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MULTI-DIMENSIONAL MODELLING TOOLS SUPPORTING DECISION-MAKING FOR WATER CONSUMPTION RATIONALIZATION

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ABSTRACT

Water demand in Saudi Arabia is posing significant challenges as a result of the continuously increasing water consumption. Model frameworks combining many-objective robust decision-making modeling were developed to identify adaptive water consumption rationalization (WCR) measures. Two modeling tools were presented: (i) predictive model for daily water consumption per family; and (ii) a conceptual model for WCR, considering different variables. Results showed that family size, monthly water bills and fixing water conservation tools are highly significant to water consumption, while the monthly income was insignificant. The variables that influence the decision-making for WCR were found to be water policies, water sector privatization, water supply & demand, water tariffs, water conservation tools, water metering and awareness campaigns. The models proposed are important tools for practitioners and policymakers seeking science-based decision assistance. Developing a robust WCR plan requires the researchers and water managers to well characterize the future water supply and demand of the study region and the vulnerabilities of their tools.

KEYWORDS: Water consumption rationalization; multiple linear regression; integrated assessment model; decision making.

1. INTRODUCTION

One of the most important aspects of sustainable development is ensuring the availability and proper water management for all. Integrated water resources management is largely regarded as the most effective management method for ensuring water security. However, many decision-makers and practitioners still find it difficult to put it into practice.

Water utilities require water consumption forecasting for a variety of reasons, including network operations, pricing policy updates and water consumption rationalization measures. Due to the advancement of smart metering, water management tools are becoming more significant today. Since the 1960s, researchers have been trying to figure out what drives urban water demand, with most attempts employing population, demographic variations and price as explanatory factors to define water consumption for various user groups.[1]

Already more than 1.4 billion people live in areas where the withdrawal of water exceeds recharge rates. In the coming decades, the global population is expected to increase from 7.3 billion now, to 9.7 billion by 2050 (UN estimate). This growth, along with rising incomes in developing countries, is driving up global food demands. With food production estimated to increase by at least 60% (FAO estimate), predicting water withdrawal and consumption is critically important for identifying areas that are at risk of water scarcity and where water use is unsustainable and competition amongst users exists.[2]

Saudi Arabia is one of the poorest countries in the world in water resources. It relies heavily on costly desalinated water and most of the water taken from underground sources is not renewable. The high water consumption rate, the cost of producing water and conveying it to cities and remote areas in Saudi Arabia stand as major challenges to the Ministry of Environment, Water and Agriculture. Billions of Riyals are spent annually by the government on supplying potable water to citizens and residents. Sheffield[3] reported that daily water per person is reported to be 265 liters in Saudi Arabia, double the European Union average (See Figure 1)

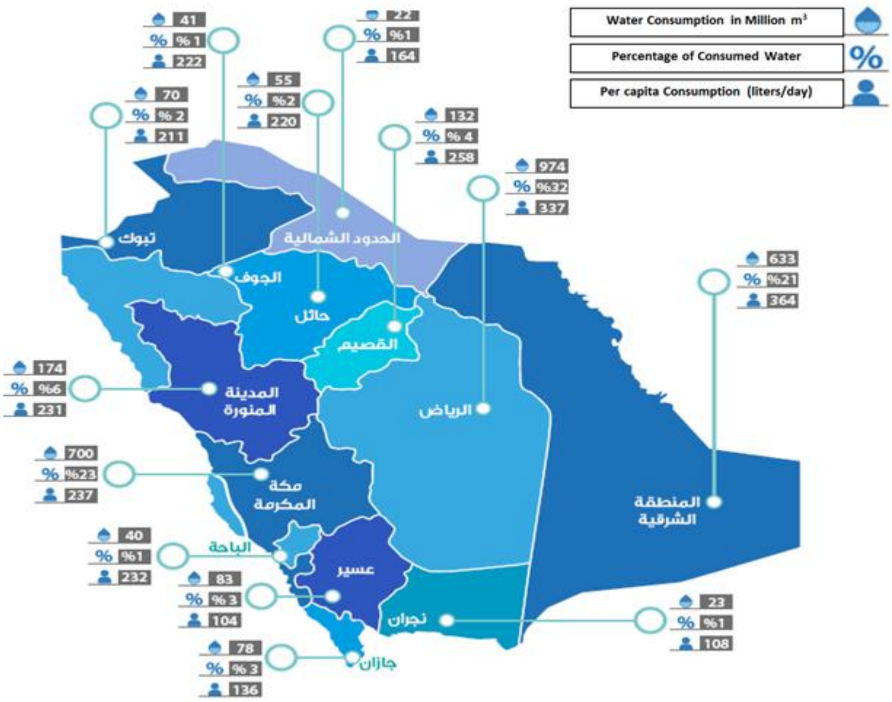

Figure (1): Water consumption and average per capita consumption in KSA regions (2015).

Source: MEWA, 2016

In the least developed economies, domestic water consumption depends on different sources that might be used for different purposes.[4] Other sources of research contributed to presenting the limiting factors in accessing water sources and demand in a developing country, the case of 69 households from Ukunda, Kenya followed a single demand equation with a dummy to control for type of water access and Ordinary Least Squares estimation techniques. Unlike developed countries' single piped sources, in developing countries households' access to water is from various sources, the case of 48 households in Kuwait, followed Linear regression and neural network models, fitted to the observed data.[5]

Over the last 30 - 40 years, major advances have been made in the development and use of a wide range of tools to assist in the planning and management of water resource systems. Decision Support Systems (DSSs) are intended to provide water resource managers and political decision-makers with assistance in making rational decisions based, as far as possible, on an objective assessment of issues https://en.wikipedia.org/wiki/Decision_support_system.

Despite the growing relevance of knowledge-based decision aids, such as the development of DSSs in water management, the water sector lacks appropriate risk assessment and decision-making tools that can be used by relevant stakeholders (e.g. water officials, risk assessors, policy-makers).

There are important highlights of theoretical and empirical work that have been assessed thoroughly to have a basic foundation on the determinants of residential water demand in both developed and developing countries.

Findings from the existing body of knowledge contribution on the analysis of household water demand functions have been given more emphasis on changing socioeconomic characteristics, water pricing, income, expenditure, water-saving technologies or appliances, household water use practices, household water-saving habit and conservation measures were among the most relevant issues discussed in this review.[4]

Water demand research typically focuses on a micro level-specific use within a household or at an aggregate level water use within a city or region. Little research has examined water use at the multi-house or census tract level, the appropriate level for many water planning decisions.[6]

The goal of this study was to gain a better knowledge of the elements that influence both water consumption and WCR so that future predictions of water use could be made and demand could be managed more effectively.

2. MATERIALS AND METHODS

Models can represent the important interdependencies and interactions among the various control structures and users of a water system; in addition, they can help identify the decisions that best meet any particular objective and assumptions.

2.1 Study area

The study was conducted in Baljurashi Governorate which is one of the governorates of Al-Baha Region in the southern part of Saudi Arabia. It is located between 19.42° N and 20.17° N latitude and 30.00° E and 41.58° E longitude, at an altitude range of 1984 to 2224 m above sea level (Figure 2). The Governorate covers an area of approximately 1362 km^2 and it is characterized by flat valleys surrounded by high mountains. According to the General Authority for Statistics,[7] Baljurashi Governorate has a human population of approximately 78,536 people.

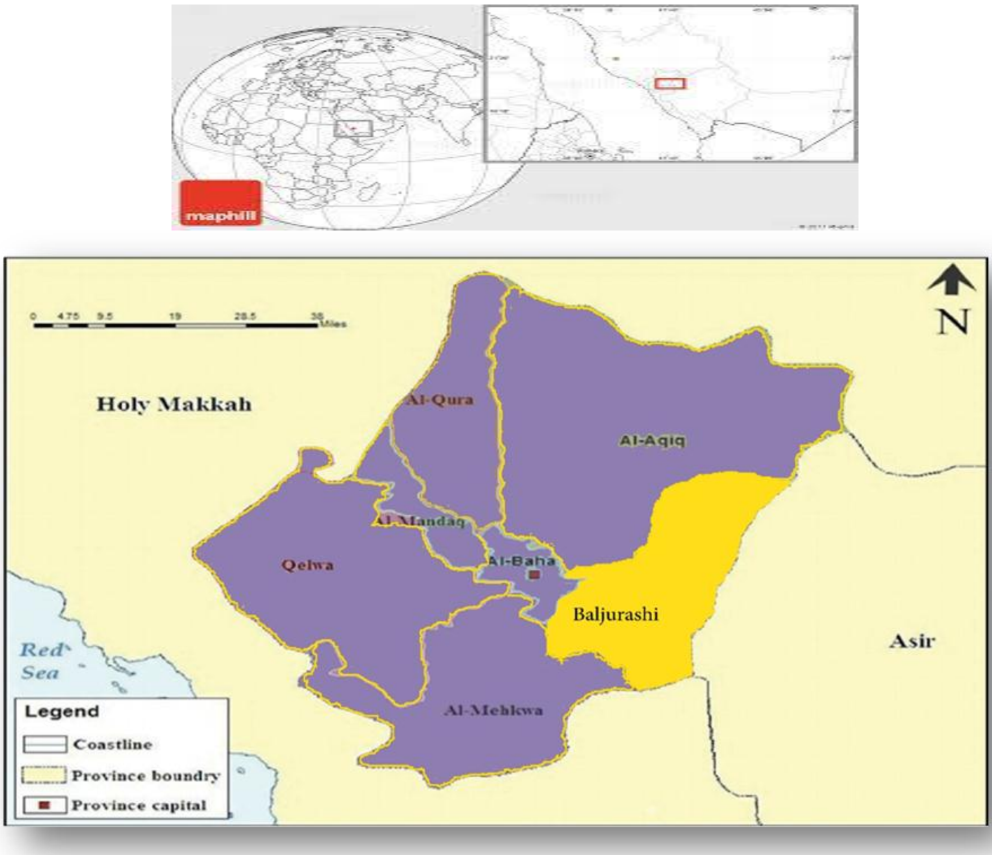

Figure (2): Location of Baljurashi Governorate.

Source: The Encyclopedia of the Earth (2020)

2.2 Description of Data

A household survey using well-tailored questions can reveal the factors that influence water consumption. Höglund[8] investigated the impact of price on water use and revenue in 282 Swedish localities using panel data methodologies. Though Höglund accepted that investigating pricing impacts at the household level may be more suitable. He pointed out that many studies at the community or utility level produced realistic household needs.

According to Polebitski and Palmer[6] Kenney et al. (2008) employed a significantly disaggregated panel data set 10,000 homes analyzed over seven years at monthly time-steps to examine price structure and water use limits on water consumption.

About 383 questionnaires issued to Baljurashi Governorate residences were returned and completed correctly. Residents were given the questionnaires in two ways: in-person and online. Google Forms was used to build the survey. The questionnaire questions were set up in a multiple-choice format, with the respondent selecting the option that best reflected his or her viewpoint. Determinants of water consumption that were derived from the questionnaire included: family size, monthly income, monthly water bill and fixing of water conservation tools which are considered as independent variables.

2.3 Multiple Linear Regression Analysis

Regression analysis[12] is a statistical technique for estimating the relationship among variables that have reason and result relation. The main focus of univariate regression is analyzing the relationship between a dependent variable and one independent variable and formulates the linear relation equation between the dependent and independent variable.

Uyanik and Guler[9] have reported that in multivariate regression analysis, an attempt is made to account for the variation of the independent variables in the dependent variable synchronically. The multivariate regression analysis model is formulated as in the following:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 \ldots \ldots . + \beta_n x_n + dummy\ variable$$

Where:

$$y = dependent\ variable, \ x_i = independent\ variable, \ \beta_i = Constant,$$

A multiple linear regression analysis was conducted to develop a model for predicting daily water consumption per family. The dependence of the daily water consumption data from 383 respondents of Baljurashi Governorate was collected on various variables related to individual households. All of the proposed independent variables were assumed to affect daily water consumption. The independent variables were family size, monthly income, monthly water bill and fixing water conservation tools.

2.4 Generating Integrated Assessment Model

Models are streamlined representations of complex systems. It attempts to reduce the world to a fundamental set of elements and laws, with the goal of better understanding and forecasting key aspects of the world.[10]

Integrated assessment and its underlying platform, integrated modeling, provide an opportunity to synthesize diverse knowledge, data, methods and perspectives into an overarching framework to address complex environmental problems. To be successful for assessment or decision-making purposes, however, all salient dimensions of integrated modeling must be addressed in relation to its purpose and context. Concerns; management options and governance arrangements; stakeholders; natural systems; human systems; spatial scales; temporal scales; disciplines; methods, models and tools.[11]

Integrated Assessment Model (IAM) could be defined as “any model which combines scientific and socio-economic aspects of water conservation primarily to assess policy options for water consumption rationalization. Various factors that influence the WCR process were reviewed. Methods and techniques for measuring and understanding consumption patterns were also reviewed, as well as prominent instruments used in the household water demand sector around the world, as well as their relative impact on per capita consumption.

The generated IAM components consisted of:

- Objectives,
- Variables,
- Constrains and
- Decisions

3. RESULTS AND DISCUSSION

3.1 Multiple Linear Regression Analysis

As per the multi regression model, family size, monthly water bills and fixing water conservation tools are highly significant while monthly income is not which might probably imply that regardless of the income, water supply is almost secured for every level of income in Saudi Arabia. In other words, the government gave equal access to every citizen of income levels.

This result goes parallel with what was mentioned in the analysis paper conducted by the Center for Strategic and International Studies(13) where it was argued for the explanation for the high rates of desalination demand is that the Saudi population has faith in its government to continue providing water.

Likewise, a study in a Chinese city suggested that income and water pricing affect household water demand in developing countries.[14] The same study also revealed that socio-economic factors determine the urban household water consumption behavior in developing countries. Contrary, Legamo.[4] has reported that Henry et al (2004) argued that water price and income do not have the expected impact on household water use and consumption. However, both studies have a similar stand from the demand management point of view.

Mukhopadhyay[5] has analyzed the freshwater consumption patterns in the private residences of Kuwait using multiple linear regression. His study suggested that a relatively high level of income, combined with the low cost of water due to high government subsidy, has led to a somewhat irrationally high rate of water consumption in Kuwaiti households.

The formula of multiple linear regression model for the daily water consumption in Baljurashi Governorate is obtained as follows:

$$Family\ water\ consumption\ (litres\ per\ day) = 600 + 200 \times Family\ Size$$
$$+0.03 \times Monthly\ income(SAR) - 33 \times Monthly\ water\ bill(SAR)$$
$$-625 \times (Factor\ fo\ Fixing\ water\ conservation\ tools\ \ (= 1\ for\ fixing\ 0\ for\ non\ fixing\ ).$$

3.2 Modeling Water Consumption Rationalization

Modeling becomes an essential tool in water management. It plays a significant role in fulfilling the core tasks of water management. Management instruments are the elements and methods that enable and help decision-makers to make rational and informed choices between alternative actions, selecting, adjusting and applying the mix appropriate to the given circumstances.[15]

Activities related to water consumption rationalization are usually motivated by the realization that there are either problems to be solved or there are opportunities to be improved. To maximize the benefits to be obtained from models, planners and managers of the water sector need to take into account a range of interlinked biophysical, economic, organizational, social and environmental factors.

3.2.1 Integrated Assessment Model

It is broadly recognized that the interconnectedness of the world requires integrated rather than piecemeal approaches to resolving complex environmental issues generally and water management specifically. Integrated assessment is a discipline that takes a holistic, problem-oriented approach to scientific assessment.

To identify decision-making tools for water consumption rationalization that are robust to Saudi Arabia's water dilemma, a model framework comprising objectives, variables, constraints and decisions was created to target the final water consumption rationalization objective.

Figure (3) shows a model of interlinked issues that must be taken into account in planning for water consumption rationalization decision making. Hamad[16] has stated that the number of the United Nations conferences stressed the idea that policy-makers are requested to adopt a holistic approach by recognizing the interrelationship between the different components of the water resources system.

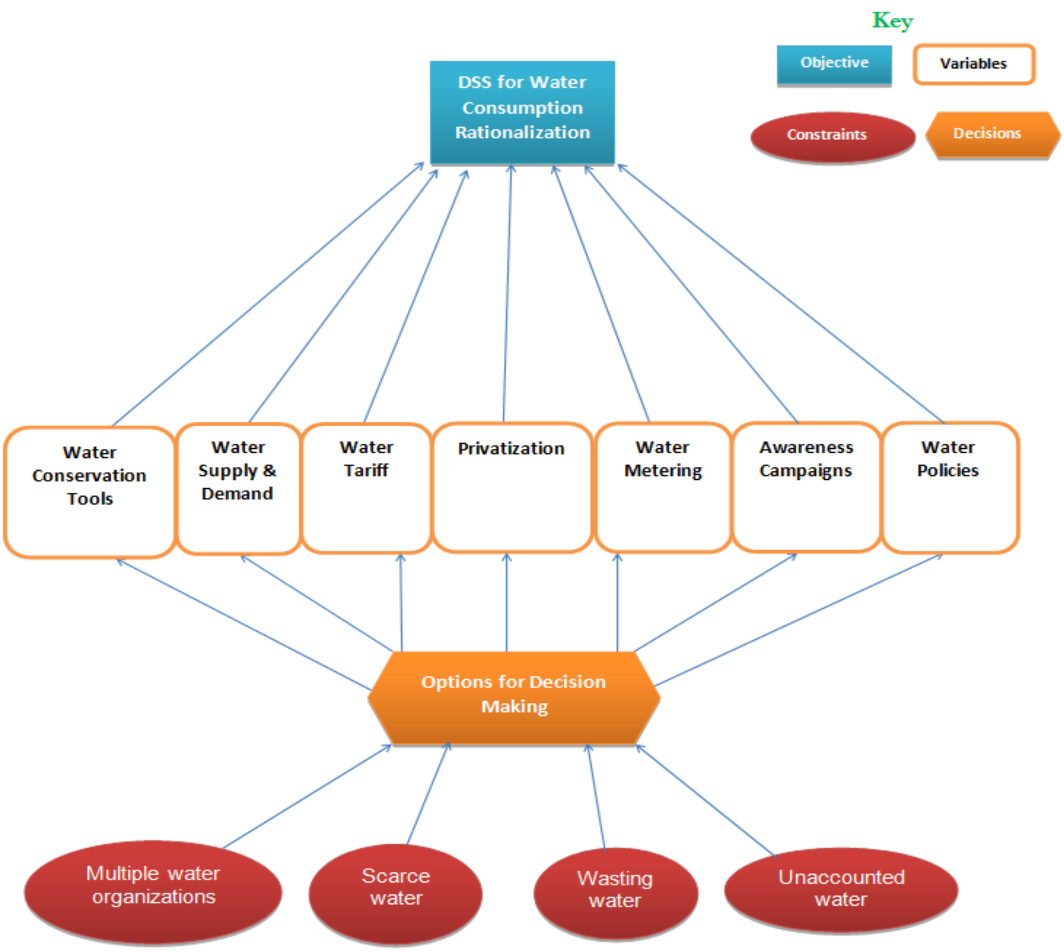

Figure (3): Model of interlinked issues that must be taken into account in planning for water consumption rationalization.

Integrated assessment and modeling (IAM) can help decision-makers develop policies to manage environmental resources and assets in a way that delivers acceptable environmental and socioeconomic outcomes. In this case study, the effective use of this (IAM) may support social learning by promoting a science-informed dialogue about water and water consumption rationalization issues.[11]

3.2.1.1 Model Variables

Model variables could deeply affect the decision-making to provide water more efficiently and conservatively. Followings are some details of these variables:

- Water Policies

Water policy is a dynamic process that needs to be reviewed from time to time, taking into consideration the outcome of previous policies, changes in supply and demand parameters, advancement in knowledge and alterations in the surrounding environment. Laws need to be implemented within the sensitivities of the local context, to be able to have been effective enough to serve the agenda of water conservation.[16]

Integrated water resources management is a key in reforming water sector policies including better planning, inter-sectoral coordination, water conservation, regulation and pricing.[17]

- Water Conservation Tools

WCR can be achieved through a variety of approaches, one of these is the use of water conservation tools that can significantly rationalize the use. The Massachusetts State Plumbing Code requires that all new or replacement installations of two-piece tank-type and floor-mounted flush meter toilets use no more than 1.6 gallons per flush. These toilets are called low-consumption, low-flush, or ultra-low-flush.[18]

The concept of adopting new ideas and innovations, such as modern technologies and water-saving tools, could be implemented via two related processes that interfere in the transfer and delivery of new ideas and innovations from their research sources until their acceptance by the public of beneficiaries. These are the diffusion and adoption processes.

- Water Supply and Demand

The relation between water demand and supply could be coordinated via using water more efficiently that balances supply and demand, focusing on the better use of existing water withdrawals or reducing excessive use rather than developing new supplies. This is consistent with the findings of Al-Zahrani[19] who pointed out the water supply and demand interaction. He stated that in present and the future we have to shift from the supply-side to demand management and conservation side, which means that we must use our water resources efficiently taking into account, economics, social and environmental conditions.

- Water Tariff & Metering:

International and regional experiences have demonstrated significant reductions in per capita water consumption after major demand control measures through pricing and metering were introduced. A significant result related to WCR could be achieved by determining the actual cost of water sector activities and reviewing the tariff from time to time. As well, water conservation practices could be motivated by increasing unit costs on higher usage of water. These findings are supported by a study related to management options for the West Bank water resources, where Abu Hantash.[15] concluded that tariff system leads to personal demand management practices which can reduce water demand to about 5% included in demand management program. Another evidence is from Bahrain which has witnessed significant reductions in water consumption when it introduced water metering and tariffs.[16] These two cases highlight a very important lesson that the introduction and enforcement of metering and billing are very effective even if the tariff rate is very modest compared to water supply costs. Water price policies with several tiers should be frequently promoted as a way to promote demand management.

Awareness Campaigns

National water rationalization campaigns could be launched regularly to raise public awareness about the importance of water conservation and the higher costs of water provision, as the Kingdom is one of the largest arid countries with low rainfall and scarcity of water. According to Anan[20] none of this will happen, until public awareness and mobilization, campaigns are undertaken to inform people about the magnitude and causes of the current and impending water crisis. The strategic awareness campaigns employ the KAP analysis, which begins with a survey of the information, trends and practices of the targeted population, with the results serving as inputs in planning and points for review when conducting the campaign's final evaluation. Furthermore, a series of practical workshops are held and mentors responsible for campaign activities, specialists, trainers and local leaders are trained to gain skills of planning extension educational programs, designing communication messages and preparing educational materials for use in the chosen combination of media.

A participatory planning approach could be employed to react to the cognitive needs and real challenges of the target community. The use of approach might increase the degree of association, which leads to acceptance of recommendations or educational indicative messages by the target community, who were consulted during the planning phase about their requirements and priorities.

- Water Sector Privatization

Water has transitioned from a common good and a public service to a commodity that is increasingly being managed according to economic principles in recent years. The private sector can play a significant role in facilitating a lot of issues related to the water sector. The involvement of privatization could entail a change in business culture and provide much-needed managerial and technical expertise in general and WCR specifically.

Privatization and liberalization of the Saudi economy present numerous investment opportunities in the water sector.[21] The review of the KSA privatization experience matches the efficiency hypothesis, where water-supply services have shown substantial improvements over the last five years based on selective key performance indicators that are recognized internationally in the water industry as valid. There is improvement in water supply revenues and revenues relative to expenditures.[22]

4. CONCLUSION

A methodological framework for the development of two modeling tools targeted at aiding management decisions about water consumption rationalization was proposed in this research. The given models were parameterized using simulated data and demonstrated a strong ability to incorporate a wide range of factors, including water consumption drivers, human activities and water consumption rationalization management measures.

Based on data collected from 383 residences, the multiple variable linear regression model developed for daily water consumption in Baljurashi Governorate can only explain 68 percent of the variation in observed daily water consumption. Water consumption was found to be significantly affected by family size, monthly water bills and water conservation tools that were installed. On the other hand, monthly income is insignificant, implying that, regardless of income, the water supply is almost guaranteed for all levels of income in Saudi Arabia. The findings of the integrated assessment model revealed that water policies, water sector privatization, water supply and demand, water tariffs, water conservation tools, water metering and awareness campaigns are the variables that influence WCR decision making. Capacity building, campaigns, and demonstrations of effective WCR are required to raise public awareness. To support decision-making for WCR programs in Saudi Arabia, more researches with other designs and models are required.

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