In countries where the water price is important, water bills often represent a proportion of household's income (Arbués et al., 2003). However, in our situation and because the price of water is negligible, the income affects indirectly the consumption of water. Since income approximates wealth, income can be used to proxy other normal and luxury goods associated with household water consumption such as swimming pools and dish washing machines. Moreover, high income families tend to have large houses which could affect water consumption.

As to weather conditions, it is known that climate and other seasonal factors affect the residential water demand. Weather variables used in the literature included temperature (Griffin and Chang, 1990), rainfall (Nauges and Thomas, 2000), temperature and precipitation (Gutzler and Nims, 2005) as well as a humidity variable based on temperature, minutes of sunshine and wind speed (Al-Qunaibet and Johnston, 1985). Being an arid city, the average maximum temperature can exhibit variations between 47°C in the summer and 5°C in the winter. The temperature is therefore expected to affect significantly the water consumption. Other weather variables were deemed either to be irrelevant (for example, rain fall) or that the appropriate data were unavailable (for example, minutes of sunshine).

The household size (that is, average persons per household) is another explanatory variable selected in the water use model. As the number of household member's increases, the per capita water consumption is expected to be affected. However, the change could be positive or negative, depending whether water uses such as washing, cooking increase more or less proportional to the increase in household size (Schleicha and Hillenbrand, 2009).

In order to calibrate the selected model, historical data from 2004 to 2010 were collected from the relevant sources. The water consumption was made available from the ministry of water and electricity while the data pertinent to population number, population growth, median household income and person per house were obtained from the ministry of planning. The maximum monthly temperature was, on the other hand, made available from the local weather authority. 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 also 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.

Model development and calibration

Before developing the predictive water demand model, we showed in Figures 1 to 2, samples of historical variations of temperature and water consumption. Figure 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 (Figure 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 month of January (274 λ/day) and then increased to 351 λ/day in the month of June, an increase of 28%. The proposed log-log model was calibrated using the mentioned historical data. The resulting model is:

$$\ln q = 3.11 + 0.25\log(Income) + 0.57\log(Household\ size) + 0.24\log(Temp) \tag{3}$$

The results of the regression analysis yielded a value of 0.977 for the adjusted R square. The parameter estimates (elasticities) were statistically significant (p-value less than 0.05 and t-stat larger than 2). For the income, the parameter estimate (0.25) is positive. In general, households with higher incomes are expected to consume

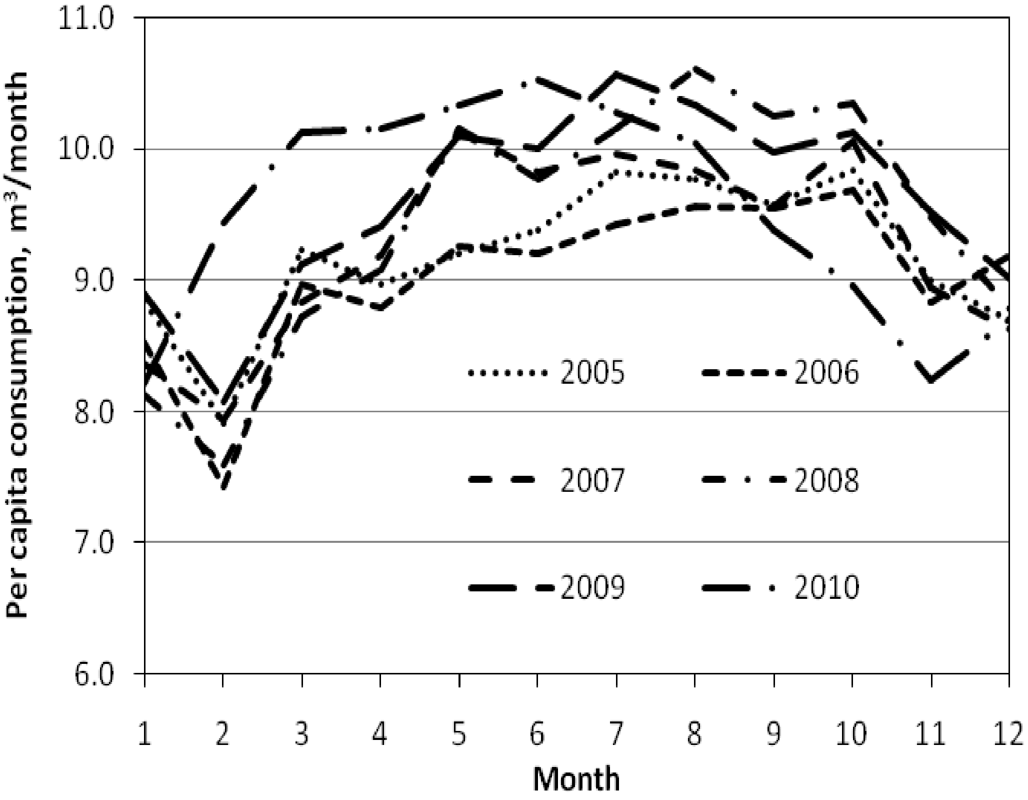

Figure 2. Samples of historical time series records of water consumption.

more of the complementary commodities associated with water through having dish washers or even pools, all of which increase the indirect water demand. Studies in the literature also provided strong empirical evidence that water demand is rather inelastic (less than 1) in terms of income changes. Moreover, our estimates for the income elasticity lie within the range of the values found in the literature (Dalhuisen et al., 2003; Garcia and Reynaud, 2003; Worthington and Hoffman, 2008). For instance, the mean and median for the income elasticities surveyed by Dalhuisen et al. (2003) were 0.43 and 0.24, respectively, with a standard deviation of 0.79.

The parameter estimate (0.57) associated with household size is also positive and is the largest of the three elasticities. As the number of household members increases, per capita water consumption goes up which suggests that several water uses such as washing or even cooking increase more than proportional to the increase in household size. According to our model, an increase in the average number of household members by 50%, that is, from two to three, raises per capita water demand by about 29%. Compared to other countries, it can be noted that in a survey of US and Canadian households, Cavanagh et al. (2002) found an elasticity of 22%. Estimates based on community level data in Sweden by Höglund (1999) are somewhat higher and range from 27 to 35%.

Finally, the parameter estimate (0.24) for the monthly maximum temperature is positive and is close to that associated with the income. Higher temperatures are expected to result in higher residential water demand for drinking and taking showers. A 100% increase in the temperature would yield an increase of 24% in water consumption.

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 depended on historical data. The available data from 2004 to 2010 were split into data for forecast (data between 2004 and 2008) and the remaining validation set (data between 2009 and 2010). Figure 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 errors. Figure 4 shows, on the other hand, a cross validation with the data that was not used for developing the model that is, data of years 2009 and 2010. Again the model shows fair agreement with the real values of per capita water consumption.

FORECAST RESULTS

The forecast model, developed in the previous section was used to predict the long term water demand for the city (that is, until 2031). Future projections of population as well as those of the explanatory variables were made on the basis of a set of assumptions: The projections for the population growth, for instance, are assumed to follow the exponential model taking the census data of 1992 and 2004 as reference points. Different annual growth rates (2.95 and 2.90%) were assumed for Saudi and non-Saudi populations, respectively. The planning authority also predicts that these high growth rates will decrease over the years due to socio-economic and cultural factors. Moreover, because of the uncertainties

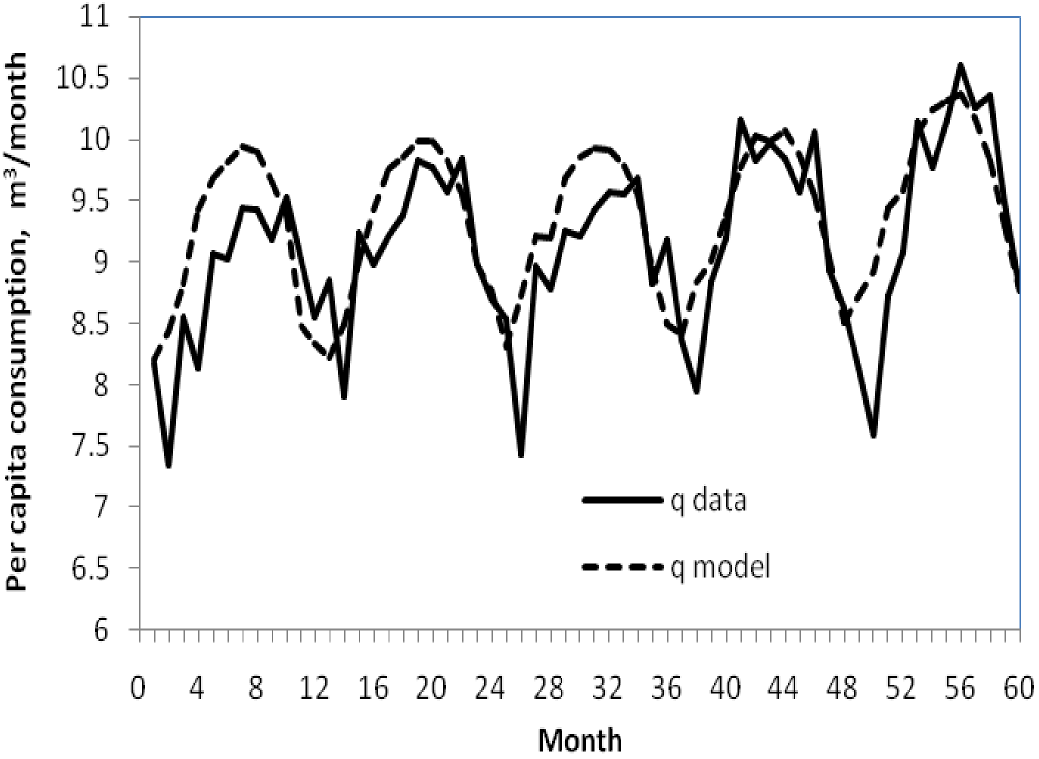

Figure 3. Validation with historical data (Data from 2004 to 2008).

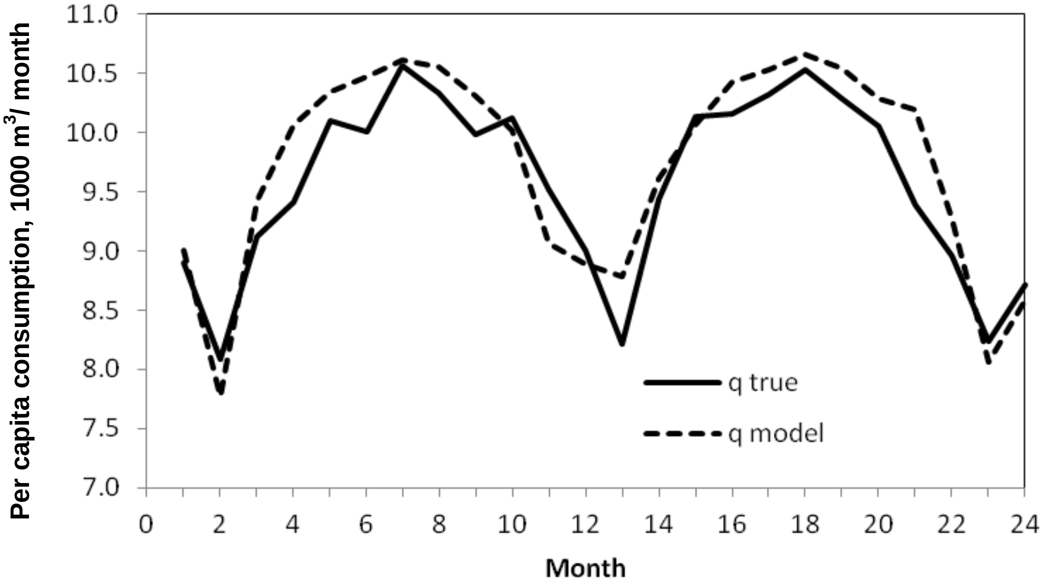

Figure 4. Cross validation with historical data not used for the validation (Data from 2009 to 2010).

surrounding the population growth, especially the immigration from outside the country, three scenarios were assumed for the decrease in the annual growth rate. The most likely growth scenario assumes an annual decrease rate of 0.16% for Saudi and 0.26% for non-Saudi. The low growth scenario, on the other hand, assumes a decrease rate of 0.25 and 0.30%, respectively, while the high growth scenario assumes

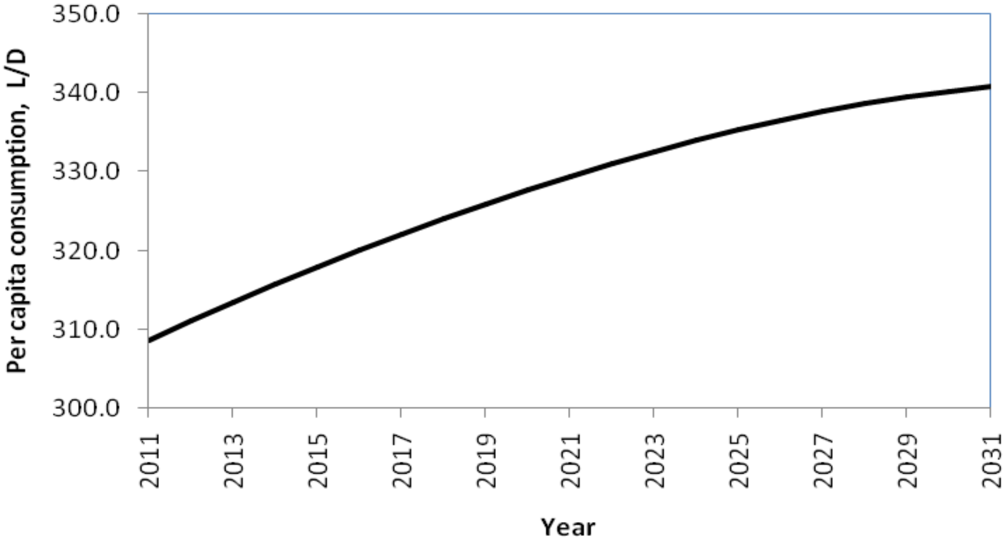

Figure 5. Projected per capita water demand.

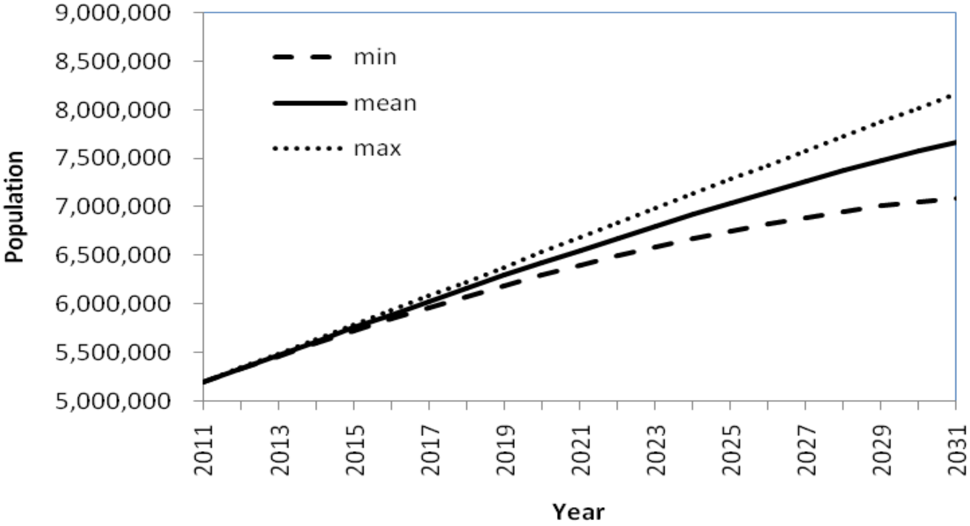

Figure 6. Populations growth scenarios.

annual decrease rates of 0.1 and 0.2%. These growth rates were provided by the department of statistics (ministry of planning). The projections for the number of houses, on the other hand, follow the arithmetic model taking also the census data for 1992 and 2004 as reference points. The annual growth rate was assumed to be 2.4%, a value also provided by the ministry of planning. This is probably a simplification given that the housing projections should also follow similar scenarios to the population growth. However, in order to limit the number of possibilities, the assumption of constant growth rate was assumed for the housing units. The future projections of the median household income are assumed to increase by a constant annual growth rate of 2.2%, a value also provided by the ministry of planning.

The results of the long term water demand are shown in Figures 5 to 7. Figure 5 shows the projections for the daily per capita water consumption for the most likely population growth. The per capita consumption is expected to increase from 308 L/day to 341 L/day. The driving force for the increase is the growth in the income and that of the household size.

Figure 6 shows the projected populations for the three scenarios. At the end of the planned period, the city population will reach around 8,100,000 for the fastest growth scenario, 7,000,000 for the lowest growth while

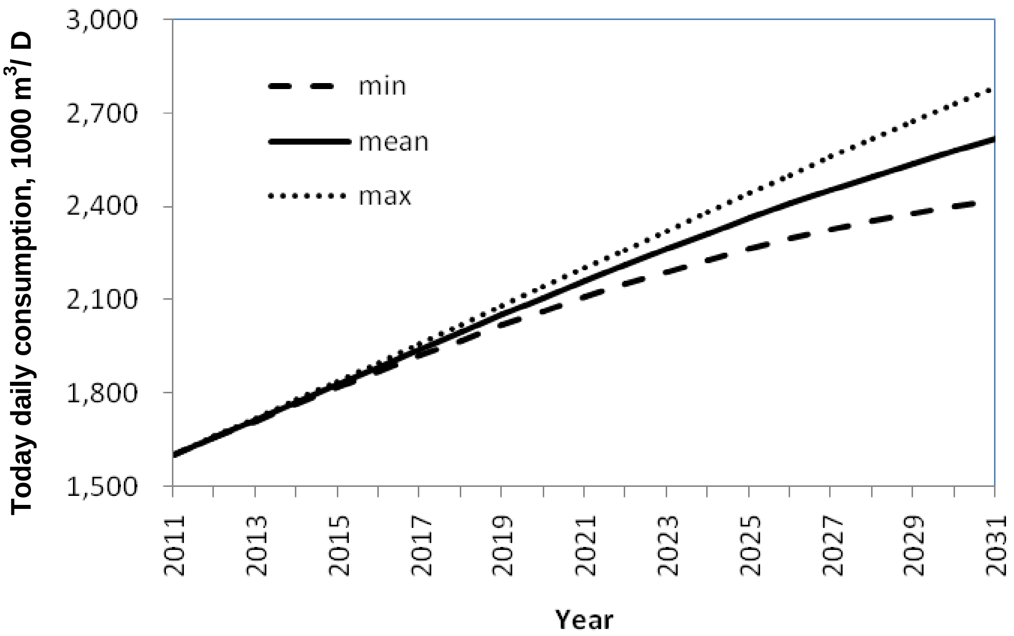

Figure 7. Projected total water demand.

the most likely scenario yields a population of 7,600,000. Figure 7 shows the resulting total water demand projections. The most likely scenario would require a demand of 2,600, 000 m^3/day by the end of the projected period, while the low and high growth scenarios would predict 2,400, 000 m^3/day and 2,800, 000 m^3/day respectively. It can be concluded that for all scenarios and even if we assume that the supply from ground water is maintained at the current level of 48% of the total supply, the projected demand would require investing heavily in new desalination plants, knowing that a medium size desalination plant has a capacity of 30, 000 m^3/day.

Impact of management of UFW and conservation measures

In the foregoing discussion, the forecast model is used to investigate the impact of some management and conservation policies. System losses and conservation measures are not directly accounted for within the predictive model as developed previously. However, an unaccounted-for-water use and conservation multiplier will be created to be used in the model. But first, we present the basic assumptions made for the impact of management of UFW and that of conservation measures.

Impact of UFW control

The data available from the ministry of water and electricity (Mowe, 2011) suggest that UFW levels in the city are about 30%, which means that the per capita water production is even higher than the daily consumption of 308 L/day. The ministry ambitious plan is to reduce the current total UFW down to 15% by 2031. Moreover, we assumed that only half of UFW is real loss that can be affected by UFW management, with a target of 5% real loss by 2031. Therefore, the impact on total production is a reduction of 10%. Thus, it is reasonable to assume that UFW management could provide a 10 to 15% reduction in total production by 2031. If 30% of total production is UFW in the year 2011, and we have a target of reducing this percentage to 15% by the year 2031, then, we can interpolate the UFW percent for any year between 2011 and 2031.

Impact of water conservation measures

Water conservation measures planned by the Ministry of Water include the following:

1. Replace toilets using 12 L per flush with toilets using 6 L per flush
2. Replace showerheads using 22 L/min with showerheads using 10 L/min
3. Replace faucets using 15 L/min with faucets using 8 L/min
4. Replace clothes washers using about 50 gallons per load with washers that use about 22 gallons per load.

It can be noted that the percent reduction in water use is about 50% for toilets, 54% for showerheads, 47% for faucets, and 56% for washers. Overall, we can assume

Table 1. Alternative assumptions for UFW management.

Parameter	Assumed (%)	Lowest (%)	Highest (%)
Percent UFW	30.0	20.0	40.0
Percent Residential	50.0	20.0	60.0
Percent Non residential	20.0	50.0	0.0
Real Losses as percent of UFW	50.0	100.0	10.0
Resulting percent real losses	15.0	40.0	2.0
Target future % real losses	5.0	25.0	5.0
Resulting % reduction in total production from UFW management	10.0	0.00	25.00
Percent of use that is fixture usage			
Residential	80	50	100
Non residential	20	5	50
Reduction in fixture use	50	40	60
2031 percent compliance with fixture replacement	90	50	100
Resulting % reduction in total production from conservation measures	24.04	6.31	43.71

Table 2. Most probable percent of reduction in water production as result of combined UFW management and conservation measures.

Year	Percent reduction in total production (%)
2011	0.0
2015	6.8
2020	13.6
2025	20.4
2031	27.2

that the replacement program will reduce water use by about 50%. We must make a series of assumptions in order to estimate the impact of implementing these conservation measures. The water that is not UFW is used by both the residential customers and the non-residential sector. Based on the data available from the ministry of water, we can make the assumption that the total water production is 30% UFW, 50% residential and 20% non-residential. Next, we make the assumption that 80% of residential water use is used in these four types of fixtures as compared to only 20% of non-residential water use.

Finally, we make the assumption that by the year 2031, a total of 90% of fixtures will be replaced. If the replacement program starts in 2011 with a target of 90% of new fixtures by 2031, then, we can interpolate the percent of fixtures replaced each year between 2011 and 2031. These assumptions can be combined to estimate the impact of conservation measures on total production, as shown in Table 1. A test of these assumptions showed that the percent reduction in total production is sensitive to the percent of total production that is residential, and the percent of residential use that is used by these fixtures. A number of alternative assumptions were tested. The most extreme set of assumptions resulted in of 6 and 44% reduction in total production. However, the most likely set of assumptions resulted in a range of 20 to 25% reduction.

Combined effects of UFW management and conservation measures

The estimated effects of UFW management and conservation measures can be combined to provide an estimated combined effect on total production. A range of all assumptions were tested resulting in a range extending from 13 to 51% reduction in total production by 2031. However, the most likely set of assumptions resulted in a range of about 25 to 30% reduction. Interpolation results of the combined effect between 2011 and 2031 are shown in Table 2. Figure 8 shows the combined effect of conservation measures and management of UFW. Since the management of UFW affects essentially the water production, it is therefore more convenient to plot the per capita water production rather than consumption. By the end of the projected period, the per capita water production will decrease by 19% from 401 L/day to 322 L/day. The corresponding total water production (Figure 9) would also decrease by about 926, 000 m^3/day.

Conclusions

This paper developed a long term water demand forecast model for the city of Riyadh, the capital of Saudi Arabia. The work was also an opportunity to shed some lights on the peculiarities and the challenges for forecasting water demand in an arid and oil rich country, where the waters sector lacks efficient management policies. The absence of a rigorous water pricing policy and the high levels of

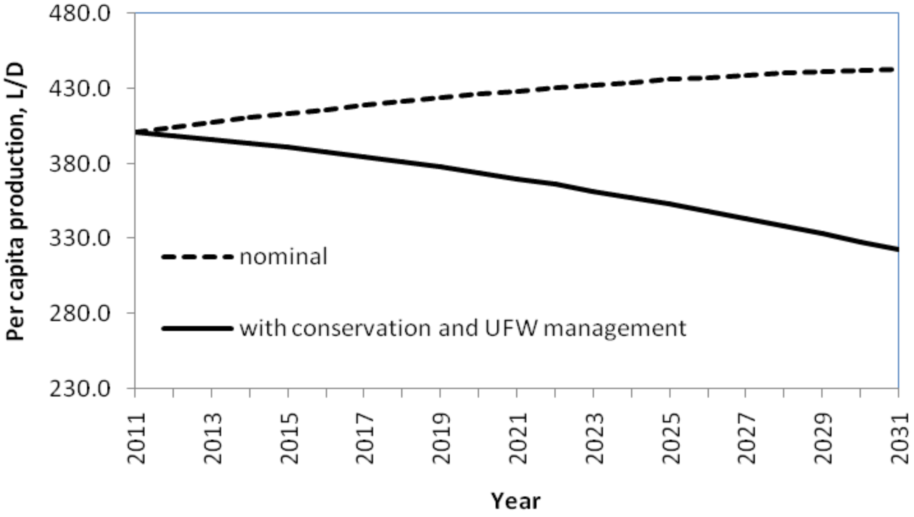

Figure 8. Projected water production per capita with combined UFW management and conservation measures.

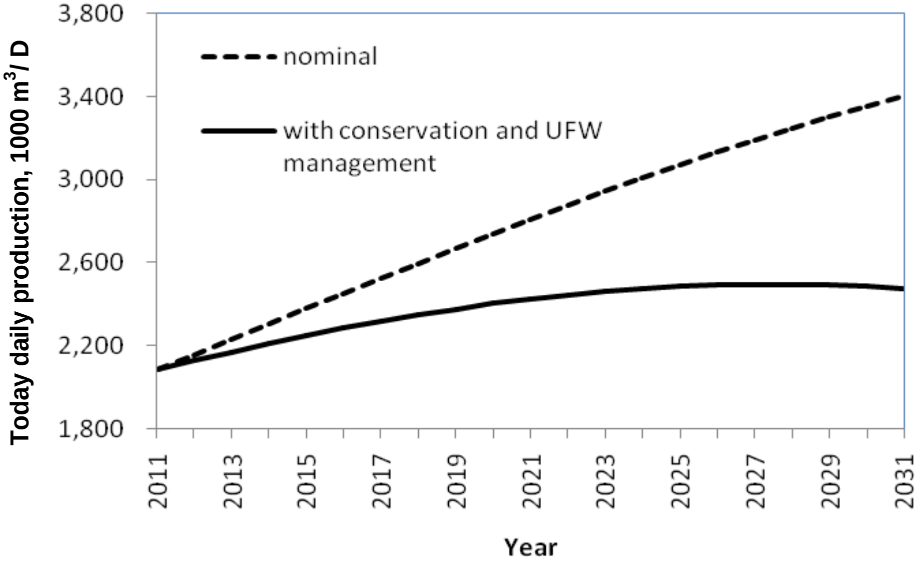

Figure 9. Projected total water production with combined UFW management and conservation measures.

UFW make the water demand both artificially high and inefficiently used. The analysis of historical data showed that a predictive model based on income, temperature and household size could predict well the water consumption trends. The model was used for the forecast of long term water demand for three scenarios of population growth. The predictive model was also used to analyze the combined impact of conservation measures and UFW control. 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 the control of UFW. Voluntary conservation measures, on the other hand, may not yield consistent and clear impact.

A final note should be made about some aspects of the developed model. It should be noted that the only variable which holds a good deal of certainty is the temperature and barring dramatic future changes in the weather. The other parameters are, on the other hand, characterized by high degree of uncertainties. Both the growths of population and housing units (needed in household size) 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 dependent on the levels of economic activity spurred by oil price, which is another uncertain parameter that introduces a good deal of uncertainty in the income, the third explanatory variable. Therefore, the current deterministic model could be improved significantly by assigning probability density functions to each explanatory variable within the forecasting model and allow the model to become stochastic or probabilistic model.

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