

Article

A Regional-Demographic Assessment of Ultra-Low Flow Ablution Tap Technology for Water Conservation and Carbon Footprint Reduction in Saudi Arabia

Hafiz Abdul Wajid ^{1,*}  and Muhammad Abid ^{2,3} 

¹ Department of Electrical Engineering, Faculty of Engineering, Islamic University of Madinah, Madinah 42351, Saudi Arabia

² Department of Mechanical Engineering, Faculty of Engineering, Islamic University of Madinah, Madinah 42351, Saudi Arabia; mabid@iu.edu.sa or drabid@ciitwah.edu.pk

³ Department of Mechanical Engineering, COMSATS University Islamabad, Wah Campus, GT Road, Wah Cantt 47040, Pakistan

* Correspondence: hawajid@iu.edu.sa

Abstract

Saudi Arabia is a water-stressed nation and meets much of its daily demand through desalination, an energy-intensive process with a significant carbon footprint. As a Muslim-majority country, residents perform ablution before five daily prayers, making this activity a substantial yet under-quantified component of residential water use. This study focuses on household-level ablution water savings across 13 regions for both Saudi and non-Saudi households by replacing standard taps with a flow rate of 5.7 L/min with a proposed Saudi Standards, Metrology and Quality Organization (SASO)-compliant ultra-low-flow tap (1.9 L/min). Moreover, this study evaluates this ultra-low-flow tap as an environmental technology capable of reducing ablution water consumption and found that per capita savings are identical for both demographic segments, but the total household savings differ because Saudi households are larger, supporting sustainable water management. Results show that under the stated assumptions, full national adoption of the proposed tap would reduce monthly ablution water use from 27 million m³ to 9 million m³, conserving 212.14 million m³ annually with 67% efficiency and offsetting 702,198 tonnes of desalination-related carbon emissions. This highlights the effectiveness of deploying a simple water-saving technology in a water-stressed environment. Conservation potential is concentrated in Riyadh, Makkah, and the Eastern Province due to their high household counts. A four-year phased implementation roadmap is proposed, beginning with 25% adoption in year one (53.01 million m³ annual savings), expanding to moderate-impact regions in year two, and reaching 75–100% adoption nationwide by years three and four. The findings demonstrate how simple and commercially available water-efficient technology can contribute to sustainable resource management by simultaneously reducing water demand, energy consumption associated with desalination, and related greenhouse gas emissions. This study supports Saudi Arabia's Vision 2030 water strategy and can potentially support UN-SDGs 6, 7, and 13 by demonstrating the substantial water, carbon, and economic benefits of a simple, commercially available tap of 400 SAR. In addition, the study develops a regionally prioritized technology deployment framework that can support decision makers in planning large-scale implementation. The analysis assumes that household members perform ablution five times daily for approximately one minute, based on field measurements, and they require validation of projected gains through actual implementation.



Academic Editor: Christos A. Aggelopoulos

Received: 10 June 2026

Revised: 15 July 2026

Accepted: 17 July 2026

Published: 21 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and

conditions of the [Creative Commons](https://creativecommons.org/licenses/by/4.0/)

[Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: low-flow rate taps/faucets; carbon emission reductions; regional water modeling; phased implementation strategy; Saudi Vision 2030; sustainable water infrastructure

1. Introduction

As a country with no permanent rivers, limited rainfall, and limited renewable groundwater, Saudi Arabia faces a severe water shortage. This situation is considered unsafe for long-term water security, as, on average, each person has access to only 89.5 m³ of renewable water per year [1]. In addition, climate change, rising temperatures, over-extracted water from aquifers, rapid population growth, expanding cities, and intensive agricultural activity have placed heavy pressure on existing limited resources [2,3]. With scarce natural water, Saudi Arabia relies heavily on desalination and produces more than 6.6 million m³ accounting for 22% of global production of desalinated water every day [1]. Desalination is regarded as one of the highest-emission utilities as it is energy-intensive and generates significant emissions; each cubic meter of desalinated water roughly produces 5.06 kg of CO₂ [4].

To address these issues, major reforms were introduced in the Saudi Vision 2030. The implementation of these reforms has resulted in reduced water use per capita from 232 L/day to 187 L/day, increased wastewater reuse from 21% to 55%, increased renewable energy use in water utilities from 3% to 35%, with an overall reduction in sector emissions by 28% [5]. However, with rapid population growth and expansion in cities, national models warn that water shortages could increase by 45% by 2030 if demand continues to rise [6]. These pressures highlight the need for effective technological solutions to be planned and implemented first at domestic and later at commercial levels, where a large amount of water is consumed daily [7,8]. In this context, water sustainable technologies, such as efficient water taps that reduce water consumption without compromising user requirements, are increasingly recognized as important tools for achieving long-term water and environmental security.

In Saudi Arabia, being a 100% Muslim country, water is frequently used in ablution (wudu) in homes, mosques, and offices. Ablution is performed at least five times a day, and, on average, a single ablution with modern taps uses 4–8 L of water [9–12]. In addition, 30–47% of water is observed to be wasted because taps are left running between washing steps. Similar patterns of using six to eight times more water than needed for a valid ablution are observed in Oman, Australia, and Malaysia ([10,11]. Studies have shown that in Saudi Arabia, a small fraction of the community follows water-saving practices at home using water-saving tools due to current awareness; however, most communities need to gain awareness to adopt such practices for water conservation during ablution [13]. This suggests that behavioral and cultural factors play an important role in determining actual water use during ablution [14,15].

In addition to technological improvements, behavioral awareness and complementary water management strategies can further enhance water conservation during ablution. Studies have shown that users' knowledge, attitudes, and religious values strongly influence water consumption behavior, while awareness campaigns and faith-based reminders encourage more responsible water use [11,14–16]. Islamic teachings also emphasize moderation and discourage excessive water use, even when water is abundantly available [17]. Another complementary approach is the reuse of ablution greywater, which, because of its relatively good quality, can be treated using simple and low-cost technologies for applications such as irrigation, toilet flushing, and cleaning ([18–21].

Keeping the importance of ablution in daily practice with a large water footprint in mind, there is a need for water conservation using suitable technological solutions. Water waste reduction of 12% and 97% is observed using automatic sensor-based taps and purpose-built fixtures for comfort and controlled mist spray, respectively, without affecting ritual validity [22]. Considering renewable energy use for water pumping, solar-powered ablution systems offer sustainable options, reducing water use by more than 50% [23]. Earlier work focused mainly on water-efficient aerators, which demonstrated strong potential but were limited by installation variability and user handling, whereas the present study provides more stable flow control and easier standardization across households by proposing full faucet replacement with low-cost electronic systems, such as Arduino-based automatic faucets. The implementation of such faucets has shown promising results, reducing water use by 44% in small mosques [24]. These studies collectively demonstrate that water conservation can be enhanced through technological interventions. However, evidence regarding the large-scale deployment potential and national-level impact of such technologies remains limited.

In this section, previous studies are categorized into three scales covering the national, regional, and facility levels. First, considering a nationwide scale, Abdella et al. [1] quantified overall water scarcity indicators and reported 89.5 m³ annual per capita renewable water access. In another study by Almulhim and Abubakar [25] employed segmentation approaches to analyze household consumption patterns across demographic groups. They identified factors such as household size, income, and education influencing water use behavior significantly. More specifically, in the context of Saudi Arabia, Suhail et al. [8] highlighted the widening gap between supply and demand utilizing detailed historical analysis of water resources. However, none of these national-scale models specifically disaggregated ablution water use as a distinct consumption category. Second, considering the regional scale, Alzahrani and Tawfik [26] analyzed heterogeneity in urban water consumption patterns across all 13 administrative regions of Saudi Arabia. Similarly, Wajid [27] developed an activity-based mathematical modeling framework for household water consumption at the regional level. Neither of these studies focused on ablution-specific analysis. Third, at the facility level, several ablution-specific studies have been conducted, such as Zaied [9], who measured ablution water use in Saudi Arabia for a range of tap types. Al Alawi et al. [10] assessed ablution consumption in Omani mosques, whereas Hurayra et al. [11] studied an Australian mosque. More recently, Wajid and Eid Alluqmani [12] quantified household savings potential using ultra-low-flow rate water aerators. However, these studies are limited to small sample sizes and have not scaled their findings to both the regional and national levels. This review reveals a clear research gap as no study has integrated these three scales to quantify the nationwide impact of ablution water-saving across all regions and population segments. The present study addresses this gap by combining regional demographic data, activity-based consumption modeling, and nationwide deployment scenarios to provide a comprehensive assessment using an ultra-low flow rate tap as a technology deployment.

Recent studies indicate that improving end-user water-use efficiency remains one of the most cost-effective approaches for reducing urban water demand, complementing supply-side strategies such as desalination and wastewater reuse [28]. Consequently, household water-saving technologies are increasingly recognized as an important component of sustainable water management [29]. Accordingly, the present study evaluates an ultra-low-flow tap as a scalable technology and investigates its potential contribution to water conservation and carbon footprint. Also, this study focuses on household ablution performed by both males and females across all regions of Saudi Arabia, making it more

representative for evaluating the nationwide impact of water-saving technologies addressing the following three objectives:

1. To quantify household ablution (wudu) water usage across all 13 regions and population segments of Saudi Arabia with standard and proposed tap types.
2. To quantify nationwide water savings achievable by replacing the standard tap with the proposed one and calculate carbon emissions linked to the desalination of producing freshwater purely in a Saudi Arabian context.
3. To identify a regionally prioritized phased implementation strategy for large-scale technology deployment and enhanced economic and environmental benefits.

The remainder of the paper is organized as follows. Section 2 presents the methodology, followed by Section 3, which presents and discusses the results. Section 4 concludes with policy recommendations, followed by Section 5 addressing limitations of this study and future research directions.

2. Methodology

2.1. Study Framework

In this study, regional water savings and associated carbon emissions offset are quantified by replacing standard ablution taps with ultra-low flow rate tap alternatives across Saudi Arabian households. Also, a yearly phased, prioritized regional implementation is proposed for quick and enhanced impact. The methodology integrates four official Saudi Arabian data sources:

1. Regional household demographics from the General Authority for Statistics (GASTAT) [30].
2. Monthly regional household average water consumption data by smart meters from Saudi Water Authority (SWA) [31].
3. Specifications of a commercially available tap of ultra-low 1.9 L per minute flow rate by Saudi Standards, Metrology and Quality Organization (SASO) [32].
4. Carbon intensity factor derived from desalination technology mix specifically for Saudi Arabia from the Saline Water Conversion Corporation (SWCC) report [33].

The selected analytical framework follows the activity-based modeling approach established by Wajid [27] based on regional disaggregation across all 13 administrative regions to quantify heterogeneity in ablution water consumption patterns. A similar framework is also used in studies by Almulhim and Abubakar [25] and Alzahrani and Tawfik [26].

2.2. Data Collection

2.2.1. Household Demographic Data

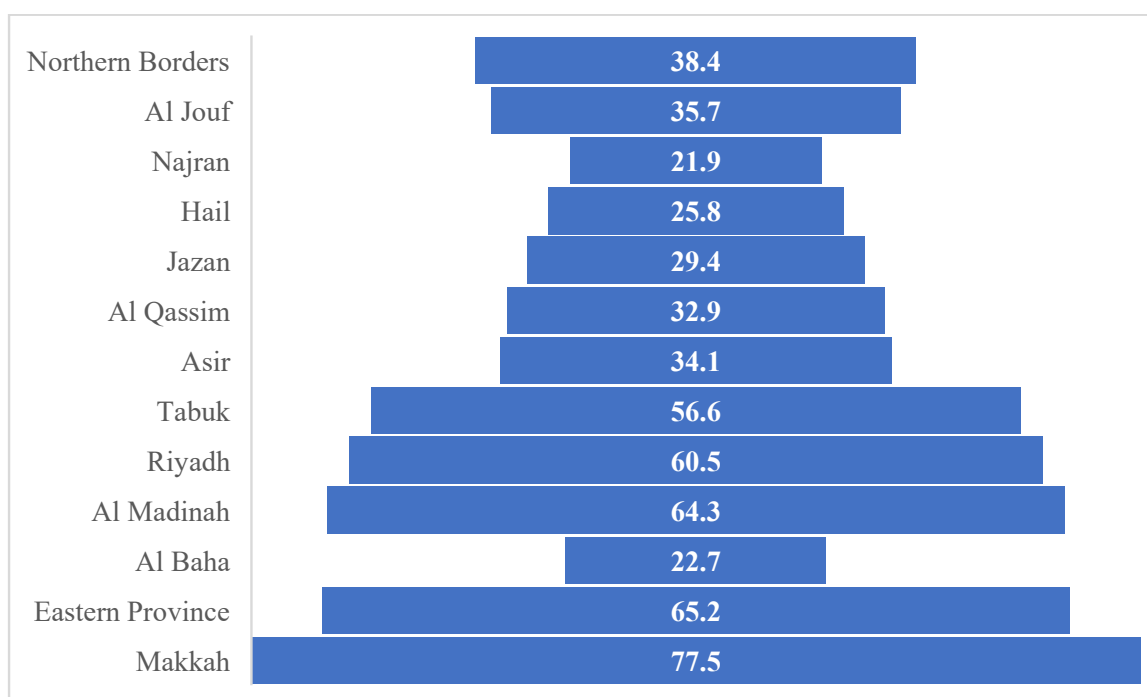
Household demographic data is obtained from the GSTAT [30] and is presented in Table 1 covering regional household count and average sizes for both the Saudi and non-Saudi population segments for all 13 regions. It is evident from Table 1 that disaggregation by household type is essential because household sizes differ significantly in both population segments. Saudi households have 4.5–5.8 members compared with 2.2–3.2 in non-Saudi households. This variation is a key factor for regional ablution water usage quantification and separate demographic segment analysis for strategic rollout, overall environmental impact, and water savings.

Table 1. Regional demographic distribution of households by size and count.

Saudi Arabian Regions	Saudi Household		Non-Saudi Household	
	Average Size	Households Count	Average Size	Households Count
Northern Borders	5.8	49,257	3.1	23,474
Al Jouf	5.7	80,069	2.5	44,961
Najran	5.4	78,162	2.9	53,318
Hail	5.2	105,794	2.2	72,182
Jazan	5	208,696	3.2	100,705
Al Qassim	5	192,468	2.6	120,779
Asir	5	303,684	2.5	175,286
Tabuk	5	130,689	2.5	76,564
Riyadh	4.8	996,166	2.6	1,277,031
Al Madinah	4.8	298,443	2.9	220,240
Al Baha	4.7	55,923	2.6	26,702
Eastern Province	4.7	662,741	2.4	687,028
Makkah	4.5	991,405	2.8	1,142,907

2.2.2. Regional Water Consumption Data

A novel contribution of this study is the use of actual monthly regional household water consumption data in cubic meters obtained from the Saudi Water Authority live dashboard [31] (Saudi Water Authority, n.d.) for the current year, 2026. This data is publicly available through the Saudi Water Authority dashboard <https://www.swa.gov.sa/en/Key-Residential-Water> (accessed on 1 April 2026), reported by smart water meters deployed across Saudi Arabia [34]. Moreover, the monthly regional average household water usage data is shown in Figure 1.

**Figure 1.** Monthly regional average household water usage reported by smart meters.

2.2.3. Ablution Tap Specifications

Tap with ultra-low flow rate of 1.9 L per minute (L/min) is selected as per the guidelines of SASO [32] and local commercial availability in Saudi Arabia for 400 SAR, including shipping by brand Peerless with the model number P1512LF-M-0.5 (manufactured by Delta Faucet Company, Indianapolis, IN, USA) [35]. It offers a certified water efficiency flow rate and has been rigorously tested in a laboratory under varying pressure conditions, earning SASO [32] and EPA WaterSense, USA [36] certifications. Moreover, locally approved and certified countrywide commercially available products ensure immediate and easy replacement. This is highly important as per the nature of this study, which aligns with life-cycle assessment approaches in water conservation research presented by Kalbusch and Ghisi [37].

2.3. Ablution Water Consumption Formulation

Monthly ablution water consumption per household and regional total are calculated using the following formulae:

$$WC_{HH}^{monthly} = 30.42 \times Q \times t \times f \times S_{HH}$$

$$WC_{regional\ total}^{monthly} = WC_{HH}^{monthly} \times N_{HH,region}$$

where

Q = Tap flow rate in liters per minute (L/min).

t = Ablution duration in minutes.

f = Daily ablution frequency.

S_{HH} = Per person average household size.

$N_{HH,region}$ = Regional household count.

The corresponding monthly household and regional ablution water savings are calculated using the formulae given below:

$$\Delta WS_{HH}^{monthly} = WC_{HH,standard}^{monthly} - WC_{HH,proposed}^{monthly}$$

$$\Delta WS_{regional}^{monthly} = WC_{regional\ total,standard}^{monthly} - WC_{regional\ total,proposed}^{monthly}$$

Moreover, the justification of the parameters used in the above mathematical formulations is summarized in Table 2.

Table 2. Key parameters and justifications.

Parameter	Value	Justification	References
Tap flow rate	5.7 L/min	Empirical observations are common in the Saudi market	Zaied [9], Wajid and Eid Alluqmani [12] and Memon et al. [38]
	1.9 L/min	SASO certified; EPA WaterSense; 67% efficient	SASO [32], EPA WaterSense [36], Kalbusch and Ghisi [37] and Englart and Jedlikowski [39]
Ablution duration	1 min	Empirical average of 1.04 min from field studies	Zaied [9], Wajid and Eid Alluqmani [12], Fidar et al. [40] and Khan [41]
Ablution frequency	5 times per day per person	Five mandatory daily prayers	Zaied [9], Al Alawi et al. [10], Hurayra et al. [11] and Raduan et al. [17]

The 5.7 L/min flow rate tap represents baseline water usage, and this tap is termed the standard tap in this study. Some households may even use higher flow rates, such as

8.2 L/min. However, the 67% proportional saving remains constant, allowing linear scaling to alternative baselines. The 1.9 L/min ultra-low flow rate tap is termed the proposed tap and is chosen to maintain adequate pressure for proper ablution completion while achieving the targeted 67% water savings. Hassan and Abdul Hamid [22] demonstrated that even mist-spray devices with 97% reduction maintain user comfort and ritual validity.

Moreover, per capita ablution water consumption is defined as the amount of water used by one person per ablution and is calculated as $(Q \times t \times f)$. Per capita value is the same for both Saudi and non-Saudi segments, contrary to total household consumption, which is different because household sizes differ for both segments. Saudi households are larger and therefore consume more water per household. We focus on household-level consumption and savings because water tap replacement is implemented at the household level.

2.4. Regional and Nationwide Carbon Emission Offset Calculation

Saudi Arabia relies heavily on energy-intensive seawater desalination, generating approximately 11.5 million m³/day of fresh water ([33], page-7) with a significant associated carbon footprint. The commitment of Saudi Arabia in mitigating this negative impact is highlighted in a study by Hamieh et al. [4], where it is presented that the average apparent emission factor improved from 21.4 kg CO₂/m³ in 2016 to 15.2 kg CO₂/m³ in 2019 (SWCC, 2023, page-58). As reported in [33] (page-59), the average emission factor for thermal desalination plants, multi-stage flash (MSF) and multi-effect distillation (MED) is 11.17 kg CO₂/m³, whereas reverse osmosis (RO) plants achieve a lower emission factor of just 1.7 kg CO₂/m³. Also, SWCC aims to increase the share of RO capacity from 22% in 2019 to 83% by 2026, while reducing thermal capacity to 17% ([33], page-68). Using this target technology mix and current best-practice emission factors, the weighted average carbon intensity is calculated as:

$$CI_{avg} = (0.83 \times 1.7) + (0.17 \times 11.17) = 1.411 + 1.899 = 3.31 \text{ kg CO}_2/\text{m}^3.$$

This value is consistent with the literature range of 2.1–3.6 kg CO₂/m³ reported for RO desalination [42,43]. Hence, the monthly regional CO₂ savings are calculated in million kg CO₂ using the following formula:

$$\Delta\text{CO}_2^{\text{monthly, regional}} = \Delta\text{WS}_{\text{regional}}^{\text{monthly}} \times CI_{avg}.$$

The countrywide carbon emissions offset is calculated by summing regional savings.

2.5. Sensitivity Analysis Framework

Sensitivity analysis against key parameters such as ablution duration and adherence frequency, tap flow rate, etc., is conducted in Section 3.5.

3. Results and Discussions

In this section, we present and discuss the regional and nationwide environmental and economic impact of proposed taps, along with an effective implementation roadmap.

3.1. Per-Household Ablution Water Consumption

We now present and discuss key insights from Table 3 in detail. With the standard tap, Saudi households consume between 3.90 and 5.03 m³ monthly, while non-Saudi households consume between 1.91 and 2.77 m³. This variation mainly reflects household size. Northern Borders has the largest Saudi households, with an average of 5.8 members, and therefore shows the highest consumption. In contrast, Makkah has the smallest Saudi households, with an average of 4.5 members, and shows the lowest consumption. Na-

tionwide, the average Saudi household uses 4.37 m³ of water monthly for ablution, compared to 2.32 m³ for non-Saudi households. Also, it is evident from Table 3 that the proposed tap adoption across regions will reduce ablution water usage by 67%. More specifically, regional monthly Saudi and non-Saudi household ablution water use ranges between 1.30 and 1.68 m³ and between 0.64 and 0.92 m³, respectively. Similarly, corresponding water savings range from 2.60 m³ in Makkah to 3.35 m³ in the Northern Borders for Saudi households, and from 1.27 m³ in Hail to 1.85 m³ in Jazan for non-Saudi households. Saudi households show consistently higher total savings across regions compared with non-Saudi households. This is due to their higher average household size.

Table 3. Monthly regional household ablution water usage and savings by demographic segment.

Saudi Arabian Regions	Standard Tap (Flow Rate 5.7 L/min)			Proposed Tap (Flow Rate 1.9 L/min)			Water Savings		
	Saudi	Non-Saudi	Total	Saudi	Non-Saudi	Total	Saudi	Non-Saudi	Total
Northern Borders	5.03	2.69	7.72	1.68	0.90	2.57	3.35	1.79	5.14
Al Jouf	4.94	2.17	7.11	1.65	0.72	2.37	3.29	1.44	4.74
Najran	4.68	2.51	7.20	1.56	0.84	2.40	3.12	1.68	4.80
Hail	4.51	1.91	6.42	1.50	0.64	2.14	3.01	1.27	4.28
Jazan	4.33	2.77	7.11	1.44	0.92	2.37	2.89	1.85	4.74
Al Qassim	4.33	2.25	6.59	1.44	0.75	2.20	2.89	1.50	4.39
Asir	4.33	2.17	6.50	1.44	0.72	2.17	2.89	1.44	4.33
Tabuk	4.33	2.17	6.50	1.44	0.72	2.17	2.89	1.44	4.33
Riyadh	4.16	2.25	6.42	1.39	0.75	2.14	2.77	1.50	4.28
Al Madinah	4.16	2.51	6.68	1.39	0.84	2.23	2.77	1.68	4.45
Al Baha	4.07	2.25	6.33	1.36	0.75	2.11	2.72	1.50	4.22
Eastern Province	4.07	2.08	6.16	1.36	0.69	2.05	2.72	1.39	4.10
Makkah	3.90	2.43	6.33	1.30	0.81	2.11	2.60	1.62	4.22
National Average	4.37	2.32	6.70	1.46	0.77	2.23	2.92	1.55	4.47

Hence, the proposed tap offers significant potential for water conservation at a national level for ablution practice with average savings of 4.47 m³ per household. Furthermore, these savings are per household, not per capita, which is identical for both Saudi and non-Saudi segments because of the same tap flow rate, duration, and frequency. Hence, larger household savings simply reflect larger household sizes.

3.2. Percentage Share of Ablution Water Usage in Total Household Consumption

Table 4 presents the share of ablution water in total household consumption, calculated using actual monthly regional smart meter data [31]. Moreover, the regional total is calculated as a weighted average of both segments using the respective household counts as weights using the given formula:

$$Total = \frac{WC_{Saudi\ HH}^{monthly} \times N_{Saudi\ HH,region} + WC_{non-Saudi\ HH}^{monthly} \times N_{non-Saudi\ HH,region}}{Total\ Regional\ Households\ Count}$$

Table 4. Regional percentage share of ablution water usage by tap type.

Saudi Arabian Regions	Average Monthly Regional Water Usage per Meter for Year 2026 [31]	Standard Tap			Proposed Tap		
		Saudi	Non-Saudi	Total (Weighted Avg)	Saudi	Non-Saudi	Total (Weighted Avg)
Northern Borders	38.4	13.1	7.0	11.1	4.4	2.3	3.7
Al Jouf	35.7	13.8	6.1	11.0	4.6	2.0	3.7
Najran	21.9	21.4	11.5	17.4	7.1	3.8	5.8
Hail	25.8	17.5	7.4	13.4	5.8	2.5	4.5
Jazan	29.4	14.7	9.4	13.0	4.9	3.1	4.3
Al Qassim	32.9	13.2	6.9	10.7	4.4	2.3	3.6
Asir	34.1	12.7	6.4	10.4	4.2	2.1	3.5
Tabuk	56.6	7.7	3.8	6.2	2.6	1.3	2.1
Riyadh	60.5	6.9	3.7	5.1	2.3	1.2	1.7
Al Madinah	64.3	6.5	3.9	5.4	2.2	1.3	1.8
Al Baha	22.7	18.0	9.9	15.3	6.0	3.3	5.1
Eastern Province	65.2	6.2	3.2	4.7	2.1	1.1	1.6
Makkah	77.5	5.0	3.1	4.0	1.7	1.0	1.3
Nationwide	59.7	10.1	5.3	5.4	3.4	1.8	1.8

Countrywide, ablution water usage represents 5.4% of total household water use with standard taps, dropping to 1.8% with the proposed taps. Also, the regional variation is driven by differences in total household consumption rather than ablution practices. Makkah has the lowest share (4%) because its total monthly consumption is high at 77.5 m³, while Najran has the highest share (17.4%) because its total consumption is low at 21.9 m³. Both regions have similar ablution water use, but the proportion differs. This pattern is consistent across both Saudi and non-Saudi households, but implementation is important because regions with low total consumption will see proportionally greater reductions in household water use from tap replacement. With the proposed taps, Najran's share falls from 17.4% to 5.8%. Conversely, high-consumption regions like Makkah will show a smaller percentage. However, each region is unique and achieves significant absolute savings due to its large household base.

3.3. Regional Water Consumption

In Table 5, household water usage is scaled to regional totals. With the standard tap, national monthly ablution water usage reaches 26.5 million m³. Saudi households contribute 17.3 million m³ (65%), and non-Saudi households contribute 9.2 million m³ (35%). The three largest regions, including Riyadh (7.02 million m³, 26%), Makkah (6.64 million m³, 25%), and the Eastern Province (4.13 million m³, 15%), dominate and together account for 66% of national consumption. With the proposed taps, national consumption drops to 9 million m³, a 67% reduction. These same three regions account for 5.93 million m³ (67%) of monthly savings, while Al-Baha contributes just 1%. This concentration has clear strategic implications. Targeting Riyadh, Makkah, and the Eastern Province first would deliver the greatest early impact. The remaining ten regions combined offer only one-third of total savings, supporting a phased approach that prioritizes high-density areas before expanding to other regions.

Table 5. Total regional monthly water usage (million m³) by tap type and demographic segment.

Saudi Arabian Regions	Standard Tap			Proposed Tap		
	Saudi	Non-Saudi	Total	Saudi	Non-Saudi	Total
Northern Borders	0.25	0.06	0.31	0.08	0.02	0.10
Al Jouf	0.40	0.10	0.49	0.13	0.03	0.16
Najran	0.37	0.13	0.50	0.12	0.04	0.17
Hail	0.48	0.14	0.61	0.16	0.05	0.20
Jazan	0.90	0.28	1.18	0.30	0.09	0.39
Al Qassim	0.83	0.27	1.11	0.28	0.09	0.37
Asir	1.32	0.38	1.70	0.44	0.13	0.57
Tabuk	0.57	0.17	0.73	0.19	0.06	0.24
Riyadh	4.15	2.88	7.02	1.38	0.96	2.34
Al Madinah	1.24	0.55	1.80	0.41	0.18	0.60
Al Baha	0.23	0.06	0.29	0.08	0.02	0.10
Eastern Province	2.70	1.43	4.13	0.90	0.48	1.38
Makkah	3.87	2.77	6.64	1.29	0.92	2.21
Nationwide Total	17.3	9.2	26.5	6	3	9

3.4. Water Savings and Carbon Emission Reduction

Table 6 presents the carbon offset potential directly linked to water savings calculated using the carbon intensity value of 3.31 kg CO₂/m³, as seen in Section 2.4. The proposed tap saves 18 million m³ of water and offsets 58.52 million kg CO₂ monthly. Riyadh (15.50 million kg), Makkah (14.66 million kg), and the Eastern Province (9.11 million kg) together account for 67% of total carbon savings, reflecting the water-savings concentration. Saudi households contribute 65% of carbon savings (38.16 million kg monthly) compared with 35% from non-Saudi households (20.36 million kg monthly). This difference is driven by household size, not per capita behavior. Larger Saudi households achieve greater total savings per household, which is important for targeting deployment.

Table 6. Monthly regional water (million m³) and emission savings (million kg CO₂).

Saudi Arabian Regions	Water Savings			Carbon Emission Savings		
	Saudi	Non-Saudi	Total	Saudi	Non-Saudi	Total
Northern Borders	0.17	0.04	0.21	0.55	0.14	0.69
Al Jouf	0.26	0.06	0.33	0.87	0.22	1.09
Najran	0.24	0.09	0.33	0.81	0.30	1.10
Hail	0.32	0.09	0.41	1.05	0.30	1.36
Jazan	0.60	0.19	0.79	2.00	0.62	2.61
Al Qassim	0.56	0.18	0.74	1.84	0.60	2.44
Asir	0.88	0.25	1.13	2.90	0.84	3.74
Tabuk	0.38	0.11	0.49	1.25	0.37	1.62
Riyadh	2.76	1.92	4.68	9.15	6.35	15.50
Al Madinah	0.83	0.37	1.20	2.74	1.22	3.96
Al Baha	0.15	0.04	0.19	0.50	0.13	0.64

Table 6. Cont.

Saudi Arabian Regions	Water Savings			Carbon Emission Savings		
	Saudi	Non-Saudi	Total	Saudi	Non-Saudi	Total
Eastern Province	1.80	0.95	2.75	5.96	3.15	9.11
Makkah	2.58	1.85	4.43	8.54	6.12	14.66
Nationwide Total	11.53	6.15	17.68	38.16	20.36	58.52

3.5. Sensitivity Analysis

Detailed multi-parameter sensitivity analysis is conducted in Table 7, examining the role of key parameters including ablution duration, home-based ablution frequency, tap flow rate, behavioral conservation, and adoption rate.

Table 7. Summary of sensitivity analysis results.

Parameter	Variation	Percentage of Base Case	Annual Water Savings (Million m ³)	Annual CO ₂ Offset (Tonnes)
Ablution duration	45 s	75%	159.00	526,290
	90 s	150%	318.00	1,052,580
	120 s	200%	423.96	1,403,307
Home-based ablution rate	80%	80%	169.63	561,476
	90%	90%	190.84	631,681
Tap flow rate	6.5 L/min	121%	256.80	849,008
	8.2 L/min	166%	351.72	1,164,193
Behavioral conservation	30% waste eliminated	70%	148.44	491,336
	47% waste eliminated	53%	112.68	372,971
Adoption rate (% of households)	10%	10%	21.21	70,220
	25%	25%	53.03	175,500
	50%	50%	106.07	351,099
	75%	75%	159.11	526,649
Rebound Effect	15% offset	85%	180.32	596,868
	Base case savings		212.14	702,198

We now discuss each key parameter sensitivity impact on savings below:

- Ablution duration time of 45 to 120 s is reported in empirical studies by Zaied [9] and Fidar et al. [40], and for which annual savings ranging from (water: 159–424 million m³, CO₂ Offset: 526,290–1,403,307 tonnes) can be achieved.
- The base case assumes all five daily ablutions are performed at home. However, annual savings of 169.63 million m³ and 561,476 tonnes CO₂ remain achievable even in the case of 80% of ablutions adherence.
- Higher tap flow rates will offer even greater proportional savings if replaced with the proposed tap.
- Eliminating 30–47% water consumption during ablution steps (i.e, keeping the tap off), experimentally proved by Zaied [9], reduces the total running time from 60s to 32–42s. As discussed above, the total ablution time is still around 60s on average, which means the combined effect of tap replacement and behavioral conservation will still offer substantial amounts of water and emissions reduction savings.

- Adoption rate refers to the percentage of total households using the proposed tap. Even 25% adoption delivers 53.03 million m³ annual savings, making it a reasonable pilot target, as further elaborated in Section 3.6.

In conclusion, the combined lower-bound scenario savings of 67.42 million m³ consider the most conservative assumptions for uncertain user-behavior parameters (ablution duration, home-based ablution frequency, and behavioral conservation). These savings are 32% of the base case scenario and do not consider the adoption rate and tap flow rate, as these are policy-controlled variables.

3.6. Rebound Effect

Another important factor that can deplete any resource conservation is known as the rebound effect. This is a well-studied phenomenon directly linked with efficiency improvements and can cause excessive consumption behavior [44,45]. For this study's focus on water-saving taps, the rebound effect could manifest in several ways, such as increased water usage duration and frequency, relaxed conservation behavior, etc. This effect can be minimized by awareness campaigns or reinforcing Islamic principles of moderation in water use, etc.

Moreover, the role of rebound analysis cannot be ignored in a more realistic estimation of achievable savings, which can support policy planning, as no empirical data exist on rebound effects for ablution water conservation in Saudi Arabia. Therefore, a 15% rebound effect based on studies by Campbell et al. [46] and Inman and Jeffrey [47] for potential behavioral offset is used, reducing annual water savings to 180.32 million m³ and CO₂ offset to 596,868 tonnes. Even with this offset, substantial benefits remain achievable.

3.7. Phased Implementation for Maximum Impact

Sections 3.1–3.4 presented the optimized potential impact. However, realistic adoption will occur gradually. Based on the adoption rate scenarios presented in Table 7 (Section 3.5), we now propose a regionally prioritized phased implementation strategy that maximizes early impact by targeting high-saving regions first. Table 8 presents tiered implementation based on regional savings and emission reduction gains.

Table 8. Strategic regional prioritization for phased implementation.

Priority	Region	Monthly Savings (Million m ³)	Tiered Cumulative Savings (Million m ³)
Tier 1 High Impact Regions	Riyadh	4.68	11.86 (67%)
	Makkah	4.43	
	Eastern Province	2.75	
Tier 2 Moderate Impact Regions	Asir	1.13	3.12 (17.65%)
	Al Madinah	1.20	
	Jazan	0.79	
Tier 3 Low Impact Regions	Al Qassim	0.74	2.7 (15.27%)
	Hail	0.41	
	Tabuk	0.49	
	Al Jouf	0.33	
	Najran	0.33	
	Northern Borders	0.21	
	Al Baha	0.19	

Tier 1 covers regions including Riyadh, Makkah, and the Eastern Province, as they account for 67.08% of potential savings. Tier 2 includes the Asir, Al Madinah, and Jazan regions, contributing an additional 3.12 million m³ monthly in water savings and bringing cumulative savings to 85% of the national total. Tier 3 comprises the remaining seven regions, with Al Baha contributing just 1% of the national total.

This tiered structure supports a practical four-year roadmap presented in Table 9, where high-impact regions are addressed first, followed by moderate-impact regions, and finally low-impact regions. This approach maximizes early returns while allowing time to address logistical challenges in less populated areas. It is important to note that regions are added in each phase in Table 9, and by the end of the fourth year, all 13 regions will achieve 100% nationwide adoption.

Table 9. Yearly phased implementation roadmap.

Phase	Timeframe	Adoption Target	Regions Added in This Phase	Cumulative Annual Savings (Million m ³)	Cumulative CO ₂ Offset (Tonnes)
1	Year 1	25%	Riyadh, Makkah, Eastern Province	53.03	175,500
2	Year 2	50%	Asir, Al Madinah, Jazan	106.07	351,099
3	Year 3	75%	Al Qassim, Hail, Tabuk, Al Jouf, Najran, Northern Borders	159.11	526,649
4	Year 4	100%	Al Baha	212.14	702,198

3.8. Economic Benefits

The economic benefit of the proposed tap replacement nationwide is calculated using the actual tiered water tariff structure in Saudi Arabia, given in Table 10 [48,49] to support policy decision-making.

Table 10. Residential water tariff structure in Saudi Arabia.

Monthly Consumption Slab (m ³)	Water Rate (SAR/m ³)
Less than 15	0.10
16 to 30	1.00
31 to 45	3.00
46 to 60	4.00
More than 60	6.00

In Table 11, we present the annual regional water cost savings obtained using the formula below:

$$\text{Annual Water Cost Savings} = 12 \times \text{Monthly Water Savings (million m}^3\text{)} \times \text{Applicable Tariff (SAR/m}^3\text{)}.$$

The applicable regional water tariff given in Table 11 is calculated based on the average monthly regional water consumption given in Table 4 (second column). Moreover, regional total monthly water savings are taken from Table 6.

Also, the total capital investment for replacing taps across 8.17 million households nationwide at 400 SAR per unit is 3268 million SAR. Therefore, the simple payback period is given by

$$\text{Payback period} = 3268/959 = 3.41 \text{ years approximately.}$$

Now the annual carbon cost benefit is estimated using a volume-weighted abatement cost of approximately 187.5 SAR (50 USD)/tonne CO₂ as per two recent Saudi-specific studies by Hasanov et al. [50] and Rowaihy et al. [51] given by:

$$702,198 \text{ tonnes} \times 187.5 \text{ SAR/tonne} = 132 \text{ million SAR approximately.}$$

Hence, the total annual economic benefit is worth 1091 million SAR, which we use to calculate the four-year return on investments (ROI) presented in Table 12.

Table 11. Regional annual water cost savings from full proposed tap replacement nationwide.

Saudi Arabian Regions	Applicable Water Tariff (SAR/m ³)	Annual Water Cost Savings (Million SAR)
Northern Borders	3.00	7.56
Al Jouf	3.00	11.88
Najran	1.00	3.96
Hail	1.00	4.92
Jazan	1.00	9.48
Al Qassim	3.00	26.64
Asir	3.00	40.68
Tabuk	4.00	23.52
Riyadh	4.00	224.64
Al Madinah	6.00	86.40
Al Baha	1.00	2.28
Eastern Province	6.00	198.00
Makkah	6.00	318.96
Nationwide Total		958.92

Table 12. Cumulative benefits over a four-year period.

Phase	Timeframe	Adoption Target	Cumulative Annual Benefit (Million SAR)
1	Year 1	25%	$1091 \times 0.25 = 272.75$
2	Year 2	50%	$1091 \times 0.50 = 545.50$
3	Year 3	75%	$1091 \times 0.75 = 818.25$
4	Year 4	100%	$1091 \times 1.00 = 1091.00$
Cumulative Benefits Over 4 Years			2727.50

Therefore, the 4-year ROI is calculated as follows:

$$4\text{-Year ROI} = (2727.50 - 3268)/3268 \times 100 = -16.5\%$$

This negative 16.5% ROI over the four-year period reflects the fact that 83.5% of the total capital investment will have recovered by the end of the fourth year. Moreover, the investment breaks even during the fourth year, which is consistent with the 3.5-year payback period and becomes positive thereafter. This aligns with the four-year phased implementation roadmap. Hence, the benefits continue to accrue in subsequent years, as shown with the projected 5-year ROI of 67% and 20-year ROI of 568%.

4. Conclusions

This study presents the first comprehensive, regionally disaggregated analysis of household ablution water consumption across Saudi Arabia and evaluates the national impact of replacing standard taps with proposed taps. Beyond quantifying environmental benefits, the study evaluates the practical deployment potential of an ultra-low-flow tap technology under national-scale conditions. The key findings are listed below:

- Ablution water usage represents a substantial share (standard tap case: 5.4% and proposed tap case: 1.8%) of household water use.
- The proposed tap achieves 67% conservation potential across all regions. However, regions with a total low average monthly consumption benefit more compared to regions with a higher total average monthly consumption by efficient interventions such as the installation of proposed taps.
- Full adoption would reduce national ablution water consumption from 27 million m³ to 9 million m³ monthly, saving 212.14 million m³ annually. Economic analysis confirms cost-effectiveness, with a 3.41-year payback period, annual benefits of 1091 million SAR, and 5-year and 20-year ROIs of 67% and 568%, respectively, supporting the proposed phased implementation strategy.
- Carbon offset potential is directly proportional to water saving, and full adoption will offset 702,198 tonnes of CO₂ annually. The proposed tap performs effectively as an environmental technology by simultaneously reducing water demand and the indirect emissions associated with desalinated water production.
- The proposed tap represents a practical clean technology solution that strengthens the water–energy nexus by reducing demand for energy-intensive desalination while improving resource efficiency at the household level.
- Sensitivity analysis highlights that even in the case of the most conservative assumptions, the annual savings remain substantial at around 67.42 million m³ and 223,160 tonnes of CO₂, supporting the proposed phased implementation strategy.
- Regions with the highest household count, such as Riyadh, Makkah, and the Eastern Province, offer the highest water-savings potential. This demands a regionally prioritized phased implementation strategy that maximizes early impact.
- A practical four-year phased implementation strategy with tiered regional prioritization is presented. The deployment framework developed in this study provides a practical pathway for technology adoption at regional and national scales.
- The proposed gradual implementation will contribute to the United Nations Sustainable Development Goals (UN-SDGs), specifically to SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), and SDG 13 (Climate Action).

Overall, the findings demonstrate that relatively simple environmental technologies can deliver substantial water conservation benefits when deployed at scale. The proposed framework may support future implementation of water-saving technologies in Saudi Arabia and other water-stressed regions facing similar water sustainability challenges. Finally, this model quantifies gains theoretically and requires validation through actual implementation and monitoring.

5. Limitations and Future Research

This study has several limitations explicitly listed below:

- First, alternative technologies such as sensor-activated taps or mist spray devices [22,24] are not considered and compared. This study focuses on a single ultra-low-flow tap model.

- Second, cultural and behavioral variabilities are not fully modeled. As in Saudi Arabian culture, the majority of people like to keep ablution intact beyond the mandatory compliance of five prayers, increasing the frequency to more than five. Also, children and elderly individuals, due to health concerns, may have different patterns for ablution, such as duration, frequency, etc., which makes the current estimates underestimated.
- Third, this study presents theoretical projections based on flow rate differences and officially reported data. The estimated annual water savings of 212.14 million m³ and carbon offset of 702,198 tonnes are model-based projections derived from the assumptions stated in Section 2.3. No pilot studies or practical implementations have been conducted to verify whether estimated savings can be achieved under practical conditions.
- Fourth, the implementation roadmap does not fully account for regional differences in population structure, maintenance cost, and local implementation challenges.
- Fifth, the obtained savings are constant (67%) and do not consider varying operating conditions such as water pressure, user behavior, ultra-low-flow tap age, and health. These practical factors can influence savings.
- Sixth, the tier-based regional prioritization is solely based on household count and potential water savings. Future prioritization frameworks could incorporate additional criteria such as locally varying water stress indices, groundwater depletion rates, desalination dependency levels, and regional water scarcity indicators. Regions with higher water stress, such as those with limited groundwater resources and high desalination reliance, could benefit from priority deployment even if their household counts are lower.

Hence, proposed future research directions should be explored as follows:

- Pilot implementation studies using alternative tap technologies assessing long-term durability and maintenance costs under identical conditions for relative performance and cost-effectiveness.
- Incorporation of cultural and behavioral variabilities.
- Understanding user satisfaction and acceptance for successful adoption through surveys or focus groups.
- Detailed analysis of large-scale implementation to support policy decision-making based on subsidy programs, financing mechanisms, and cost–benefit analysis.
- Smart water meters and real-time monitoring could provide accurate data on actual savings and user behavior, enabling performance tracking and behavioral feedback.
- Quantification of rebound effects specific to ablution water conservation in Saudi Arabia.
- Development of a multi-criteria regional prioritization index for impactful deployment strategy based on water stress indicators, groundwater availability, population density, and economic factors.

Author Contributions: Conceptualization, H.A.W. and M.A.; methodology, H.A.W. and M.A.; formal analysis, H.A.W. and M.A.; investigation, H.A.W. and M.A.; writing—original draft preparation, H.A.W. and M.A.; writing—review and editing, H.A.W. and M.A.; supervision, H.A.W.; project administration, H.A.W. All authors have read and agreed to the published version of the manuscript.

Funding: The authors extend their appreciation to the Deanship of Scientific Research, Islamic University of Madinah, Saudi Arabia, for funding this research.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All used data is given in the methodology section and properly cited with links there.

Acknowledgments: The author greatly appreciates anonymous reviewers' constructive feedback, which enhanced the quality of this work.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Abdella, F.I.; El-Sofany, W.I.; Mansour, D. Water scarcity in the Kingdom of Saudi Arabia. *Environ. Sci. Pollut. Res.* **2024**, *31*, 27554–27565. [\[CrossRef\]](#)
2. Baig, M.B.; Alotibi, Y.; Straquadine, G.S.; Alataway, A. Water resources in the Kingdom of Saudi Arabia: Challenges and strategies for improvement. In *Water Policies in MENA Countries*; Springer: Cham, Switzerland, 2020; pp. 135–160.
3. DeNicola, E.; Aburizaiza, O.S.; Siddique, A.; Khwaja, H.; Carpenter, D.O. Climate change and water scarcity: The case of Saudi Arabia. *Ann. Glob. Health* **2015**, *81*, 342–353. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Hamieh, A.; Rowaihy, F.; Al-Juaied, M.; Abo-Khatwa, A.N.; Afifi, A.M.; Hoteit, H. Quantification and analysis of CO₂ footprint from industrial facilities in Saudi Arabia. *Energy Convers. Manag. X* **2022**, *16*, 100299. [\[CrossRef\]](#)
5. Ansari, M.M.A.; Alam, M.M. Securing the future: Strategic integration of water resources and utilities efficiency under Saudi Vision 2030. *J. Bus. Insight Innov.* **2025**, *4*, 108–121.
6. Hussien, W.E.A.; Memon, F.A.; Savić, D.A. Assessing and modelling the influence of household characteristics on per capita water consumption. *Water Resour. Manag.* **2016**, *30*, 2931–2955. [\[CrossRef\]](#)
7. Singha, B.; Eljamal, O.; Karmaker, S.C.; Maamoun, I.; Sugihara, Y. Water conservation behavior. *J. Environ. Manag.* **2022**, *317*, 115484. [\[CrossRef\]](#)
8. Suhail, M.; Faraj, T.K.; Ahmad, W.; Ravshanov, A.X.; Khan, M.N. Issues of water resources in Saudi Arabia: Past, present, and future. *Sustainability* **2024**, *16*, 4189. [\[CrossRef\]](#)
9. Zaied, R.A. Water use and time analysis in ablution from taps. *Appl. Water Sci.* **2017**, *7*, 2329–2336.
10. Al Alawi, A.A.S.; Parameswari, K.; Kumarasamy, G.; Al Kaabi, K.S. Assessment of ablution water consumption in mosques. In *Proceedings of the International Conference on Civil Infrastructure and Construction (CIC)*; Qatar University Press: Doha, Qatar, 2023; pp. 1260–1265.
11. Hurayra, M.A.; Ahmed, A.; Alim, M.A.; Rahman, A. Water savings in places of worship: A case study for St Mary's Mosque in Australia. *Sustainability* **2024**, *16*, 6568. [\[CrossRef\]](#)
12. Wajid, H.A.; Eid Alluqmani, A. Enhancing water sustainability in ablution (wudu): Lessons from Prophet Muhammad's (ﷺ) wudu practice and the role of water-efficient aerators. *J. Umm Al-Qura Univ. Eng. Archit.* **2025**, *16*, 1119–1129. [\[CrossRef\]](#)
13. Ouda, O.K.; Shawesh, A.; Al-Olabi, T.; Younes, F.; Al-Waked, R. Review of domestic water conservation practices in Saudi Arabia. *Appl. Water Sci.* **2013**, *3*, 689–699. [\[CrossRef\]](#)
14. Ghazali, I.; Padzil, N.W.S.; Mohamad, E.B.; Al-Mashjari, L.A.; Irianto, I.; Herawan, S.G. The water tap design for ablution activities considering cultural influences: A design for sustainability. *Front. Environ. Sci.* **2023**, *11*, 1281318. [\[CrossRef\]](#)
15. Ghazali, I.; Tanjung, T.; Irianto, I.; Muhida, R.; Herawan, S.G.; Asih, H.M. Integrating cultural perspectives in online ablution water usage monitoring: A design for sustainability. *Front. Commun.* **2024**, *9*, 1411711. [\[CrossRef\]](#)
16. Fauzi, M.A.B.M.; Yunus, S.I.B.; Abidin, F.N.B.Z. The relationship between knowledge, values, skills, attitude and sustainable practices towards water conservation practices during ablution. *Int. J. Acad. Res. Bus. Soc. Sci.* **2020**, *10*, 958–969. [\[CrossRef\]](#)
17. Raduan, M.I.B.; Ibrahim, M.; Yaacob, M. Ethics of water usage in the context of ablution. *Int. J. Acad. Res. Bus. Soc. Sci.* **2018**, *8*, 958–969. [\[CrossRef\]](#)
18. Ameer, S.; Muhammad, N.; Jadoon, K.Z.; Sheikh, N.; Rahman, K.U. A systematic literature review on potential of ablution greywater reuse: Current insights, challenges, and future prospects. *Appl. Water Sci.* **2025**, *15*, 173. [\[CrossRef\]](#)
19. Shafiquzzaman, M.; Alharbi, S.K.; Haider, H.; AlSaleem, S.S.; Ghumman, A.R. Development and evaluation of treatment options for recycling ablution greywater. *Int. J. Environ. Sci. Technol.* **2020**, *17*, 1225–1238.
20. Risma, U.; Sari, D.P. Integrating green building principles and Islamic jurisprudence (fiqh) in ablution wastewater reuse for urban mosques in Indonesia. *Bord. J. Arsit.* **2025**, *7*, 163–176.
21. Kumar, I.; Shah, J.; Nasit, N. A review of sustainable greywater management for low-income urban households: Exploring challenges, risks, and economic feasibility. *Circ. Econ. Sustain.* **2026**, *6*, 43. [\[CrossRef\]](#)
22. Hassan, B.H.; Abdul Hamid, S.B. Water conservation in ablution: An evaluation of mist spray devices and their financial impact on water usage and sustainability in communal facilities. *Built Environ. J.* **2025**, *22*, 76–90. [\[CrossRef\]](#)

23. Abidin, M.N.Z.; Aziz, K.A.A. Innovative solar ablution system: A green approach to water conservation. *Int. J. Acad. Res. Bus. Soc. Sci.* **2024**, *14*, 4271–4282. [CrossRef]
24. Jamil, A.; Imran, A.; Firdaus, F.; Sari, D.A.L. Development of prototype of Arduino-based automatic ablution faucet to save water usage. *J. Electr. Eng. Inform.* **2025**, *3*, 33–41. [CrossRef]
25. Almulhim, A.I.; Abubakar, I.R. A segmentation approach to understanding water consumption behavioral patterns among households in Saudi Arabia for a sustainable future. *Resour. Environ. Sustain.* **2024**, *15*, 100144. [CrossRef]
26. Alzahrani, F.; Tawfik, R. Regional heterogeneity in urban water consumption in Saudi Arabia. *Water* **2025**, *17*, 1156. [CrossRef]
27. Wajid, H.A. Activity-based mathematical modeling of household water consumption. *J. Umm Al-Qura Univ. Eng. Archit.* **2025**, *16*, 574–582. [CrossRef]
28. Kakwani, N.S. How much reduce as a strategy is effective for urban water management? *Water Policy* **2026**, *28*, 67–85.
29. Fernández-Vizcarra, L.; Chambilla-Zuñiga, J.; Gutiérrez-Aguilar, O.; Buele, J. Advances in end-user water conservation technologies: A scoping review. *Front. Sustain.* **2026**, *7*, 1793323. [CrossRef]
30. General Authority for Statistics (GASTAT). *Saudi Census Statistics 2022*; GASTAT: Riyadh, Saudi Arabia, 2026. Available online: <https://www.stats.gov.sa/en/> (accessed on 1 April 2026).
31. Saudi Water Authority. Water Sector Dashboard: Key Residential Water Indicators. Available online: <https://www.swa.gov.sa/en/Key-Residential-Water> (accessed on 1 April 2026).
32. Saudi Standards, Metrology and Quality Organization (SASO). 2026. Available online: <https://www.saso.gov.sa/en> (accessed on 1 April 2026).
33. Saline Water Conversion Corporation (SWCC). *Desalination Energy Consumption: A Comprehensive Report*; SWCC: Riyadh, Saudi Arabia, 2023.
34. Wajid, H.A.; Alsisi, R.H.; Abid, M.; Abid, Z. Regenerative water management in Saudi Arabia using smart water metering. *Int. J. Energy Environ. Econ.* **2025**, *33*, 563–576.
35. Peerless. Peerless P1512LF-M-0.5 Flute Bathroom Faucet, 0.5 GPM Flow Rate, Chrome. Amazon.sa. Available online: <https://www.amazon.sa/> (accessed on 1 April 2026).
36. US Environmental Protection Agency. WaterSense. Available online: <https://www.epa.gov/watersense> (accessed on 1 April 2026).
37. Kalbusch, A.; Ghisi, E. Comparative life-cycle assessment of ordinary and water-saving taps. *J. Clean. Prod.* **2016**, *112*, 4585–4593. [CrossRef]
38. Memon, F.A.; Ton-That, L.; Butler, D. An investigation of domestic water consumption through taps and its impact on urban water flows. *Water Sci. Technol. Water Supply* **2007**, *7*, 69–76. [CrossRef]
39. Englart, S.; Jedlikowski, A. The influence of different water efficiency ratings of taps and mixers on energy and water consumption in buildings. *SN Appl. Sci.* **2019**, *1*, 525. [CrossRef]
40. Fidar, A.M.; Memon, F.A.; Butler, D. Performance evaluation of conventional and water saving taps. *Sci. Total Environ.* **2016**, *541*, 815–824. [CrossRef] [PubMed]
41. Khan, F. Less Water, More Holy: Tools for Sustainable Ablution. Master's Thesis, University of the Arts London, London, UK, 2022.
42. Lienhard, J.H.; Thiel, G.P.; Warsinger, D.M.; Banchik, L.D. *Low Carbon Desalination: Status and Research, Development, and Demonstration Needs*; MIT: Cambridge, MA, USA, 2016.
43. Do Thi, H.T.; Toth, A.J. Investigation of Carbon Footprints of Three Desalination Technologies: Reverse Osmosis (RO), Multi-Stage Flash Distillation (MSF) and Multi-Effect Distillation (MED). *Period. Polytech. Chem. Eng.* **2023**, *67*, 41–48. [CrossRef]
44. Greening, L.A.; Greene, D.L.; Difiglio, C. Energy efficiency and consumption—The rebound effect—A survey. *Energy Policy* **2000**, *28*, 389–401. [CrossRef]
45. Hertwich, E.G. Consumption and the rebound effect: An industrial ecology perspective. *J. Ind. Ecol.* **2005**, *9*, 85–98. [CrossRef]
46. Campbell, H.E.; Johnson, R.M.; Larson, E.H. Prices, Devices, People, or Rules: The Relative Effectiveness of Policy Instruments in Water Conservation. *Rev. Policy Res.* **2004**, *21*, 637–662. [CrossRef]
47. Inman, D.; Jeffrey, P. A review of residential water conservation tool performance and influences on implementation effectiveness. *Urban Water J.* **2006**, *3*, 127–143. [CrossRef]
48. Ministry of Environment, Water and Agriculture. 2026. Available online: <https://www.mewa.gov.sa/en/> (accessed on 1 April 2026).
49. Wajid, H.A. A Strategic Mathematical Model for Smart Water Meter Deployment in Saudi Arabia: Optimizing Regional Impact on Water and Carbon Emission Savings. *J. King Saud Univ. Sci.* **2026**, *in press*.

50. Hasanov, F.J.; Aliyeva, H.; Almozaini, M.S.; Bollino, C.A. Evaluating hypothetical carbon pricing for Saudi Arabia using a macroeconometric modeling framework. *Energy Econ.* **2025**, *145*, 108437. [[CrossRef](#)]
51. Rowaihy, F.; Hamieh, A.; Odeh, N.; Hejazi, M.; Al-Juaied, M.; Afifi, A.M.; Hoteit, H. Decarbonizing Saudi Arabia's energy and industrial sectors: An integrated techno-economic assessment of CCS. *Energy Convers. Manag. X* **2026**, *29*, 101536. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.