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An integrated approach to water conservation: fuzzy logic assessment of water tariffs in Abu Dhabi Emirate's residential sector

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Abstract

Background Abu Dhabi, a part of the United Arab Emirates, is situated in an arid region where water scarcity is a significant concern. The residential sector in Abu Dhabi consumes a large portion of the available water resources, leading to a critical need for effective water management strategies. This study aims to understand the relationship between water tariffs and water consumption in the residential sector in Abu Dhabi. It employs an integrated fuzzy logic model, a form of artificial intelligence, to assess the impact of water tariffs on water consumption. The model includes variables such as water tariffs, the level of water awareness, the level of water behavior, and the level of technology use. The objective of these variables is to evaluate their impact on the water-saving index, which represents the ratio of daily water consumption per capita in Abu Dhabi to the global average.

Results The findings of this study, based on a survey measuring the level of water awareness, behavior, and technology use, revealed a potential strategy for reducing water consumption in Abu Dhabi's residential sector. It was observed that increasing water tariffs, while maintaining current levels of water awareness, behavior, and technology use, could lead to a reduction in water consumption. However, it was also found that the impact of further tariff increases on water conservation diminishes after a certain threshold, indicating the necessity of a balanced approach in tariff adjustment. Interestingly, the study also highlights that Abu Dhabi residents demonstrate high levels of water behavior and technology use, indicating a positive trend toward water conservation.

Conclusions This study emphasizes the importance of increasing water awareness among Abu Dhabi residents as a means to foster sustainable water consumption practices. While water tariffs can contribute to reductions in water consumption, the effects tend to decrease beyond a certain point. Therefore, a comprehensive approach involving water tariffs, increased water awareness, and the adoption of water-saving technologies may be the most effective strategy for water conservation. The insights from this study extend beyond Abu Dhabi and offer valuable guidance for addressing water conservation challenges worldwide. It highlights the importance of adopting a multi-faceted approach in water management, and the potential for such strategies to have international relevance in the pursuit of sustainable water consumption.

Keywords Water conservation, Water awareness, Water behavior, Fuzzy logic, Water tariffs

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Background

Groundwater is the major source of water in the UAE, supplying 61% of the total water, mainly for agricultural purposes. However, only 3% of the groundwater is fresh and suitable for domestic use, with the remaining 97% either brackish or saline (EAD 2015). Hence, most of the domestic water supply originates from desalination plants, which consume substantial amounts of energy and generate large volumes of greenhouse gases (GHGs). According to Abu Dhabi Water and Electricity Authority, fuel-powered electric and water production facilities in the UAE emitted more than 35 million tons of CO_2 equivalent in 2014, with nearly half of that resulting from water production alone (ADWEA 2015; Al Hamedi et al 2023; Gonzalez et al 2016). Moreover, the annual water consumption per capita in the emirate is nearly three times the global average (EAD 2015). The water demand in the UAE is expected to reach almost 8.8 billion cubic meters by 2030 (Mohsen et al. 2016), almost double the yearly water demand in 2008. Apart from limited water resources, the residential water sector in the UAE also faces challenges such as high population growth and overconsumption, leading to a widening gap between water supply and demand.

Additionally, the history of free or inexpensive water prices over the past two decades, combined with inadequate water strategies, has encouraged many consumers to adopt a wasteful water consumption pattern (Allan 2001). In fact, the pricing of water in Abu Dhabi Emirate was subsidized in the last 20 years, with Emirati residents paying nothing for their water bill, while expatriate consumers paying lower prices than the actual cost of production and distribution. This led to a general feeling that water is cheap and plentiful and created lavish water consumption habits (Srouji 2017).

On the other hand, water demand for irrigation and cooling purposes is very high in Abu Dhabi due to the hot and arid climate and high evaporation rates. Moreover, the majority of Abu Dhabi residents enjoy a high standard of living and have more resources to afford high-water usage appliances, such as swimming pools, large gardens, and luxurious water features. Additionally, the lack of awareness campaigns and educational programs about the importance of water conservation among the general public contributed to higher water consumption in the residential sector.

Hence, the need for a proper assessment and planning for water-saving influences and consequences in UAE is of great importance in order to measure and evaluate the effect of each factor on the consumption levels of residential customers, and to develop a comprehensive understanding of their impact (Lim et al. 2018). To achieve this, a fuzzy logic model was employed to measure the effects of specific factors on the water-saving index, which represents the ratio of water consumption per capita in Abu Dhabi to the global average. The study focused on four key input variables: water tariffs, level of water awareness, level of water behavior, and level of technology use. By analyzing these factors and their effects on the water-saving index, valuable insights can be gained into the dynamics of water consumption in the residential sector of the Abu Dhabi Emirate.

This research aims to provide evidence-based recommendations for policymakers and stakeholders to develop targeted strategies for promoting water conservation. Understanding the interplay between water tariffs, awareness, behavior, and technology use is crucial for fostering sustainable water consumption practices and addressing the challenges posed by water scarcity in the emirate. The notion behind this work is the limited understanding of the combined water consumption influences on water conservation practices in the region. While previous studies may have individually examined some of these factors, there is a lack of comprehensive research that considers their interrelationships and evaluates both their individual and collective impacts on water consumption patterns.

Fuzzy logic was a well-suited approach for this study (Zadeh 1965). One of the primary advantages of fuzzy logic is its ability to handle uncertainty (Alhamad and Saraiji 2023), which is particularly relevant when dealing with subjective factors such as the level of water awareness, behavior, and technology use. These variables are difficult to quantify precisely, and fuzzy logic provides a framework for representing and reasoning with imprecise information. By incorporating linguistic variables and membership functions, fuzzy logic allows for a more accurate representation of the inherent fuzziness and variability in these factors (Nguyen et al. 2018). Furthermore, the complex relationships among these influences can be effectively modeled using fuzzy logic, as it enables the capturing of nonlinear patterns and interactions.

Water consumption influences in the residential sector

Residential water consumption is affected by several factors, including water tariffs (Alhamad 2018a, b; Kayaga and Smout 2014; Lopez-Nicolas et al. 2018; OECD 1999, 2008), level of water awareness (EEA 2001; Lucas and Cordery 2019; Stavenhagen et al. 2018), level of water conservation behavior (Al-Maadid et al. 2022; Salas-Zapata et al. 2023; Vickers 1999), and their utilization of water-efficient technologies in their households (Inman and Jeffrey 2006; Keating and Styles 2004; Tsai et al. 2011; Vickers 1999). Water tariffs refer to the amount paid per unit of water and any additional taxes or fees imposed by water authorities. Awareness of water scarcity is the degree of customers' understanding of their water consumption numbers, water resources scarcity problems, and the carbon footprint of water production processes. Water conservation behavior refers to the habits and practices that customers are adopting to save water, such as closing taps when not in use and using water-efficient appliances. The use of water-efficient technologies includes water-efficient appliances and fixtures, such as performance showerheads and low-flush toilets, as well as residential graywater systems that recycle water for irrigation or toilet flushing.

While there is evidence of a correlation between these factors and customers' water consumption levels, accurately measuring their individual impact on water consumption is challenging. This is due to the inherently interconnected relations between such factors. For example, a customer with high awareness of water scarcity and shortage problems will probably invest in water-efficient technologies, but other factors such as financial capacity and household ownership can also influence their decision. In such cases, self-awareness and efficient behavior are likely to be more effective in shaping customers' consumption levels. On the other hand, a customer with low awareness of water scarcity is unlikely to conserve water, adopt high behavior levels, or invest in water-efficient technologies, making water tariffs more critical in shaping their water consumption levels. Below are the water-saving influences in the residential sector:

Water tariffs

Water tariffs are considered one of the most important factors that affect the water consumption of residential customers. Water tariffs are the amount paid by the customer per unit of water as well as any taxes or fees required by the water authority (Alhamad 2018b). They affect the behavior of residential customers toward water conservation. It is expected that higher water tariffs will force customers to adopt a more conservative water consumption behavior. Kenney et al. (2008) showed that increasing water tariffs resulted in a reduction in water consumption in the residential sector in Colorado—USA. In contrast, reducing water tariffs led to an increase in water consumption. Kayaga and Smout (2014) showed that the successful water tariff structure accompanied by proper incentives applied to the residential water sector in Zaragoza (Spain) was very effective in reducing water consumption by 27% between 1996 and 2008.

However, some other studies showed that due to the inelasticity of water demand in relation to water tariffs reducing residential water consumption through higher tariffs can be limited in many cases and mainly depends on place and time (Arbues and Villanua 2006; Olmstead and Stavins 2009). For instance, for a 10% water price increase, only 3–4% water savings were reported in urban residential areas in the USA. Moreover, it was reported that water price elasticity was found to be higher in Europe than in the USA (OECD 1999, 2008). Other studies suggest that the response to increased water tariffs depends on the time of the years in which it was introduced and the characteristics of the water customers. For example, Beecher et al. (1994) argued that since water consumption fluctuates within the seasons of the year due to weather conditions, seasonal water pricing could be more effective in reducing residents' water consumption. Suárez-Fernández et al. (2022) confirmed that a substantial number of households in Granada (Spain) are insensitive to water price changes except for environmentally aware customers, who are the most likely to reduce their water consumption in response to price changes. Olivier (2006) showed that when water tariff reforms were introduced in Manaus (Brazil), customers showed different responses in which the poorest households mostly reduced their water consumption.

Level of water awareness

Water awareness pertains to the level of understanding individuals have about the significance of conserving water resources and the potential consequences of excessive usage. Several studies have investigated the relationship between water awareness and water consumption in residential settings. For example, Willis et al. (2011) provided solid evidence that customers with high environmental and water attitudes in Gold Coast City (Australia) consumed less water compared to other customers. A study conducted on female school students in central Jordan (Middlestadt et al. 2001) found that the implementation of an interactive curriculum aimed at promoting water conservation resulted in a significant reduction in water consumption among the students and their families. Similarly, another study (Çoban et al. 2011) showed that students from a Turkish school who participated in water education workshops exhibited enhanced understanding and attitudes toward water usage even after a span of three months following the workshops.

In many cases, water awareness may be achieved by educating customers about their own consumption levels. For example, installing water meters for households can raise residents' water awareness by informing the customers about their household consumption and the need for conservation. It also gives them direct feedback when consumption reaches certain high levels and can be efficient in detecting leaks and high-consumption appliances. Studies across Europe estimated that household consumption can be reduced by 10–25% after installing water meters (EEA 2001). The implementation of smart metering solutions, facilitating customers to digitally track their daily water usage patterns in real time through integrated computer applications (Bastidas Pacheco et al. 2020, 2021), holds significant potential for effectively enhancing consumer awareness regarding their water consumption tendencies (Cominola et al. 2018), household leaks (Luciani et al. 2019), and irregular water usage patterns (Mayer 2022).

Moreover, reading the water bill is a strong indicator of customer awareness and can be effective in water conservation. Alhamad (2018a, b) showed that while the majority of Abu Dhabi residents value water for different reasons (cost, environmental aspects, religious reasons, and saving water resources), most of them do not read their water bills, which may indicate that they have limited information about their own consumption. Salman et al. (2008) suggested that non-tariff policies such as boosting the information level of the water bill and technological innovations could enhance the efficiency of the pricing system to promote water saving.

Level of water behavior

Water behavior refers to the actions and practices that effectively reduce water usage, and is regarded as a conservation measure. Meanwhile, water awareness is viewed as a conservation incentive, which involves methods and regulations aimed at promoting conservation. For example, educating individuals about the carbon footprint of desalinated water production can raise their level of water awareness (Bello et al. 2018; Gómez-Llanos et al. 2020), but does not lead to water conservation unless concrete steps are taken to reduce consumption. Kilic and Dervişoğlu (2013) showed that while secondary school students in Istanbul (Turkey) have positive attitudes toward water conservation, their water-saving behavior was very weak, and they concluded that having a positive attitude does not guarantee that students will engage in water-saving practices, just as having a negative attitude does not necessarily mean they will neglect water conservation. Hence, water awareness alone may not be effective in reducing water consumption unless coupled with educating people on how to save water, which simply translates to water behavior (Alhamad 2018a). Examples of water behavior in the residential sector include turning off water taps while brushing teeth, taking a shower instead of a bath, plugging the sink while washing dishes, watering gardens during the coolest hour of the day, collecting rainwater, and recycling graywater (Grafton et al. 2011).

Moreover, leak detection and repair are strong indicators of positive water behavior. Water leakage is the most popular cause of water wasted in domestic water distribution systems (Daadoo et al. 2017). Studies by The European Economic Area (Nixon and EEA 2003) reported that water losses due to water network leakages as a percentage of the total water urban supply accounts for 30% in Italy, 35% in Ireland and Hungary. Macy and Maddaus (1989) reported 10–25% savings for residential toilet leak repairs. EEA (2001) reported 10–25% water savings due to information, publicity, and leakage repairs that took place after installing household water metering systems in some EEA countries.

The motivation behind adopting a water-conservative behavior is complex and can be related to many reasons. Gregory and Leo (2003) argued that water behavior is mainly affected by environmental awareness which develops reasoned (involvement, attitudes, intentions) and unreasoned (habits, reflexes) influences on water behavior. Personal, cultural, and religious convictions can also have a strong influence on conservative water behaviors. Ariztia et al. (2018) suggested that water consumption can be connected to the decisions people make in their daily routines, and within these routines, individuals exercise their judgment to discern between correct and incorrect options. Abu Baker et al. (2021) revealed that people's attitudes toward the environment, including their motivations, worries about environmental issues, and intentions, have a meaningful impact on their water consumption. Cominola et al. (2023) argued that water behavior is tied to how people think, feel, and act. This includes individual's perception, attitudes, beliefs, awareness, habits, and judgments. Furthermore, the role of culture and religion in shaping water usage behaviors has been highlighted in many scholarly investigations (Al-Maadid et al. 2022; Burger 2019; Laurent and Lee 2018; Tagat and Kapoor 2018). For example, Al-Maadid et al. (2022) survey results in Qatar showed that 64% of respondents believe that their water-saving behavior is heavily influenced by religious beliefs and their developed religious personal views. Hence, many awareness campaigns in Qatar stressed on religious obligations to conserve water. Burger (2019) examined the impact of faith on water conservation behaviors among Christians in Amman (Jordan). The findings revealed that religion can play a role in promoting general environmental friendly actions, particularly in the context of water-saving behaviors.

Level of technology use

Water technology usage in the residential sector can have a significant impact on water consumption. Water-saving devices and/or fixtures such as low-flow toilets, showers, and faucets are being distributed and installed by many water authorities worldwide, either free of charge or at low cost, through "retrofit" programs (Tsai et al. 2011). For example, the Northumbrian Water Authority

(UK) and Santa Clara Valley Water District (USA) provided free water-saving kits that include fixtures such as shower flow regulators, shower timers, tap inserts, toilet leak detection capsules, irrigation trigger hose guns, and many more.

Furthermore, water-saving technology can also include rain harvesting, domestic gray water treatment, timely-controlled irrigation sprinkler systems, water-efficient appliances such as washing machines and dishwashers, and many more. Several studies have examined the relationship between water technology usage and water consumption in households. A study in the USA assessed the water-saving potential through the retrofit program and collected micro-component water consumption data from different households in three cities, Seattle (Mayer et al. 2000) with 37 households, San Francisco (Mayer et al. 2003) with 33 households, and Tampa (Mayer et al. 2004) with 30 Households. The participating households underwent water retrofits with high-efficiency showerheads, faucets, toilets, dishwashers, and clothes washers. Results showed that clothes washers and toilet replacements were the highest contributors to water savings. Moreover, results showed that the retrofit program managed to achieve 37.2% water savings in Seattle, 39% in San Francisco, and 50% in Tampa Bay. Another study project conducted at St Leonards Middle School in East Sussex (South East England) assessed the performance of low-volume flush toilets (Keating and Styles 2004). The project aimed to replace the current toilets (9L/flush) with new efficient toilets (4.5 L/flush). Results showed that a water saving of almost 16% of daily personal consumption was noticed.

Rainwater harvesting is the practice of capturing and holding onto rainwater to prevent it from running off. This process includes gathering rainwater from rooftops, rooftop terraces, and other impermeable surfaces, then storing and treating it for on-site use (de Sá Silva et al. 2022). Abdulla and Al-Shareef (2009) studied the potential for potable water savings by using rainwater in residential sectors in Jordan. The results showed a potential water savings of 0.27–19.7% depending on the location within Jordan's 12 governates. Villarreal and Dixon (2005) studied the potential water saving of water harvesting from the rooftops of the Ringdansen project residential building blocks in Sweden. They reported a water-saving potential of almost 60% of the main water supply if rainwater was solely used for toilet flushing, 40% for laundry, and 30% for mixed-use.

Gray water refers to the urban wastewater originating from activities like bathing, showering, using hand basins, operating washing machines, dishwashers, and using kitchen sinks (Yoonus and Al-Ghamdi 2020). Unlike black water (toilet waste), gray water does not contain human waste and is relatively less contaminated. It can be recycled and reused for non-potable purposes, such as irrigation, flushing toilets, and washing outdoor areas. Edwin et al. (2014) studied the potential water savings from domestic gray water treatment for urban residential reuse in Indian homes. They reported a potential reduction of almost 28.5% in potable water use. Another study by Karpiscak et al. (1990) reported a 32% reduction in the total household water use of a single-family residence in Tucson, Arizona (USA).

Methods

The first step in this work was to study the current literature and models related to the assessment of water consumption in the residential sector. This step was crucial as it gives insights into the methods and strategies used in the assessment of water consumption. Moreover, it defines the water-saving factors and variables which have the highest influence on residents to lower their water consumption. The literature study revealed that water consumption in the residential sector is strongly influenced by water tariffs, level of water awareness, level of water behavior, and technology use in residents' homes. Hence, these variables were adopted in this study as input for the fuzzy model. On the other hand, the output of the fuzzy model was chosen as the water-saving index (WSI), defined as the ratio between the daily water consumption per capita in Abu Dhabi, and the daily world-average water consumption. Hence, if the water-saving index is less than one, this means that the water consumption per capita in a specific country is less than the world's average water consumption, and vice versa. According to the Environment Agency-Abu Dhabi (2016), the water consumption of Abu Dhabi Emirate per capita is almost 3 times the world average, which means that the value of the current WSI can be used as 3.

In order to prepare the fuzzy logic model, both input and output variables need to be fuzzified. Fuzzification is a process in which a certain crisp variable is converted into fuzzy. This is primarily possible if one can establish that the variable under consideration is not deterministic and carries a considerable amount of uncertainty due to imprecision, ambiguity, or vagueness (Ross 2017; Alhamad and Saraiji 2022). Then, the variable can be represented using an appropriately designed membership function which can characterize the vagueness, or most accurately, the fuzziness of the variable. Membership functions were first introduced by Zadeh (1965) in his first research paper "Fuzzy Sets." The fuzzification process includes two major aspects: The first one is to find the best membership function that describes the variable based on the current literature and the second aspect is to represent this membership function with the proper linguistic terms. Hence, pre-defined variables such as water tariffs (input) and water-saving index (output) can be easily fuzzified based on the current state of both of them. For example, the current water tariffs ($2 per cubic meter) can be said to be "medium or current tariffs" or have a 100% membership degree in the medium or current subset. Anything lower than the current water tariffs can be part of the "low tariffs" membership function subset, and anything higher can be part of the "high tariffs" subset. Values between 1 and 2 are having different degrees of membership in both the low and medium subsets, and consequently, values between 2 and 3 have different degrees of membership in both medium and high subsets. The same applies to the water-saving index, where the current value of 3 can be said to be "current WSI," while anything lower or higher can be said to be "low WSI" and "high WSI," respectively. The membership functions of water tariffs (WT) and water-saving index (WSI) are shown in Figs. 1 and 2, respectively.

However, the fuzzification of the rest of the input variables (level of water awareness, level of water behavior, and level of technology use) is not straightforward. Data related to the level of each one of these variables in Abu Dhabi households are needed. Although several studies have been done to measure the people's overview of different water-saving policies in Abu Dhabi Emirate (Alhamad 2018a), the water usage patterns of Abu Dhabi residents (Yagoub et al. 2019), water demand forecasting (Kizhisseri et al. 2021; Mohamed et al. 2020; Younis 2016), and the environmental awareness of Abu Dhabi youth (MOEW 2014), the need for recent robust data was required. Moreover, it is believed that measuring the level of water influences through their direct indicators gives more reliable and consistent data. For example, measuring the level of technology use through actual indicators such as the respondent's adoption of water-efficient appliances or water recycling activities is more accurate than asking opinion questions related to the effect of water technologies in saving water.

Hence, in order to fuzzify the input variables of water awareness, water behavior, and technology use, a survey was designed and distributed among a sample of students and employees of United Arab Emirates University (UAEU) in Al Ain-Abu Dhabi. The output of the survey will be used as a baseline for the fuzzification of these input variables. The survey comprises a total of 32 questions. The initial 10 questions gather personal information such as age, gender, place of residence within the Abu Dhabi Emirate, education level, etc. The remaining questions are formulated either as Yes or No inquiries or as 5-point Likert scale questions, where respondents choose the answer that best describes their opinion or behavior, or indicate their level of agreement/disagreement with a given statement on a scale of 1 to 5. On this scale, 1 represents complete disagreement, while 5 signifies complete agreement. The survey participants were selected to include individuals who are residents of the Abu Dhabi Emirate only. No additional survey sampling was required. A total of 91 responses out of 120 distributed surveys were collected. This number was appropriate for Abu Dhabi Emirate with a population of 1,567,000.

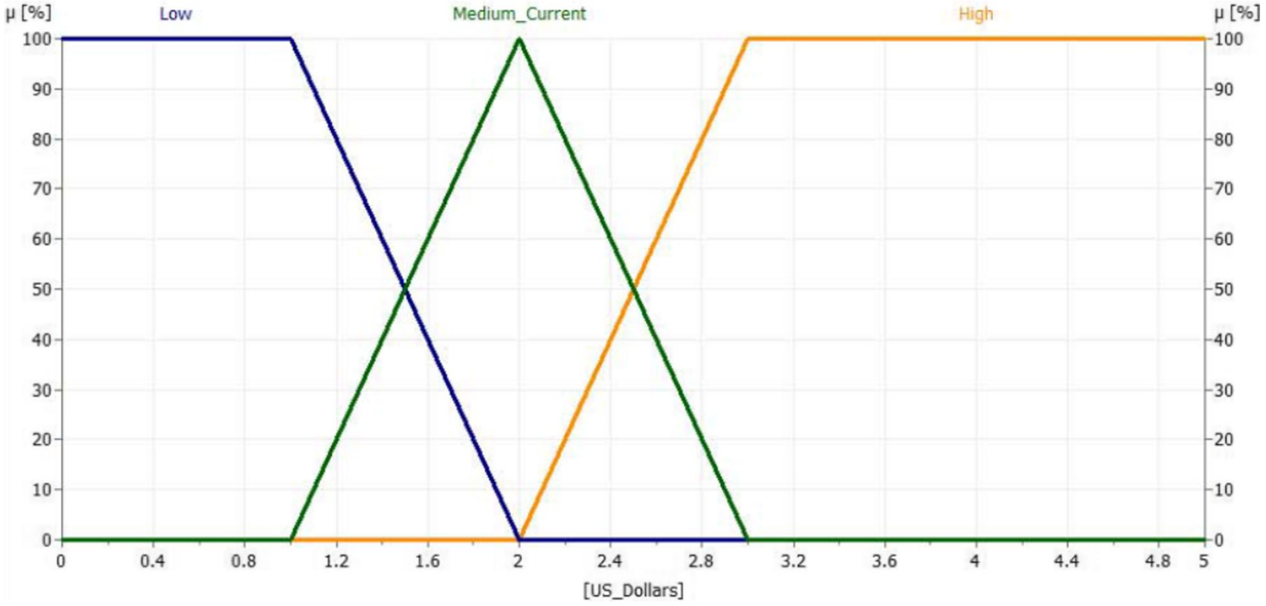


Fig. 1 Water tariffs (WT) membership function-input

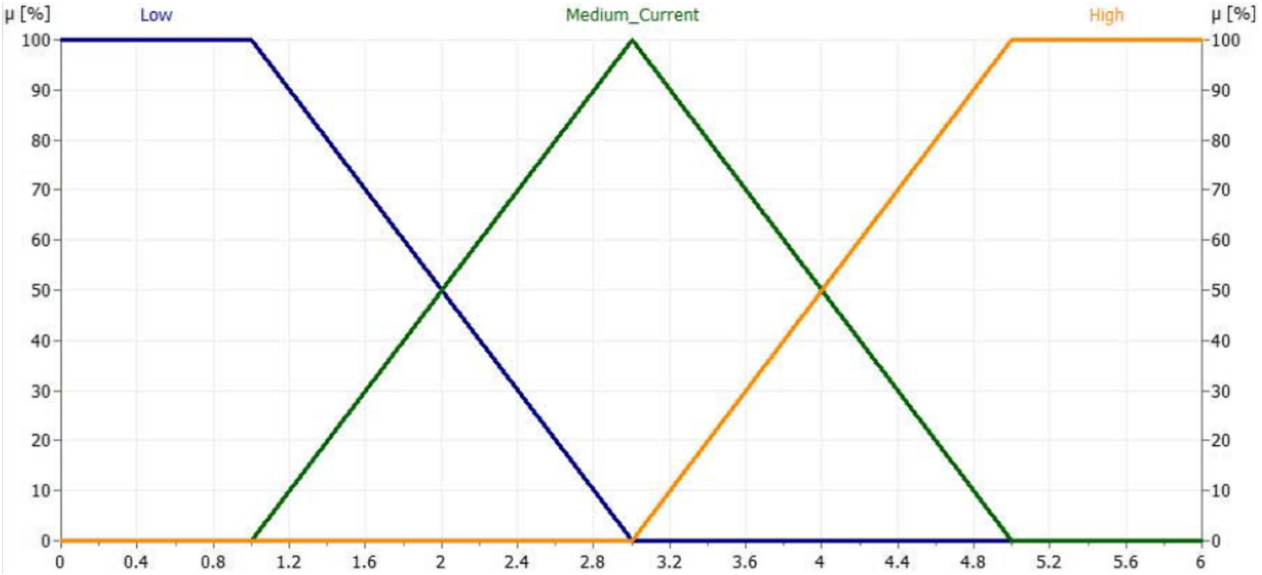


Fig. 2 Water-saving index (WSI) membership function-output

The statistical analysis of the data was conducted using IBM SPSS Statistics version 29. Table 1 shows a summary of the descriptive statistics of the respondents' traits collected at the beginning of the survey.

A tailored set of questions were designed to measure the level of awareness, positive water behavior, and technology usage through their direct indicators, and then, a combined variable for each set of these questions (components) was developed (based on the median of components) to represent the level of awareness (WA), water behavior (WB), and technology use (TU). For this purpose, it was assumed that the Likert scale items data are continuous variables rather than ordinal variables. It must be noted that this assumption may not be very accurate compared to other analysis methods such as factor analysis. However, it is justified in many cases to avoid the complexity and sophistication of factor analysis methods (Robitzsch 2020). Moreover, the idea behind the survey was not to develop generalized results about the respondents but rather to provide clear insights needed for designing the membership functions (fuzzification of variables). Tables 2, 3 and 4 show the descriptive analysis for the combined variables "level of water awareness," "level of water behavior," and "level of technology use," respectively, along with their individual components, and Figs. 3, 4 and 5 show the frequency charts of the same variables.

To begin the fuzzification process, the frequency charts derived from the histogram of the combined variables were carefully examined. These charts provided valuable insights into the distribution of data points and directed the determination of linguistic terms associated with different levels of the variables. Hence, it was utilized to guide the fuzzification process.

Linguistic terms such as "low," "medium," or "high" were assigned to represent different levels of water awareness, water behavior, and technology use according to the observed frequency distribution. Linguistic terms were assigned to different ranges or bins based on the observed frequency distribution in the histogram. By analyzing the shape of the histogram, including peaks, valleys, and clusters, appropriate linguistic terms were determined to represent various levels of the variables. For instance, the frequency distribution of the combined variable for water awareness (Fig. 3) revealed a concentration of data points around the value of 3 and dropping beyond this value, and hence, this point was assigned the linguistic term "medium," which refers to the current state of water awareness of Abu Dhabi residents and reflected on the membership function which has a scale from 0 to 100% as 60%. Anything below that value was assigned a linguistic term of "Low," with variable degrees of being "Low" and "medium" in the range from 40 to 60%, and anything above this value was assigned a linguistic term of "High," with variable degrees of being "medium" and "High" from 60 to 80%. The shape and parameters of the membership functions were established considering the observed frequency distribution, expert knowledge, and domain understanding. The membership function of the level of water awareness is shown in Fig. 6.

A similar approach was used for the technology use as the frequency distribution of the combined variable for

Table 1 Summary of descriptive statistics for the survey respondents' traits

Variable	Categories	Frequency (No.)	Percentage (%)
Age	Less than 18	12	13.2
	18–24	61	67
	25–40	9	9.9
	More than 40	9	9.9
	Total	91	100
Gender	Male	39	42.9
	Female	52	57.1
	Total	91	100
Location within Abu Dhabi Emirate	Abu Dhabi city	11	12.1
	Al Ain city	59	64.8
	Al Gharbiah	2	2.2
	Other	19	20.9
	Total	91	100
Housing status	Owner	65	71.4
	Tenant	26	28.6
	Total	91	100
Educational level	Secondary school	2	2.2
	High school	36	39.6
	Bachelor	48	52.7
	Higher education	5	5.5
	Total	91	100
Number of family members	1–2	3	3.3
	3–5	18	19.8
	6–8	32	35.2
	More than 9	38	41.8
	Total	91	100
Number of toilets in the household	1	3	3.3
	2	5	5.5
	3	10	11
	4	8	8.8
	5 and more	61	67
	Total	91	100
Availability of water services such as swimming pools and fountains	Yes	36	39.6
	No	55	60.4
	Total	91	100
Availability of landscape irrigation services	Yes	66	72.5
	No	25	27.5
	Total	91	100

technology use (Fig. 5) revealed a concentration of data points around the value of 3.5 and continued to be almost of the same level of frequency values as the end of the scale, and hence, this point was assigned a linguistic term of "High," which refers to the current state of technology use of Abu Dhabi residents and reflected on the membership function which has a scale from 0 to 100% as 70%. Values below 70% were assigned linguistic terms of "low" and "medium" with different degrees of each subset based on the histogram distribution. The membership function of the level of technology use is shown in Fig. 7.

For the water behavior membership function, the frequency distribution of the combined variable for the water behavior (Fig. 4) showed that the concentration of data points is around the maximum value of 5, which indicates a high level of water behavior among Abu Dhabi residents. Hence, this point was selected to be the "high" subset. However, the values of frequency of data

Table 2 Descriptive analysis for the combined variable "Level of Water awareness" and its components

	WA-1	WA-2	WA-3	Level of water awareness (WA)
Responses	90	90	90	–
Mean	2.69	3.64	3.31	3.33
Median	3.00	4.00	3.00	3.00
Mode	2	5	3	3.00
Std. deviation	1.34	1.33	1.06	1.07
Variance	1.81	1.78	1.138	1.14

WA-1 I periodically read the water bill and study its details

WA-2 The impact of public awareness on water consumption is effective

WA-3 How do you rate the water consumption in UAE compared to the average global consumption?

Table 3 Descriptive analysis for the combined variable "Level of Water behavior" and its components

	WB-1	WB-2	WB-3	Level of water behavior (WB)
Responses	90	90	90	–
Mean	4.13	4.41	3.43	4.20
Median	5.00	5.00	3.00	5.00
Mode	5	5	5	5.00
Std. deviation	1.265	1.048	1.391	1.20
Variance	1.600	1.099	1.934	1.44

WB-1 I turn off the tap while brushing my teeth

WB-2 I make sure that the water taps are turned off before I leave the house

WB-3 I carry out periodic maintenance on taps and water pipes to ensure that they are free of any leakage

Table 4 Descriptive analysis for the combined variable "Level of Technology use" and its components

	TU-1	TU-2	TU-3	Level of technology use (TU)
Responses	90	90	90	–
Mean	3.62	4.02	2.69	3.6778
Median	4.00	4.00	3.00	4.0000
Mode	5	5	1	3.00
Std. deviation	1.259	1.122	1.346	1.13006
Variance	1.586	1.258	1.812	1.277

TU-1 On an individual level, I don't mind paying an extra amount to install/purchase new technologies that save water

TU-2 Do you think that the use of modern methods at the domestic level for water retreatment, such as (residential graywater systems), contributes to saving water?

TU-3 Do you reuse water at home, such as: water from air conditioners for agriculture or water for fishponds, etc.?

points between 3 and 4 are almost constant; hence, they were selected to be the "medium" subset, and this was also reflected in the membership function of the water behavior by making the "medium" subset to be constant between 60 and 80% after converting to a scale of 0 to 100%. Values below 40% were selected to be on the "Low" Subset with different degrees of being "low" in the range of 40% to 60%. The membership function of the level of water behavior is shown in Fig. 8.

Following the fuzzification process, the subsequent step involves the application of fuzzy logic rules or inference mechanisms to assess the influence of each variable on the water-saving index. This step enables the evaluation of the fuzzy relationships between the input variables (water tariffs, level of water awareness, level of water behavior, and level of technology use) and the water-saving index. Fuzzy logic rules are formulated to capture expert knowledge or domain understanding regarding the impact of the input variables on the output variable (water-saving index). These rules typically take the form of "if–then" statements, specifying the relationships between linguistic terms or fuzzy sets of the input and output variables. For instance, an illustrative fuzzy logic rule could be expressed as follows:

> *"If the water tariffs are high and the level of water awareness is high and the level of water behavior is high and the level of technology use is high then the water-saving index is low"*

The process of generating or extracting fuzzy rules, which serve as a pivotal tool for mapping input variables to the output variable, does not have a standardized methodology. Rather, it heavily relies on the expertise and knowledge of the individual responsible for establishing the fuzzy logic model (Bai and Wang 2006). Hence, these rules are derived through a combination of expert knowledge and the literature on the topic under consideration. The number of rules needed for the fuzzy logic model to fully describe the simulated system corresponds to the total number of potential scenarios that may arise as a result of the arrangement of the input membership function subsets (Alhamad and Saraiji 2022). The proposed model has 4 input variables with 3 subsets each. Hence, the number of needed rules is equal to 81 rules.

Once the fuzzy logic rules are established, the subsequent stage involves conducting fuzzy inference. Fuzzy inference integrates the linguistic terms or fuzzy sets of the input variables, utilizing the defined rules to determine the corresponding fuzzy set or linguistic term for the water-saving index. Various inference mechanisms can be employed, such as Mamdani (1980), which was used in this study, or Sugeno (1985), depending on the specific requirements and characteristics of the study.

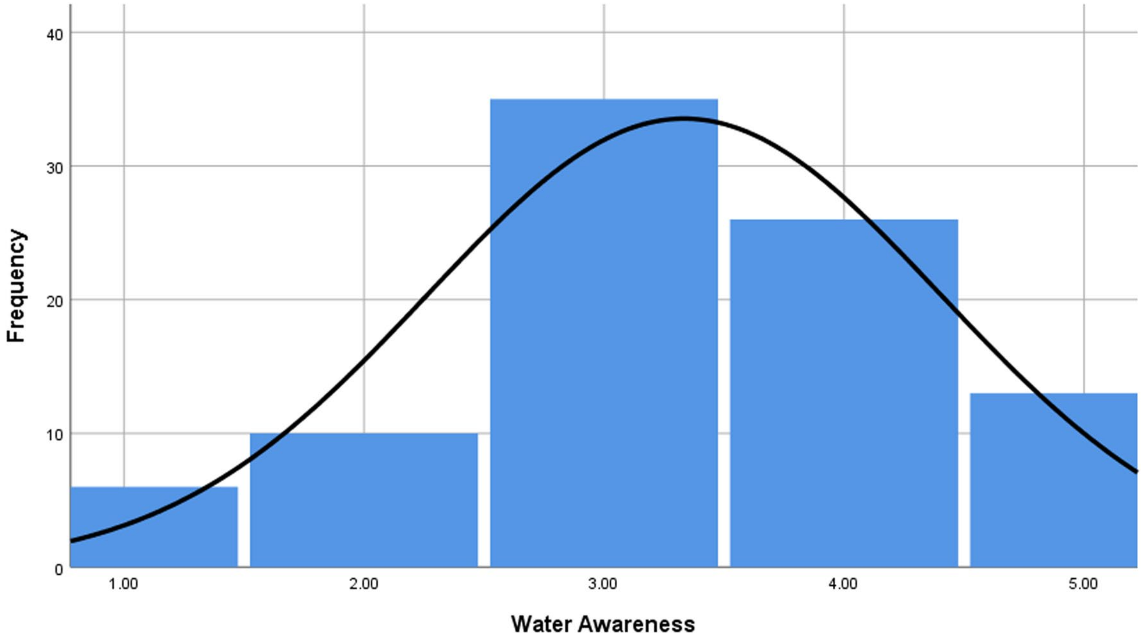


Fig. 3 Frequency chart for the combined variable of water awareness (WA)

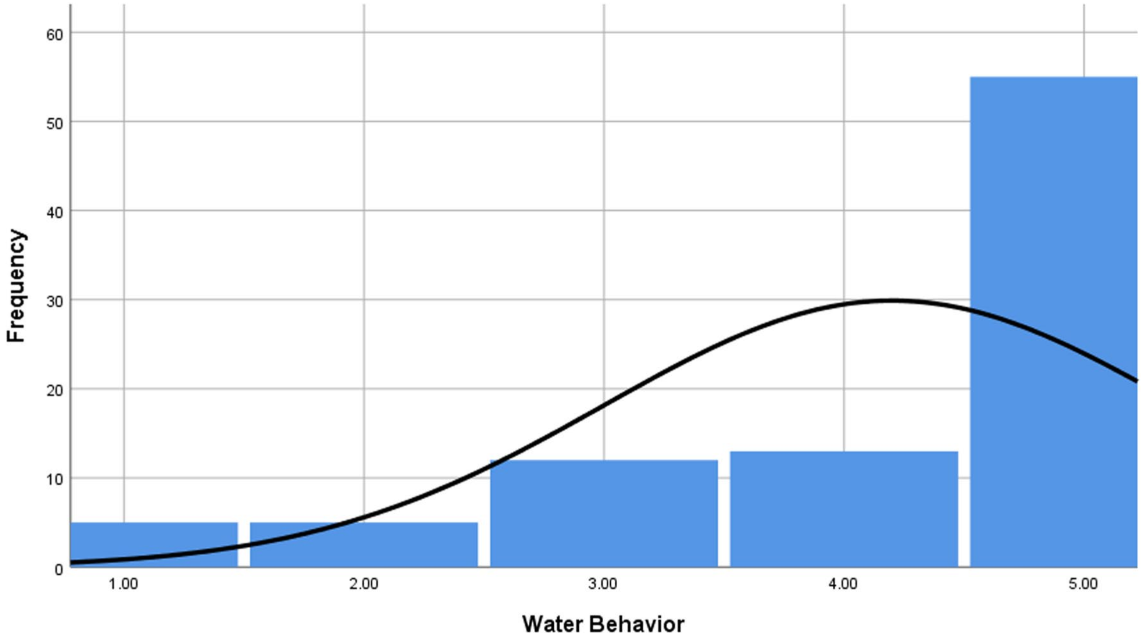


Fig. 4 Frequency chart for the combined variable of water behavior (WB)

The output of the inference process is a fuzzy set or linguistic term representing the overall impact or degree of influence of the input variables on the water-saving index. To obtain a crisp output or a numerical value for the water-saving index, a defuzzification process is typically applied. Defuzzification methods, such as centroid or max membership, are utilized to convert the fuzzy set into a crisp value that can be interpreted and compared. The methodology used in this work can be summarized in Fig. 9.

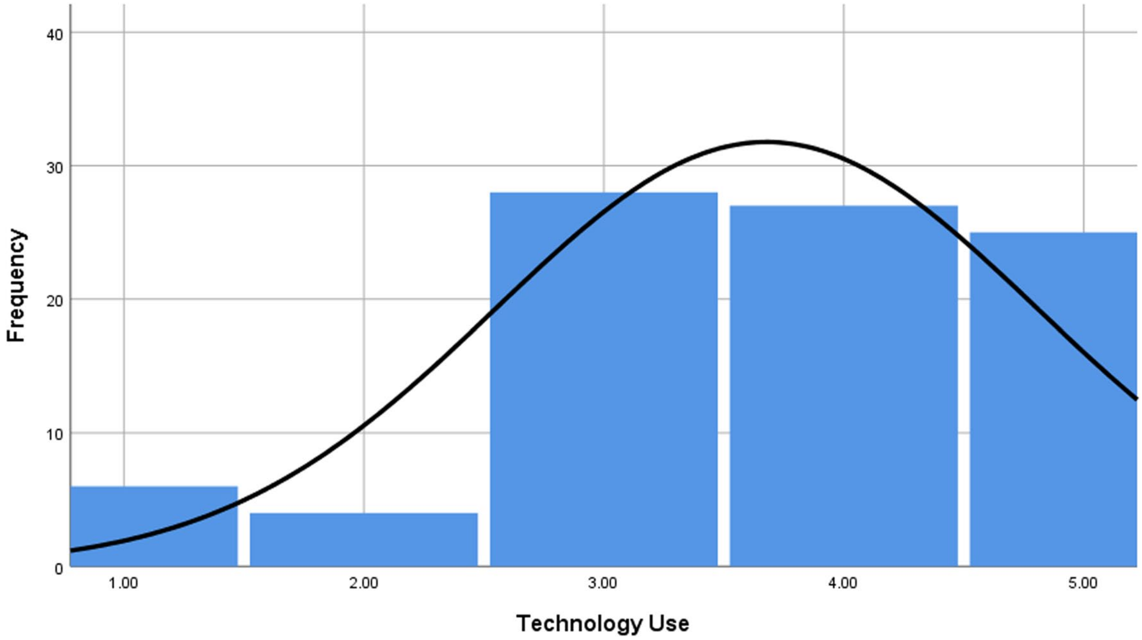


Fig. 5 Frequency chart for the combined variable of technology use (TU)

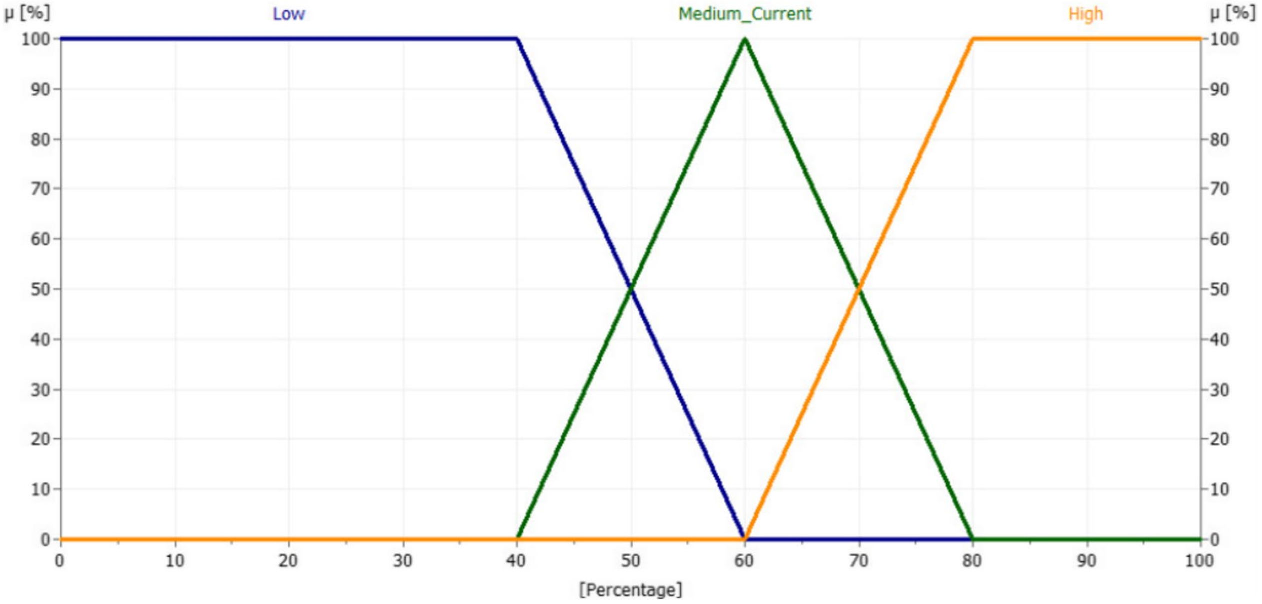


Fig. 6 Level of water awareness (WA) membership function—input

Results

In this section, we present the findings derived from our analysis focusing on the correlation between water tariffs, water awareness, water behavior, and technology use. These findings are elucidated through a series of figures illustrating how different variables influence the water-saving index (WSI).

Figure 10 showcases the WSI in relation to water tariffs and water awareness across various levels of water behavior and technology use. It is evident from the figure that as both water behavior and technology use percentages increase, there is a corresponding rise in the WSI.

Figure 11 zooms into the relationship between the water-saving index (WSI) and water tariffs, with an

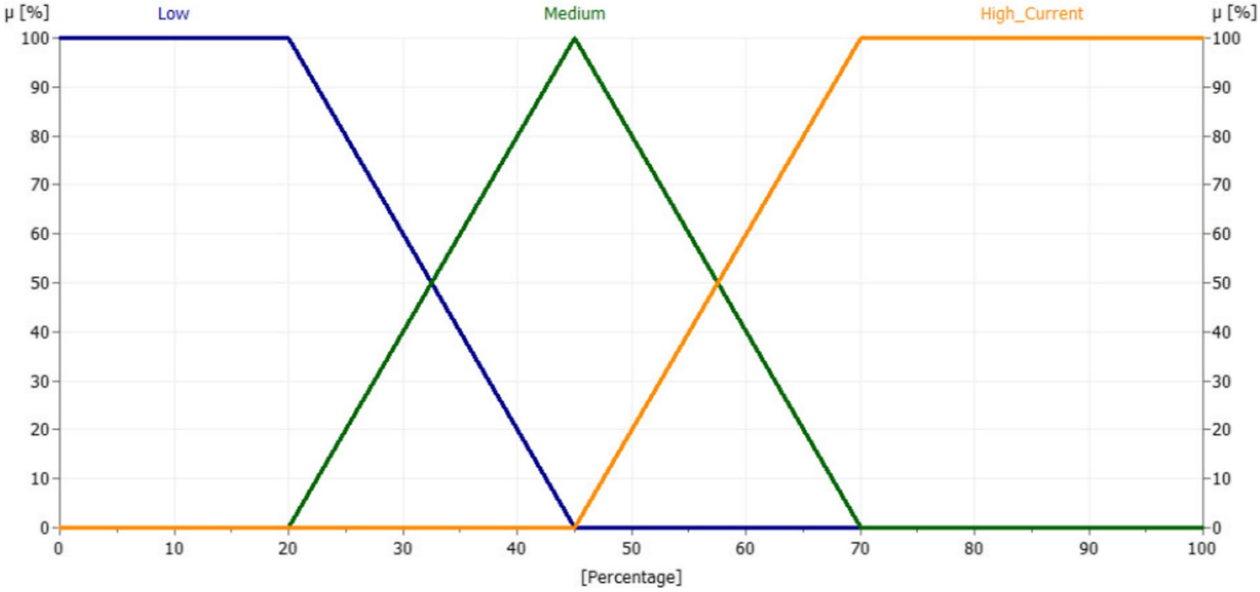


Fig. 7 Level of technology use (TU) membership function—input

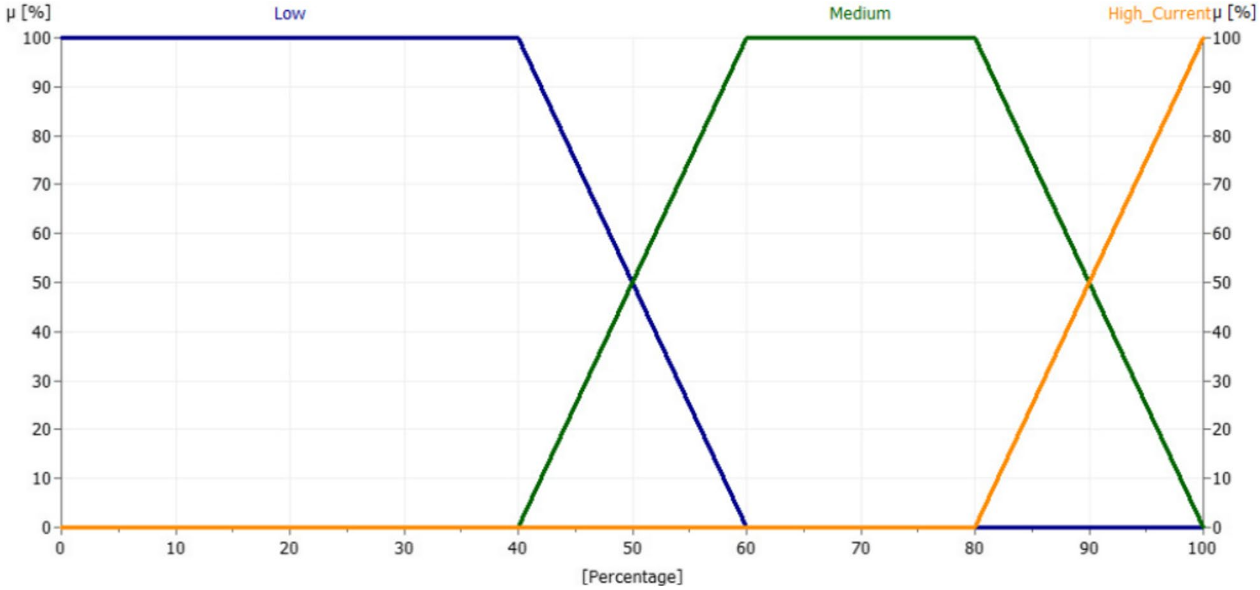


Fig. 8 Level of water behavior (WB) membership function—input

emphasis on varying water awareness levels. This figure offers insights into how water awareness plays a role in the determination of the WSI in the context of changing water tariffs.

Lastly, Fig. 12 highlights the water-saving index (WSI) as a function of water tariffs, but this time focusing on the influence of different water behavior levels. This allows for a nuanced understanding of the role of consumer behavior in impacting water savings amidst fluctuating tariffs.

Further interpretation and discussions on these results will be provided in the subsequent sections.

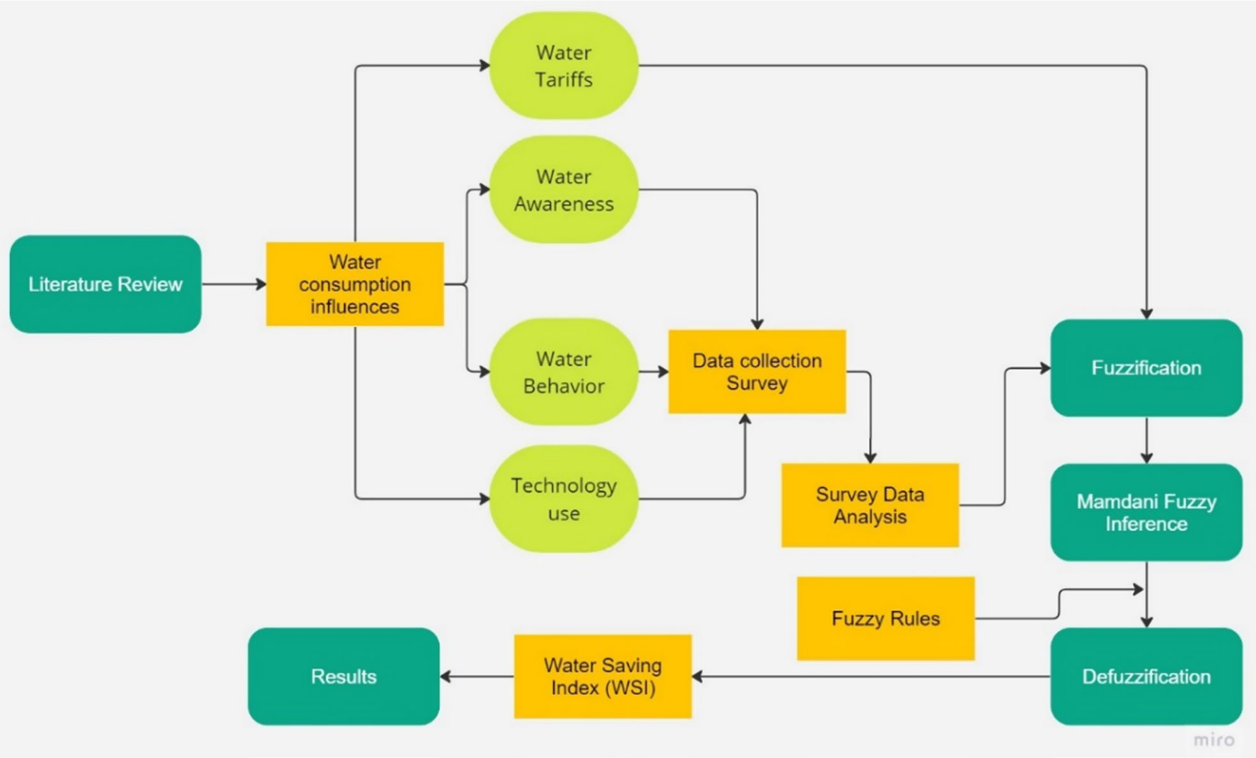


Fig. 9 A flowchart of the methodology used in this work

Discussion

Figure 10 shows the contours of the water-saving index (WSI) with respect to water tariffs and the level of water awareness, considering varying degrees of water behavior and technology utilization (low, medium, and high). For instances characterized by low levels of water behavior (30%) and technology use (30%), the WSI contours exhibit a minimum attainable level of 3.0. This finding implies that no significant reduction in water consumption can be achieved under these circumstances. Moreover, it suggests that further improvements in water behavior and technology utilization are necessary to enhance water conservation efforts as the current levels fall short of achieving notable efficiency in water usage, highlighting the need for additional measures and/or approaches to promote more effective water-saving strategies.

Furthermore, as the levels of water behavior and technology use increase to 50% (medium subset), there is minimal variation in the WSI, which consistently maintains a value greater than 2.7 across different water tariffs and water awareness levels. Conversely, at high levels of water behavior and technology use (90%), a notable and substantial decrease in the WSI is observed. Notably, the WSI can approach a value of approximately 1.3 when the water tariffs reach $3 per cubic meter, coupled with a water awareness level surpassing 80%. Beyond this threshold, any further increase in water tariffs no longer influences the WSI value significantly. This indicates that other factors may play a more prominent role in influencing water consumption patterns in these situations. Moreover, water tariffs demonstrate their effectiveness in reducing water consumption within a certain range. Nevertheless, beyond this range, the impact of increasing water tariffs on reducing water usage seems to diminish.

The analysis of the contours presented in these figures reveals significant implications for various aspects of water resource management. These findings offer valuable insights for policymakers in formulating effective policies and regulations aimed at promoting water conservation. Additionally, the WSI contours provide a basis for setting targets and goals, enabling the monitoring and evaluation of implemented measures. Moreover, the visual representation of the contours contributes to public awareness and education, empowering individuals to make informed decisions and actively participate in water conservation efforts. A compelling case study highlighting the practical implications of the WSI contours can be observed in a water-stressed city implementing a comprehensive water conservation program. By carefully analyzing the contours, policymakers gain valuable insights into effective strategies for reducing water consumption.

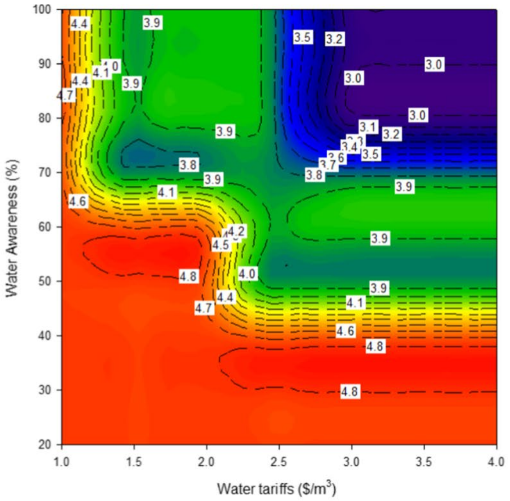
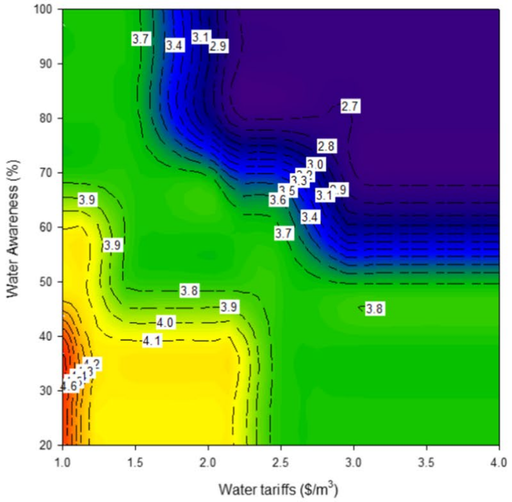
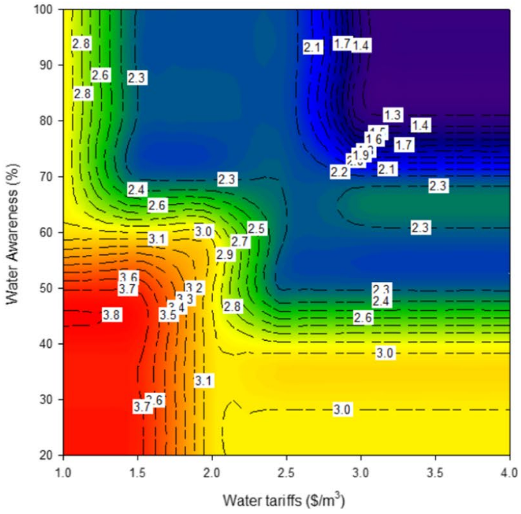
Water Behavior (%)	Technology Use (%)	Water Saving Index (WSI)
30	30	
50	50	
90	90	

Fig. 10 WSI as a function of water tariffs and water awareness for various levels of water behavior and technology use

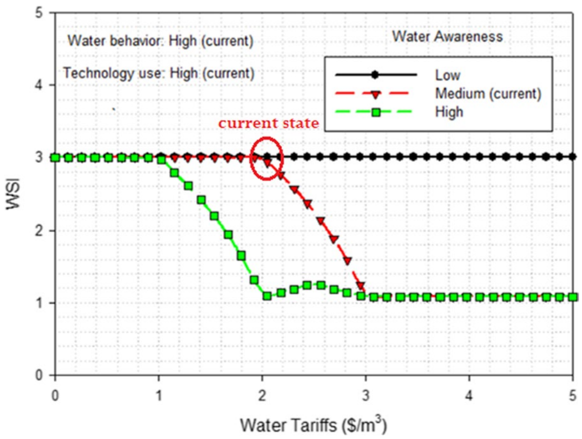


Fig. 11 Water-saving index (WSI) as a function of water tariffs for different water awareness levels

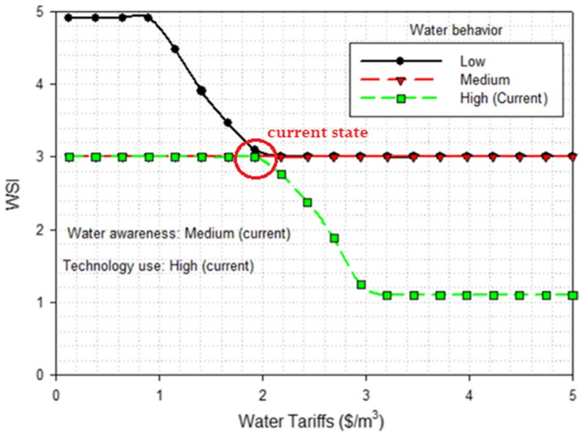


Fig. 12 Water-saving index (WSI) as a function of water tariffs for different water behavior levels

The findings suggest that a combination of higher water tariffs, heightened water awareness campaigns, and widespread adoption of advanced water-saving technologies can lead to substantial water savings. In response, the city's water authority sets ambitious targets, such as a 20% reduction in water usage within a five-year timeframe, and implements an array of educational initiatives to promote water-conscious behaviors and incentivize the adoption of efficient technologies. Concurrently, they adjust water tariffs to reflect the true cost of water and encourage conservation. By regularly monitoring the water-saving index (WSI) indicated by the contours, the water authority observes a progressive decline in the WSI as residents embrace water-saving practices. This decline signifies tangible and significant reductions in water consumption throughout the city. This case study serves as a tangible demonstration of how the insights derived from these contours inform evidence-based policymaking, facilitate goal setting, and drive successful water conservation outcomes in real-world scenarios.

In relation to the prevailing conditions in Abu Dhabi Emirate, Fig. 11 illustrates the water-saving index as a function of water tariffs ($/cubic meter) for high levels of technology use and water behavior, along with three different levels of water awareness: low, medium, and high. The circle on the graph represents the current state, with water tariffs set at $2/cubic meter and a corresponding water-saving index of 3. The selection of the levels for technology use and water behavior was based on the survey results and the designed membership functions, aiming to represent the current values among Abu Dhabi residents. It is observed that for a low level of water awareness, the water-saving index remains constant at a value of 3, regardless of the variations in the other variables. This finding suggests that all variables including water tariffs, level of water behavior, and technology use have limited influence on the water-saving index when the level of awareness is low.

Furthermore, the graph reveals two potential scenarios for reducing the water-saving index in Abu Dhabi Emirate. The first scenario involves increasing the water tariffs within the range from $2/cubic meter to $3/cubic meter while maintaining the existing levels of water awareness, water behavior, and technology use. In this scenario, the graph demonstrates a decrease in the water-saving index from 3 to almost 1. However, beyond this threshold ($3/cubic meter), further increases in water tariffs have no measurable impact on reducing the water-saving index. This implies that increasing the water tariffs may have diminishing returns in terms of promoting water conservation. In other words, the additional benefits gained from higher water tariffs in terms of promoting water conservation become progressively smaller. This finding underscores the importance of considering alternative strategies, such as enhancing water awareness, water behavior, and technology use, to complement and maximize the effectiveness of water conservation initiatives, rather than relying solely on increasing water tariffs.

Alternatively, the second scenario entails enhancing the level of water awareness while maintaining the current state of water tariffs, water behavior, and technology use. The graph clearly illustrates that an increase in water awareness results in a significant reduction in the water-saving index. This finding underscores the critical role of awareness-raising initiatives, education campaigns, and public outreach programs in promoting sustainable water consumption practices. By increasing individuals' understanding of the importance of water conservation and encouraging mindful water usage, substantial improvements in the water-saving index can be achieved. These findings highlight the need for targeted interventions and effective communication strategies to enhance water awareness among residents of the Abu Dhabi Emirate's residential sector. Moreover, it is noteworthy that this scenario of enhancing water awareness proves to be beneficial even at lower water tariffs as the graph reveals that the reduction in the water-saving index starts at lower water tariff levels than the current rate of $2/cubic meter. This observation suggests that improving water awareness can yield positive outcomes in terms of water conservation efforts, regardless of the specific tariff structure in place.

Figure 12 illustrates the water-saving index in relation to water tariffs ($/cubic meter) for high level of technology use, medium level of water awareness, and three different levels of water behavior: low, medium, and high. These specific levels of technology use and water awareness were selected to align with the current values reported by Abu Dhabi residents, as determined through the survey and membership functions. The circle on the graph represents the current state, characterized by water tariffs of $2/cubic meter and a corresponding water-saving index of 3. It is again noticed that increasing the water tariffs above the threshold of $3/cubic meter exhibits diminishing effects on the water-saving index. This finding suggests that further elevating the water tariffs beyond this point has a limited impact on promoting water conservation. Furthermore, the graph underscores the significance of water behavior in influencing the water-saving index. Reducing the level of water behavior has a substantial effect on increasing the water-saving index, resulting in a value of 5 in the worst-case scenario. This highlights the importance of promoting responsible water behavior and encouraging individuals to adopt water-saving practices in order to achieve significant improvements in water conservation outcomes. Additionally, for the case of medium water behavior, the graph reveals a constant line with a water-saving index of 3. This indicates that, within this specific range of water behavior, the other variables, such as water tariffs and the level of water awareness, have no discernible effect on the water-saving index.

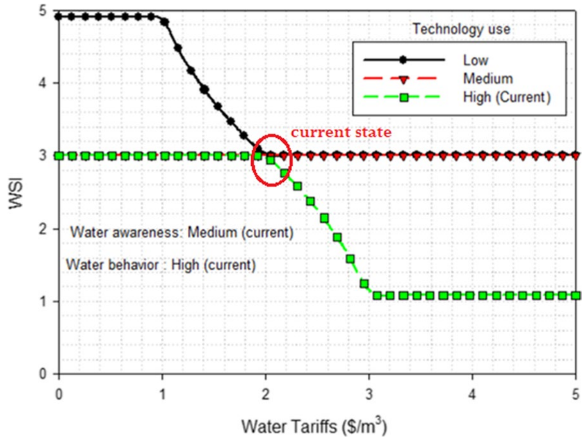


Fig. 13 Water-saving index (WSI) as a function of water tariffs for different technology use levels

Figure 13 shows the relationship between water tariffs ($/cubic meter) and the water-saving index for high level of water behavior, medium level of water awareness, and three different levels of technology use: low, medium, and high. The chosen levels of water awareness and water behavior reflect the current values reported by residents in Abu Dhabi, as determined through the survey and membership functions. The circle on the graph represents the current state, characterized by water tariffs of $2/cubic meter and a water-saving index of 3. Consistent with the previous findings, the graph highlights that increasing water tariffs beyond the threshold of $3/cubic meter results in diminishing effects on the water-saving index. This suggests that the impact of raising water tariffs on promoting water conservation diminishes beyond this point. Furthermore, the graph emphasizes the significance of technology use in shaping the water-saving index. Lowering the level of technology use demonstrates a notable effect, leading to an increase in the water-saving index up to a value of 5 in the worst-case scenario. This finding underscores the importance of considering technological advancements and innovative solutions as effective means to promote water conservation. Additionally, for the case of medium technology use, the graph reveals a constant line with a water-saving index of 3. This indicates that within this specific range of technology use, the other variables, such as water tariffs and the level of water awareness, have no measurable effect on the water-saving index. These observations provide valuable insights for policymakers and stakeholders in designing effective water conservation strategies.

Conclusions

This study assessed the impact of water tariffs on water consumption in the residential sector of Abu Dhabi Emirate using a fuzzy logic model. The analysis focused on four key factors: water tariffs, level of water awareness, level of water behavior, and level of technology use. The output of the model is the water-saving index, defined as the ratio of daily water consumption per capita in Abu Dhabi to the global average. The results highlighted the importance of considering the interplay between water tariffs and other influencing factors and provide valuable insights into the factors influencing water conservation in the residential sector of Abu Dhabi Emirate. The findings indicate that increasing water tariffs may have diminishing returns in terms of promoting water conservation, especially beyond a threshold of $3/cubic meter. This implies that alternative strategies, such as enhancing water behavior, raising water awareness, and promoting the use of water-saving technologies, should be considered in conjunction with water tariffs to achieve significant reductions in water consumption. Moreover, the survey findings emphasized the favorable position of Abu Dhabi residents regarding water behavior and technology use. The high levels of water behavior and technology adoption demonstrated a positive trend toward sustainable water consumption practices. This presents an encouraging starting point for implementing effective water conservation measures, and leveraging these strengths can contribute to further reductions in water consumption and enhance the water-saving index.

Moreover, the outcomes of this study provide valuable insights for policymakers, water management authorities, and stakeholders in the residential sector of the Abu Dhabi Emirate. This study revealed that a comprehensive approach encompassing multiple factors is essential for effective water conservation strategies. Merely increasing water tariffs may not yield significant improvements unless accompanied by efforts to raise water awareness, promote sustainable water behavior, and enhance the adoption of water-saving technologies. Hence, in designing an effective water tariffs structure, it is essential to consider not only the economic aspects but also the broader context of other water-saving influences. Failing to take these factors into account could undermine the potential benefits of the tariff increase in reducing water consumption. A well-crafted water tariff system should be sensitive to regional variations in climate, socioeconomic conditions, and access to alternative water sources. It should also align with public awareness campaigns promoting water conservation and complement existing regulations and policies aimed at sustainable water management. Consequently, water tariffs can be calibrated within an optimal range that encourages responsible water usage without placing undue burdens on vulnerable communities or jeopardizing essential water needs for domestic use.

The findings of this study hold significant implications beyond the specific context of Abu Dhabi, offering valuable guidance for addressing water conservation challenges on a global scale. The generated WSI contours underscore the importance of promoting sustainable water management practices through behavioral changes, technological advancements, and appropriate tariff structures to achieve significant water conservation outcomes. Moreover, the results stressed the importance of a multi-faceted approach, encompassing various factors that influence water consumption, highlighting the need to move beyond a singular focus on increasing water tariffs, and consider a broader range of strategies for promoting sustainable water management practices worldwide. The study emphasizes the critical role of raising water awareness among individuals through effective awareness campaigns and education programs, tailored to specific cultural, social, and economic contexts. These initiatives, which resonate with local communities, are universally relevant in addressing water conservation challenges. Moreover, the study underscores the significance of water behavior and technology use in achieving meaningful water savings. Encouraging the adoption of water-saving practices, such as responsible water behavior and the utilization of water-efficient technologies, has cross-cutting relevance and can contribute to reducing water consumption across diverse settings.

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Author contributions
IMA conceived the study, developed the methodology, performed the data analysis, and supervised the project and significantly contributed to writing and editing the manuscript. OAH, as an undergraduate student, assisted in data collection, and conducted preliminary data analysis and contributed to writing the methodology section. AS, as an undergraduate student, aided in data collection and performed preliminary data analysis and contributed to writing the methodology section. HS, as an undergraduate student, assisted in data collection and performed initial data analysis and contributed to writing the results section. HB, as an undergraduate student, aided in data collection and conducted initial data analysis and contributed to writing the results section. SN provided expertise in fuzzy logic modeling, assisted with data analysis, and reviewed and edited the manuscript and contributed to the discussion section with his knowledge on water conservation. DREE guided the project, assisted in shaping the research objectives, contributed to the writing and editing of the manuscript, and managed communication with the journal and also helped in interpreting the data and discussing the results. All authors gave final approval of the version to be published and agreed to be accountable for all aspects of the work, ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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