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Evaluating Future Alternatives for a Sustainable Water Management System in the Kingdom of Bahrain

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Abstract

The Kingdom of Bahrain, situated in an arid region, faces extreme water scarcity, which is expected to be exacerbated by climate change. The water management system in the Kingdom is modeled using the Water Evaluation and Planning (WEAP) dynamic model to assess its sustainability in terms of financial, economic, and environmental costs. The associated costs of the current management system were estimated under climate change impacts for 2022-2035, while the effectiveness of various management interventions in reducing these costs was evaluated both individually and in combination for the same period. The findings reveal that implementing these interventions has the potential to reduce municipal water demand by 30% by 2035, resulting in cumulative financial savings of approximately $1.25 billion. This reduction would also yield significant environmental benefits, including a cumulative reduction of 12,615 million tons of carbon dioxide (CO_2) emissions and 2,383 million cubic meters of desalination brine discharge to the marine environment. Additionally, enhancing treated wastewater utilization through strategies such as afforestation and managed aquifer recharge could further mitigate environmental impacts and support Bahrain's goal of achieving carbon neutrality by 2060. These results provide critical insights for policymakers to enhance the sustainability of Bahrain's water management system, ensuring continued socio-economic development while reducing environmental impacts. Future modeling should address uncertainties related to population growth and spatial demographics using stochastic approaches. Furthermore, addressing data gaps on agricultural water consumption and cropping patterns is essential for simulating the agricultural sector and supporting effective decision-making.

Keywords

Desalination, Climate Change, Irrigation Efficiency, Crop Water Requirement, Treated Wastewater, Managed Aquifer Recharge

1. Introduction

The Kingdom of Bahrain is located in one of the driest regions in the world and faces acute challenges in meeting its escalating water demands. It is ranked as one of the most water-stressed countries in the world with one of the lowest per capita renewable freshwater shares (80 m^3/y/capita), significantly below the water poverty line of 500 cubic meters per year [1]. With its rapid socio-economic development and population growth coupled with the deterioration of its limited groundwater resources due to their over-exploitation, Bahrain has to rely heavily on non-conventional water resources, namely desalinated water to fulfill its domestic water requirements. However, desalination incurs substantial financial, economic, and environmental costs [2]. Moreover, with deteriorating groundwater resources, the kingdom started reusing tertiary treated wastewater in the agricultural sector. However, only around 40% of the available tertiary treated wastewater is being utilized, while the rest is being discharged to the sea, which under the scarcity conditions of Bahrain represents a major lost opportunity.

The current water management approach in Bahrain relies primarily on the supply side engineering approach which is associated with increasingly high economic and environmental costs which are proving to be unsustainable. Escalating water demands due to population growth, changing lifestyle and consumption patterns, and inefficient water supply and use, necessitates an urgent and comprehensive evaluation and implementation of sustainable water management practices. Furthermore, climate change is anticipated to exacerbate water scarcity and acts as an additional stressor on the water management system in the Kingdom of Bahrain. With increased temperatures and altered precipitation patterns, municipal and agricultural water demands are expected to increase, while water supply diminishes. Furthermore, as a Small Island Developing State (SIDS), Bahrain is particularly vulnerable to sea level rise, which poses a significant threat to groundwater resources by seawater intrusion. Moreover, the country's dependence on energy-intensive desalination processes exacerbates its environmental and economic challenges [3].

This research aims to evaluate the sustainability of Bahrain's current water management system, assess the impacts of climate change on water resources, and propose and evaluate various management interventions to enhance sustainability. A comprehensive assessment of the water management system is made for identifying key issues and evaluating the effectiveness of both current and proposed solutions. The findings from this research are directed towards sustainability-related policy makers to provide insights to help in achieving Bahrain's sustainable development goals, the objectives of the Unified Water Strategy for Gulf Cooperation Council Countries (GCC UWS 2035), and the Kingdom's commitments for climate action [4].

2. Literature Review

2.1. Water Resources in the Kingdom of Bahrain

Bahrain has an estimated availability of about 80 cubic meters of renewable freshwater per capita per year, far below the Middle East and North Africa average of 1400 cubic meters and the global average of 6000 cubic meters per person [5]. Groundwater underflow from Eastern Saudi Arabia represents its only conventional renewable freshwater resource. The Kingdom's non-conventional sources are represented by desalinated water and tertiary treated wastewater. Groundwater, particularly from the Dammam Aquifer System, was historically the primary water source used to meet the Kingdom's water supply until the introduction of desalination in 1975. Groundwater over-extraction has led to significant declines in groundwater levels and its quality deterioration due to seawater intrusion, which necessitated a shift to desalination. Desalination, despite high production costs and environmental impacts, is now the main component of the water supply portfolio of Bahrain and the primary source used to meet escalating municipal water requirements in the Kingdom [5] [6]. Building on these efforts, the Kingdom has also made remarkable progress in achieving the Sustainable Development Goals, reaching 100% in providing safely managed sanitation services, safely treating wastewater, and ensuring access to safely managed drinking water services for its population. These accomplishments reflect Bahrain's unwavering commitment to sustainable water and sanitation management, aligning with Goal Six of the SDGs and setting a benchmark for environmental stewardship and resource optimization in the region [7]. Treated wastewater, increasingly used for irrigation and other purposes since the late 1980s, is the second important non-conventional water source, though its utilization remains below 50% of its available volumes due to infrastructure limitations [8].

2.2. Water Uses and Demand in the Kingdom of Bahrain

Total demand for water in Bahrain has surged from about 120 million cubic meters (MCM) in 1950 to approximately 430 MCM in 2015, driven by population growth, higher living standards, and industrial development. The municipal sector is the largest consumer, accounting for 59.5% of the total water demand, followed by agriculture at 32.8%, and industrial and commercial uses at 7.7% (**Figure 1**). Due to extremely low annual rainfall (averaging 76 mm) and high variability, agriculture in Bahrain relies on irrigation. Currently, Bahrain's agricultural sector depends essentially on groundwater and tertiary treated wastewater effluent. The agriculture sector in Bahrain faces growing challenges, including deteriorating groundwater quality, soil salinity, and low irrigation efficiency, which have contributed to a decline in cultivated land area from 6460 hectares in 1965 to approximately 3100 hectares in 2017 [9]. The municipal sector's demand has steadily increased due to urbanization driven by population growth, making it the main consuming sector of water, with per capita consumption remaining relatively high at about 330 liters per day [10]. The industrial sector has also seen a rise in water demand, primarily supplied by groundwater and desalinated water [11].

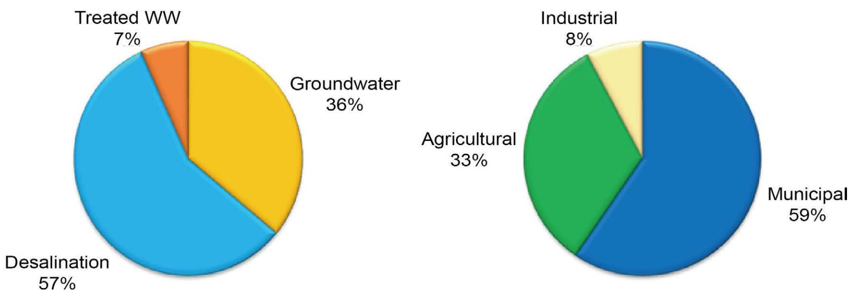


Figure 1. Water uses and sources in the Kingdom of Bahrain (2015).

3. Material and Methods

3.1. Model Data and Development

The Water Evaluation and Planning (WEAP) software is used for simulating the dynamics of the water management system in Bahrain (**Figure 2**). It facilitates modeling the interaction of all the system components of water users and water sources, allowing comprehensive analysis of the system performance, depicting water demand and supply under various future scenarios, and more importantly, evaluating the impacts of different management policies on the system sustainability.

Data on municipal water production from desalination plants were obtained from the Electricity and Water Authority, and data on wastewater (generated, received, produced and reused tertiary treated wastewater) were provided by the Sanitary Engineering Affairs (SEA) for the period 2013 to 2021 and were used to form the basis for the development of the model. The study area was divided into two main regions or catchments: Muharraq Island (Muharraq Governorate) and Bahrain Island (comprising the other three governorates: Capital, North and South Governorates), each analyzed as a separate catchment area. The municipal sector water demand is categorized into distinct sub-sectors, including Domestic (household), Economic (commercial, tourism, agriculture), and Government/Public Utilities. Information on the consumption of these 4 sectors in terms of per capita for the domestic and per unit for the others was obtained from Electricity and Water Authority's (EWA) monthly billing data. Domestic water consumption data was specifically segmented for Bahraini and non-Bahraini populations, highlighting variations in consumption. The economic sector (commercial, tourism, and agriculture) and government/public utilities sectors also contribute significantly to total municipal water demand, though consumption rates in these sectors were held constant for certain years (2018-2021) due to data limitations.

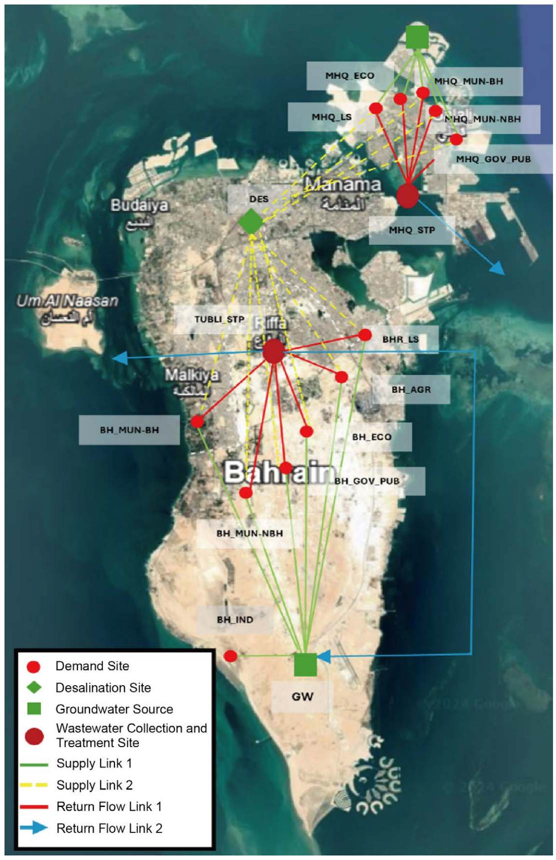


Figure 2. WEAP model schematic for the water management system (sources and uses) in the Kingdom of Bahrain.

Additionally, leakage rates were estimated by calculating the difference between water production and consumption obtained from billing records. The consumption of tertiary treated wastewater volumes was allocated at 75% for agricultural farms and 25% for landscape areas based on historically recorded flow data. The two users, *i.e.*, agricultural farms and landscape areas, are supplied from the same source (treatment plant) without dedicated flowmeters for each, and such allocation estimate provides a reasonable representation of water use [12]. Population data from 2013 to 2021 were obtained from the Bahrain Open Data Portal, with projections for 2022 to 2032 also sourced from the same portal. For the years 2033 to 2035, a constant population growth rate of 2.6%, calculated based on the year 2032, was assumed due to the absence of official projections.

From 2013 to 2021, the municipal sector consumed the largest proportion of total water, followed by the agricultural and industrial sectors. Future capacities for desalination and sewage treatment plants were based on planning data from EWA and SEA. The number of trees for landscape demand was standardized to palm trees to simplify water requirement calculations.

3.2. Model Performance Validation

The developed model included all available data and statistics from the water sector for the years 2013-2021. The water sector dynamics throughout this time in the two regions of the Kingdom of Bahrain were simulated using the model. All this information has been compiled and scrutinized for reliability and precision. The observed (actual/governmental) data and the simulated (modeled) results of the municipal water supply for different demand sites and the inlet flow to wastewater treatment plants were subsequently compared. To confirm that the developed model represents and is applicable to the actual situation, various statistical criteria were employed: Nash-Sutcliffe Efficiency (NSE) Value, Relative Root Mean Square Error (RRMSE) and the coefficient of determination (R^2) [13]. **Table 1** illustrates the characteristics and statistical criteria used to evaluate the performance of the model.

Table 1. Statistical criteria for the evaluation of the model's performance.

	NSE*	R^{2**}	RRMSE (%)***
Municipal Water Consumption in MHQ	0.99	0.99	0.9
Municipal Water Consumption in Bahrain	0.99	0.99	0.2
Collected Wastewater in MHQ STP	0.73	0.94	4.4
Collected Wastewater in Tubli STP	0.59	0.7	4.7

Note: * Nash-Sutcliffe Efficiency (NSE): >0.75 = value well; 0.36 - 0.75 = satisfactory; <0.36 = less satisfactory; **Coefficient of Determination (R2): 1 = perfect; >0.5 = acceptable; <0.5 = no prediction capability; ***Relative Root Mean Square Error (RRMSE): <10% = excellent; 10% - 20% = good; 20% - 30% = acceptable; >30% = poor (Eryani *et al.*, 2022; Campi *et al.*, 2015).

3.3. Scenario Development

Several scenarios were developed to evaluate the sustainability of Bahrain's water management system for the period 2021-2035. The first scenario is developed to represent the continuation of the current water conditions and policies (business-as-usual), while the second is run under the same conditions but under climate change. The objective of these two scenarios is to estimate the impacts of climate change on the water management system in Bahrain and to have a "reference scenario" that can be used in the comparison with the management intervention scenarios to estimate their effectiveness. The following is a detailed description of each.

- **Business-as-Usual (BAU) Scenario:** This scenario projects the current water management system's practices into the future without any significant changes. It assumes the continuation of current water use patterns and existing management practices and policies. The water consumption for the municipal and agricultural sectors in addition to the development of generated wastewater inflows to sewage treatment plants (STPs) are analyzed on a monthly basis for the period 2022 to 2035.
- **Business-as-Usual Scenario under Climate Change:** This scenario considers the impact of climate change on future water usage patterns. Higher tempera-

tures significantly affect water demand in the municipal sector, with increased consumption for domestic activities, especially during the hot summer months (Al-Zubari *et al.*, 2018). Climate projections for Bahrain were generated using the HCLIM-ALADIN Regional Climate Model (RCM) with a vertical resolution of 10 km, aligning with the broader Regional Initiative for the Assessment of Climate Change Impacts on Water Resources and Socio-Economic Vulnerability in the Arab Region (RICCAR). This analysis utilized a six-member ensemble of projections consistent with IPCC's Sixth Assessment Report (AR6) and the CMIP6 global climate model under the SSP5-8.5 emissions scenario [14]. For localized analysis, a bias-adjusted dataset focused on the central region of Bahrain was employed, using daily weather data to address climate impact research needs in fields such as hydrology and agriculture. This approach enables the calculation of climate change indicators reliant on absolute thresholds, particularly in temperature and precipitation-sensitive sectors. The model projections indicate a temperature increase of approximately 0.9˚C by 2035.

- **Intervention Scenarios:** These scenarios examine a variety of management strategies that could improve the effectiveness of Bahrain's water sector while reducing associated economic, financial, and environmental costs, as well as representing options for the adoption of climate change. Using the developed WEAP model, the efficacy of various management alternatives was evaluated. These included: 1) reduction of leakage in the municipal water distribution network; 2) reducing per capita consumption in the municipal sector; 3) improving irrigation efficiency in the agricultural sector; and 3) increasing the reuse of treated wastewater across all appropriate sectors, including agriculture, landscaping and managed aquifer recharge. For each of these management interventions, the targets of the GCC Unified Water Strategy 2035 [4] [15] were adopted **Table 2.**

Table 2. Demand reduction of management interventions.

Sector	Management Intervention Tool	Target
Municipal Sector (supply)	Reduce physical leakages in the municipal water distribution network	Minimum 10% by 2035
Municipal Sector (demand)	Reduce the per capita water consumption in the municipal sector	250 liter/capita/day by 2035
Agriculture Sector	Increase average irrigation efficiency	Minimum 60% by 2035
Agriculture and Wastewater Sector	Increase volume of treated wastewater used in the agriculture sector	Implement programs to increase treated wastewater use in agriculture by 2025

3.4. Scenarios Cost Comparison

The effectiveness of the implementation of the selected management intervention scenarios, individually and combined, is evaluated in terms of cost reduction in comparison to the reference scenario (*i.e.*, Business-as-Usual under climate change scenario). The cost parameters used in the comparison are: water demand in 2035 and cumulative water demand for the period 2021-2035; financial costs of municipal water supply; energy requirements (natural gas); desalination CO_2 Emissions; desalination brine discharge; and generated wastewater.

4. Results and Discussion

4.1. Municipal Water Supply under Business As-Usual Scenario under Climate Change (2013-2035)

Water consumption and annual water use rates for the 4 municipal sub-sector categories—including Bahraini and non-Bahraini households, economic, and government & public utilities—were obtained from EWA monthly billing data from 2013 to 2017. Due to unavailable category-specific data from 2018 to 2021 for Muharraq and Bahrain, a relationship between population and the number of units was developed for the economic and government sectors based on the 2013-2017 data, allowing for an estimation of unit numbers for 2018-2021. The annual water use rate (m^3/unit) has been held constant since 2017. For domestic categories, where population data and household water consumption share are known, per capita water consumption was derived. Literature supports the link between population growth and increased demand for public services, as population expansion typically leads to higher public expenditures and economic growth [16] [17]. In 2021, desalination plants provided a total of 354 MCM, with EWA planning to increase this to 443 MCM by 2025. If these expansions proceed as planned, the municipal sector is not expected to face water supply shortages, assuming current usage patterns persist. However, a word of caution, these conclusions are based on annual and monthly averages, and results may vary under peak daily demand scenarios.

Figure 3 illustrates the aggregated monthly water transmission flows to various sectors in Bahrain from January 2013 to December 2035. Each color represents a different transmission link, indicating the water source and its destination across various sectors/sub-sector, including economic (ECO), government/public utilities (GOV_PUB), and municipal demands divided into Bahraini (MUN_BH) and non-Bahraini (MUN_NBH) populations in Bahrain and Muharraq catchments. As expected, the total aggregated demand for the municipal sector will be increasing with seasonal fluctuations as the population increases and their consumption pattern persists, and the expansion in the economic and public sub-sectors. The largest volume of water transmission appears to be directed toward the economic sector (ECO) and the municipal sector for Bahrainis (MUN_BH), reflecting these sectors' significant water demand. The increase from 2022 onward aligns with projected population growth and anticipated demand under a business-as-usual scenario.

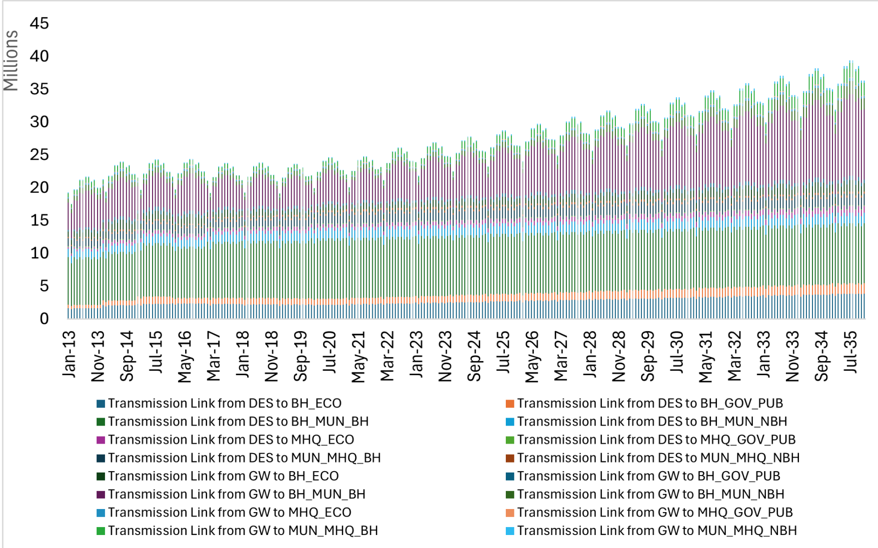


Figure 3. Monthly water transmission to Various Sectors from desalination and groundwater sources (2013-2035)-MCM.

4.2. Comparison between Reference Scenario and Reference Scenario under Climate Change

Seasonal data from the years 2000 to 2020 was used to estimate the link between temperature and municipal water use in Bahrain. A relationship between monthly per capita consumption and monthly temperature is found by dividing total monthly consumption by the year's population as shown in Figure 4. Despite the fact that this method is, in theory, the best accessible tool for investigating the actual relationship between temperature and municipal water use in Bahrain, it has a number of flaws in its computation and provides a very rough estimate. This is due to the absence of statistics on the monthly residential population. The monthly per capita consumption for the twelve months of the year is calculated using an estimate of the total yearly population. The collected data (2000-2020) indicates that a 1˚C increase in temperature raises municipal water demand by 0.7 cubic meters per capita per year with a predicted 0.9˚C increase in Bahrain's climate projections, using the HCLIM-ALADIN Regional Climate Model.

Figure 5 presents a comparison of the demand in the municipal water sector without and with climate change under business as usual. The difference between the two is the incremental impact due to the increase in temperature. Seasonal fluctuations are evident, with demand peaking during the hotter months, further accentuated under the climate change scenario due to heightened demand from increased temperatures. The gap between the two scenarios widens progressively over time as temperature increase, highlighting the cumulative impact of climate change on Bahrain's water demand through 2035.

As for the agricultural sector, Chowdhury *et al.* [18] evaluated the effects of climate change on crop water requirements (CWRs) for all crops grown, which included major crops such as wheat, maize, barley, tomato, potato, clover, dates, citrus, and grapes under four scenarios in Al Jouf region of the Kingdom of Saudi

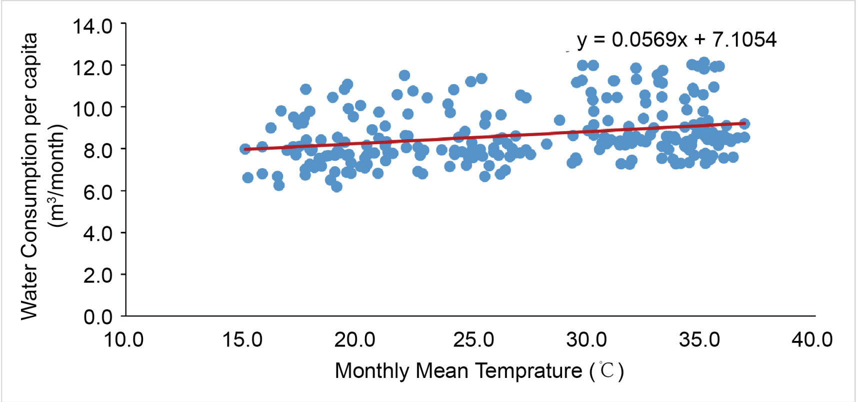


Figure 4. Impact of climate change on the monthly per capita water consumption (m^3/month).

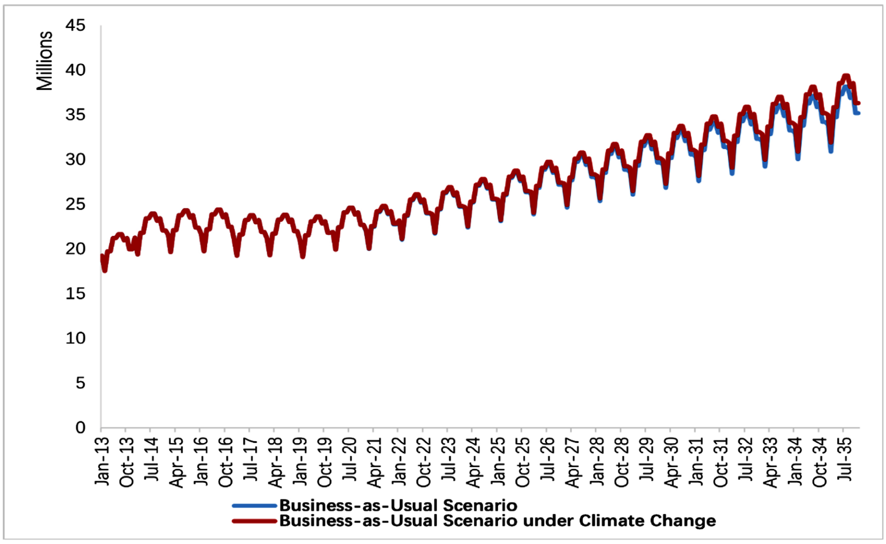


Figure 5. Transmission link flows to the Municipal sector under the Business-as-Usual Scenario and the Business-as-Usual with Climate Change Scenario (2013-2035).

Arabia. They concluded that a 1˚C increase in temperature can raise the overall CWR by 2.9%. in the region. Due to the lack of studies on the impact of climate change on the plant/crops water needs in the Arabian Gulf area in addition to the proximity of the study area (*i.e.*, Al-Ahsa) to Bahrain, the outputs of the study were considered to calculate the impact of climate change on water consumption in the agricultural sector.

The findings indicated that the agricultural water demands are predicted to increase by around 2.6 MCM (2.3 MCM is accounted to farms and 0.3 MCM to landscape) over the next 14 years compared to the same years without climate change as shown in Figure 6 with a cumulative increase of 18.4 MCM. It is worth noting that the calculated climate change impact on the crop water requirement is based on only one parameter which is change in temperature. As stated in Food and Agriculture Organization (FAO) Irrigation and drainage document 56, the Penman-Monteith equation is used to estimate crop water needs. However, it requires knowledge of several environmental data including air temperature, wind speed, precipitation, and humidity. A change in the concentration of gases in the atmosphere can also have a significant impact on the resulting shift in climatic parameters (composition of greenhouse gases) [19]. According to Abdelhadi (personal communication, September 2022) the computed average increase in the reference crop evapotranspiration (ETO) when considering all the above-mentioned parameters is about 15% for the common crops in Bahrain when comparing the data between the years (1971 to 2000) and the last ten years (2010-2020).

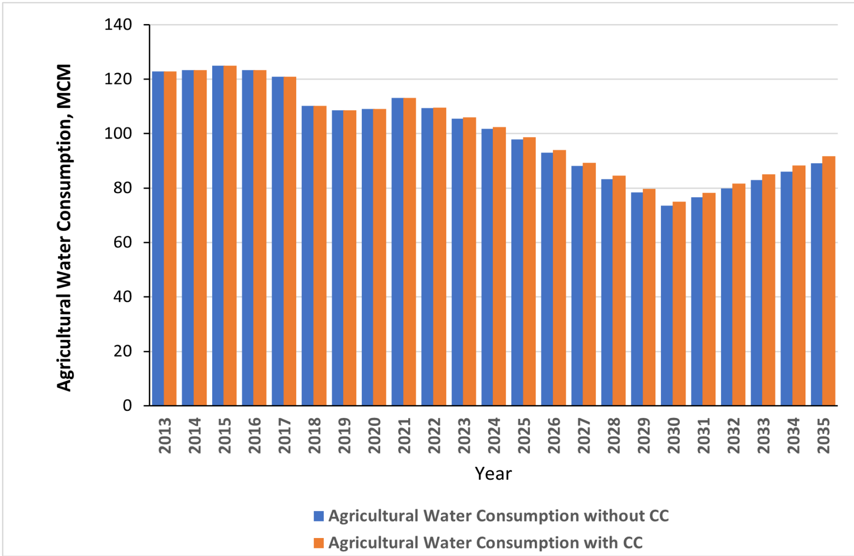


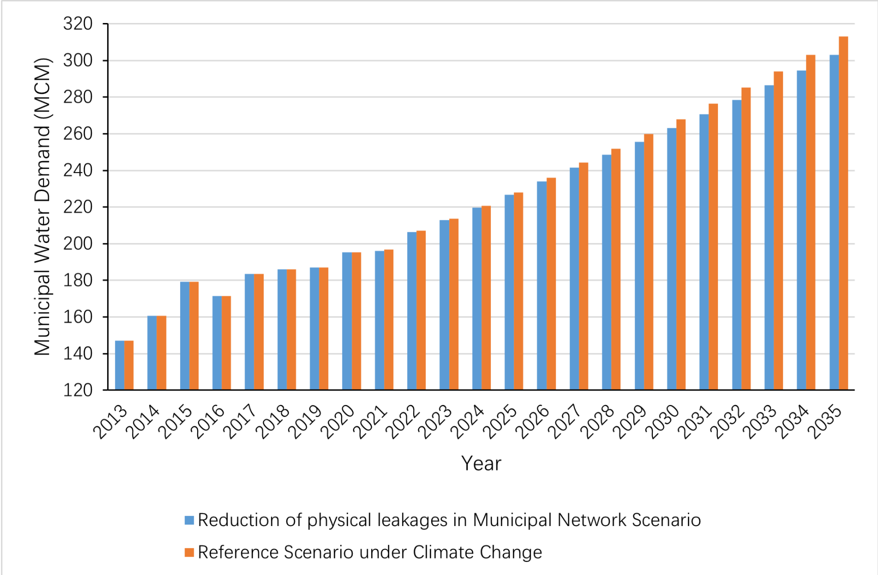
Figure 6. Impact of climate change on agricultural water consumption.

4.3. Reduction of Physical Leakages in the Municipal Water Distribution Network

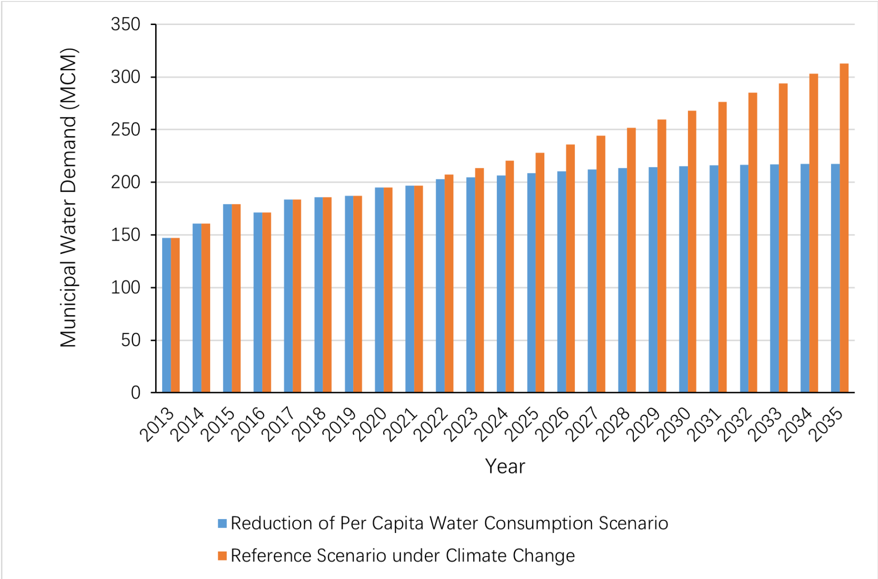
Reducing physical leakages in the municipal water distribution network is crucial for water conservation and meeting municipal water demand. The plan involves decreasing network leakages from 28.2% in 2020 to 10% by 2035, as outlined in the fifth strategic objective of the GCC UWS and Implementation Plan 2035 [15]. The target is chosen to represent the benchmark for international best practice. This can be achieved through the installation of leak-detecting devices, multi-frequency leak locators, and routine maintenance. Figure 7(a) illustrates the projected impact of leakage reduction compared to the reference scenario under climate change. By 2035, reducing leakage is expected to decrease municipal water production by 10 million cubic meters (MCM), resulting in a cumulative savings of 59 MCM of water in desalination plant production over the 14-year projection period from 2021 to 2035.

4.4. Reduction in Per-Capita Municipal Water Consumption

High municipal water usage in Bahrain is primarily due to relatively high per capita income, changing lifestyles, and low water tariffs. A long-term strategy to manage



(a)



(b)

Figure 7. Comparison between municipal water demand under the reference scenario and a) Reduction of physical leakages scenario; b) Reduction of per capita water consumption scenario.

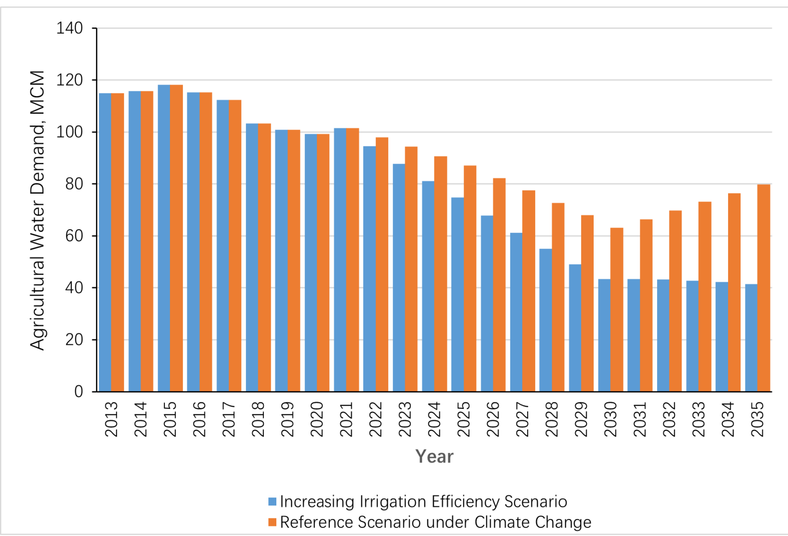
water demand includes reducing per capita water consumption through measures such as reviewing and restructuring the water tariff system to more targeted subsidies, promoting water-saving devices, improving public awareness, and implementing water saving building codes. These alternative aims to gradually reduce per capita water consumption from the current levels (168.81 cubic meters per year in Bahrain catchment and 142.21 cubic meters per year in Muharraq catchment) to 91.27 cubic meters per year (250 liters per day) by 2035, in line with the set target of the GCC UWS (2015-2035). The non-Bahraini population was excluded as their water consumption is already below the set target. Implementing this alternative is projected to reduce water demand from 313 MCM in the reference scenario under climate change to 218 MCM by 2035, as depicted in Figure 7(b), resulting in a cumulative savings of 627 MCM over the period from 2022 to 2035.

4.5. Increasing Irrigation Efficiency in Agriculture

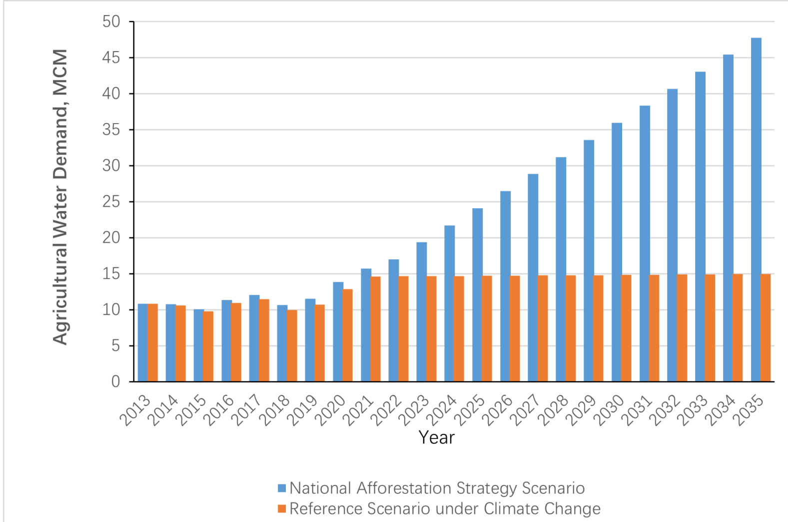
In Bahrain, the high-water consumption in the agricultural sector is primarily due to the widespread use of traditional irrigation techniques, which result in poor irrigation efficiency and significant water losses [9]. In 2021, the average annual water use for agriculture was 39,463 cubic meters per hectare, with an irrigation efficiency of only 32% [4]. Improving irrigation efficiency to 60% by 2035, as per the GCC UWS's sixth strategic objective, would reduce annual water use to around 21,000 cubic meters per hectare. Tools to achieve this include changing crop types, implementing advanced irrigation methods, controlling groundwater demand through adopting modern irrigation practices, introducing modern agricultural systems (e.g., smart agriculture and soilless culture), and implementing volumetric groundwater metering and pricing. Figure 8(a) illustrates that increasing irrigation efficiency could reduce agricultural water demand from 79.8 MCM under the Reference Scenario to 41.4 MCM by 2035, with cumulative water savings of approximately 271.7 MCM during the projection period (2022-2035). However, the government's successful efforts in preserving agricultural lands and safeguarding them from urbanization are projected to result in a continued increase in agricultural water demand in the coming years.

4.6. Increasing Volume of Treated Wastewater Used in the Agriculture Sector

The wastewater sector in Bahrain faces challenges related to low efficiency in wastewater recovery and a significant gap between treated wastewater production



(a)



(b)

Figure 8. Comparison of agricultural water demand between the reference scenario and a) Increasing irrigation efficiency scenario; b) National afforestation strategy scenario.

and utilization. Despite modern treatment facilities, only about 40% of treated wastewater is reused. As part of its commitment to the United Nations Framework Convention on Climate Change (UNFCCC) and its goal of achieving carbon neutrality by 2060, Bahrain has initiated the National Afforestation Strategy (NAS), which aims to double the number of trees to 3.6 million by 2035. This strategy will significantly increase the demand for treated wastewater for landscape irrigation. Figure 8(b) shows that under the NAS, the demand for treated wastewater will rise from 15 MCM in the Reference Scenario to 47.8 MCM by 2035, resulting in cumulative increase of treated wastewater utilization would be around 246.2 MCM during the period of the projection (2022-2035). Additionally, the volume of treated wastewater discharged to the sea will decrease by 22.6 MCM in 2035, with the NAS utilizing 68.7% of generated treated sewage effluent (TSE). Water requirements for the afforestation strategy are calculated using the landscape evapotranspiration formula, accounting for specific tree species suited to local conditions. Figure 9 illustrates the increased water demand when applying this formula compared to a constant annual water use rate, with a 3.4 MCM increase in 2035.

4.7. Increasing Volume of Treated Wastewater Used in the Agriculture Sector

Even with NAS utilization, there will be a surplus of treated wastewater in Bahrain. This surplus could be utilized in Managed Aquifer Recharge (MAR). The MAR option offers multiple benefits, including a secured water supply, improved water quality, prevention of seawater intrusion, and re-pressurization of overdrafted aquifers [20]. As part of an integrated water resources management plan, MAR can significantly contribute to restoring groundwater resources and is being currently investigated by SEA as an option to store surplus treated wastewater.

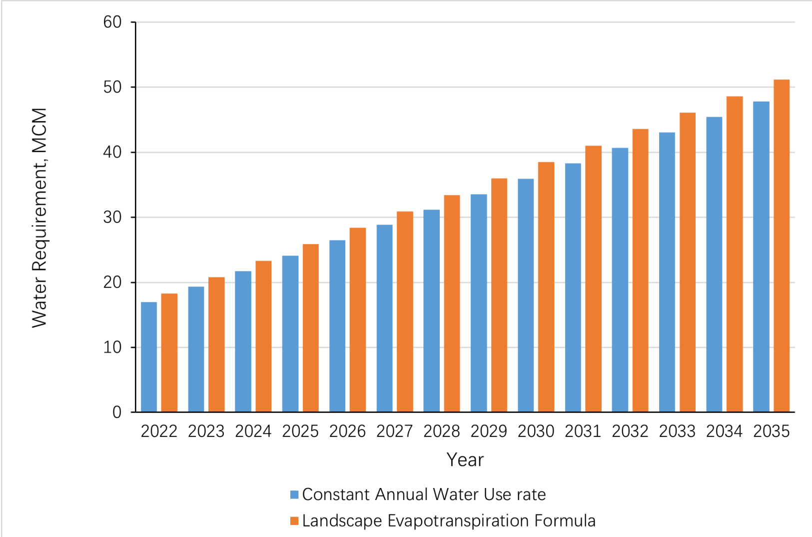


Figure 9. Comparison of water requirement using constant annual water use rate vs using landscape evapotranspiration formula-MCM.

Figure 10 shows that applying MAR from 2022 to 2035 would increase groundwater storage by 21% in 2035 compared to the Reference Scenario. Furthermore, implementing MAR could reduce unutilized treated wastewater discharge to the sea by 111 MCM from Bahrain catchment, and by 37 MCM in Muharraq catchment in 2035 (**Figure 11**). However, it should be noted that despite the implementation of MAR, there is a persistent increase in the volume of treated effluent discharged into the sea. This trend is primarily attributed to monthly inflows surpassing the design capacity of STPs, leading to reduced reuse rates. The decline in reuse is associated with the deterioration of effluent quality due to hydraulic overloading of treatment facilities and the absence of sufficient distribution infrastructure.

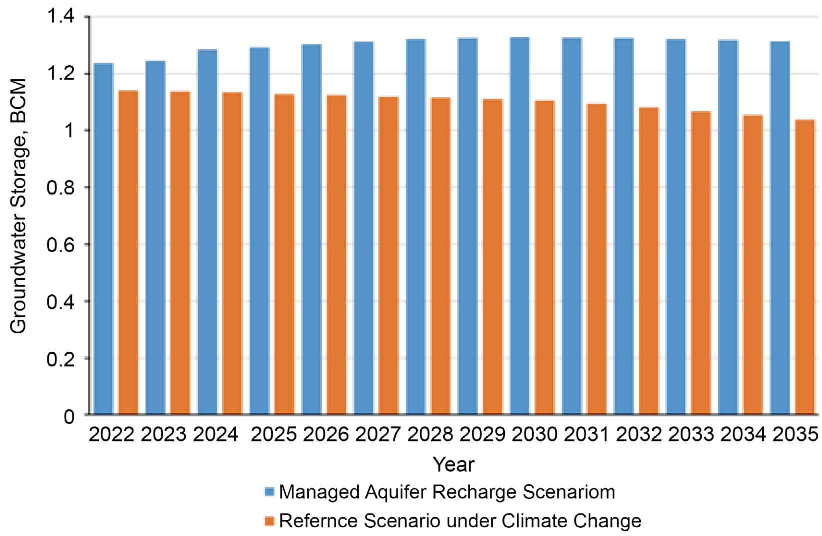


Figure 10. Comparison of increase in groundwater storage between reference scenario and managed aquifer recharge scenario.

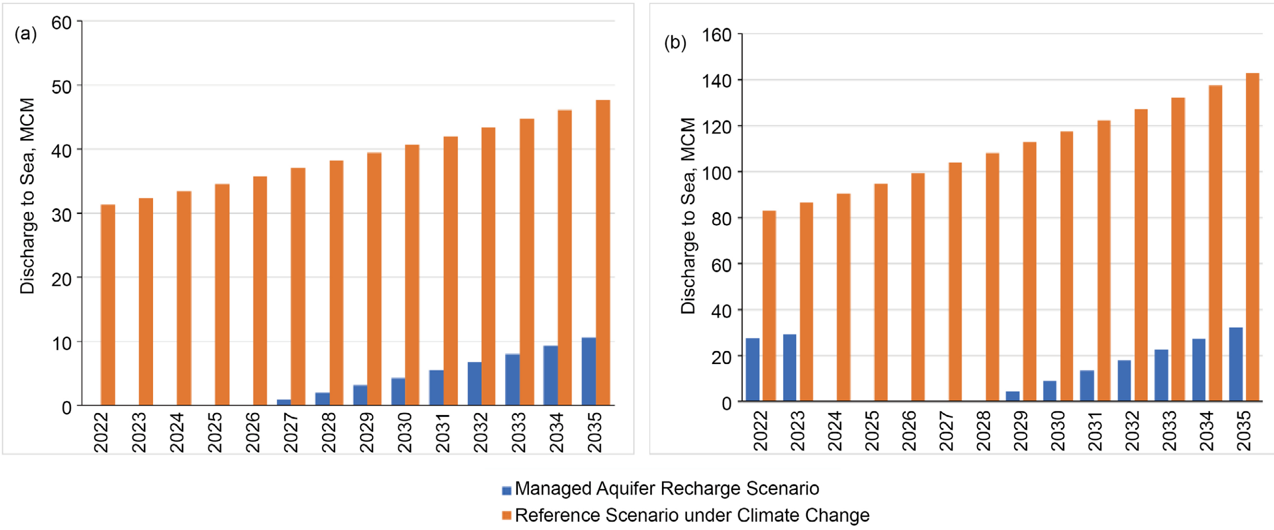


Figure 11. Comparison of discharge to sea amounts between reference scenario and managed aquifer recharge scenario for a) Muharraq catchment; b) Bahrain catchment.

4.8. Combined Effects of All Management Options

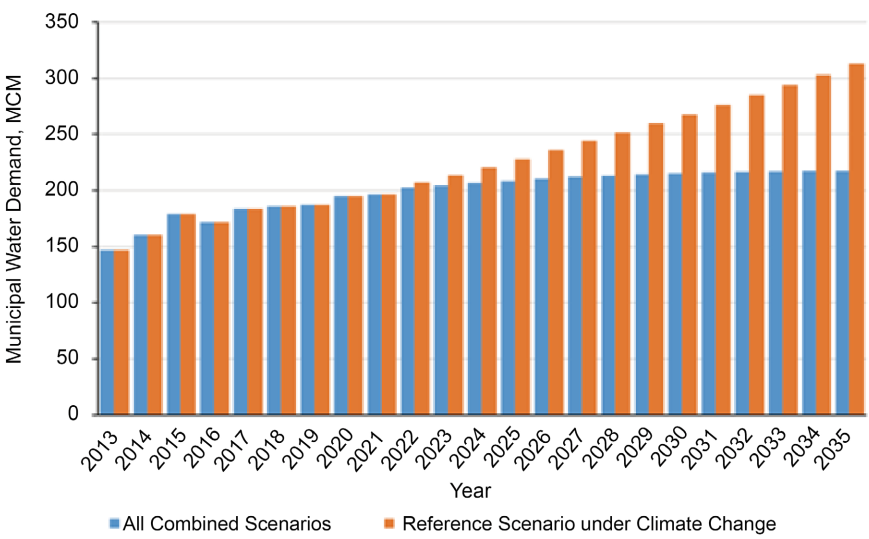


Figure 12. Comparison of municipal water demand between reference scenario under climate change and all combined scenarios.

The combined impact of implementing a comprehensive set of water management strategies, focusing on demand management and efficiency in Bahrain was evaluated to illustrate the effectiveness of integrated water resources management in achieving higher levels of sustainability of the water management system. This integrated scenario combines measures to enhance municipal water efficiency (reducing per capita consumption and physical leakage), improving agricultural irrigation efficiency, and increasing the use of treated wastewater through the NAS and MAR. The modeling results indicate that total municipal water demand could be reduced from approximately 313 MCM under the Reference scenario to about

218 MCM by 2035. This translates to cumulative water savings of about 627 MCM over the period from 2022 to 2035, achieving a reduction of around 30.5% in water usage by 2035. Figure 12 illustrates the projected annual water demand reduction under the combined management scenario.

4.9. Combined Effects of All Management Options

The demand for desalinated water in Bahrain is projected to rise due to population growth and the effects of climate change, increasing cumulative brine discharges from 13,504.4 MCM to 13,682.7 MCM under the RCP8.5 scenario between 2022 and 2035. This rise will elevate the salinity and temperature impacts of municipal water supply. The cumulative financial cost increase due to the additional 46.9 MCM municipal water demand is estimated at 93.6 million US$ (35.2 million Bahrain Dinars; BD) (Table 3). The primary driver for this increased demand is the domestic/household sector. Climate change also affects CO_2 emissions and energy demand, with an additional 127.1 MCM of natural gas needed, leading to cumulative increased CO_2 emissions of approximately 943.6 Mkg over the same period. Additionally, these conditions will result in a 1.3% cumulative increase in wastewater inflows to treatment plants from 2022 to 2035.

Table 3. Reference scenario results (with and without climate change).

Parameter	Current	Annual Totals in 2035			Cumulative Total by 2035		
	2021	Reference	CC	Difference	Reference	CC	Difference
Municipal Water Demand (MCM)	196.8	304	313	9	3553.8	3600.7	46.9
Cost of Water Supply (MUS$/BD)	393/ 147.6	606.4/ 228	624.5/ 234.8	18.1/ 6.8	7088.8/ 2665.4	7182.2/ 2700.5	93.6/ 35.2
Natural Gas (MCM)	533.3	823.8	848.2	24.4	9630.8	9757.9	127.1
CO_2 Emissions (Mkg)	3959.6	6116.5	6297.6	181.1	71502.5	72446.1	943.6
Brine Discharge (MCM)	747.8	1155.2	1189.4	34.2	13504.4	13682.7	178.3
Wastewater Generated (MCM)	146.6	226.4	233.1	6.7	2646.8	2682	35.2

Increased municipal water demand necessitates the expansion of desalination plants, resulting in higher financial, economic, and environmental costs. Mitigating these expenses can be achieved by reducing physical leakages and per capita water consumption in the municipal sector. Research indicates that decreased water consumption lowers production and distribution costs, reduces gas emissions, air pollution, and brine discharge, and slows down the depletion of natural gas reserves. The financial cost of the municipal water supply (production, transmission and distribution) is at 1.99US$ (0.750 BD/m^3) [11], and CO_2 emissions from desalination are estimated at 20.12 kg/m^3 (Al-Zubari *et al.*, 2018). Brine discharge from desalination plants is harmful to the marine environment, with each cubic meter of desalinated water producing about 3.8 m^3 of brine [5].

Reducing municipal water demand through adaptive management interventions will result in significant financial savings, reduced CO_2 emissions, and lower brine discharge, as shown in **Table 4**. The combined management measures can save up to 627 MCM of water, 1251 million US$ (MUS$) (470.25 MBD) in financial costs, 12,615 Mkg of CO_2 emissions, 2,382.6 MCM of brine discharge, and 1699.2 MCM of natural gas by 2035. It is important to note that while reducing physical leakages improves supply efficiency, it does not affect municipal water demand, whereas reducing per capita consumption provides substantially greater demand-side impact. Additionally, employing treated wastewater for irrigation preserves water resources in areas with limited freshwater, allowing reserves to be used for drinking and industrial processes [21], as shown in **Table 5**. The use of treated wastewater in the NAS and MAR represents a major economic opportunity for Bahrain, and they can further reduce treated wastewater discharge to the sea, contributing to environmental sustainability and enhancing ecotourism in areas like Tubli Bay [5].

Table 4. Cost reduction associated with adaptive management interventions in the municipal sector for the period 2022-2035.

Management Interventions	Total Cumulative Reduction (MCM)	Financial Saving (MUS$/MBD)	CO_2 Emission (Mkg)	Brine Discharge (MCM)	Natural Gas (MCM)
Reduction of physical leakages in the municipal water distribution network	59	118/44.3	1187	224.2	159.9
Reduction in per-capita municipal water consumption	627	1250/470.3	12615	2382.6	1699.2
All adaption measures combined	627	1250/470.3	12615	2382.6	1699.2

Table 5. Effectiveness of increasing treated wastewater reuse utilization for the period 2022-2035.

Management Interventions	Total Reduction in 2035 (MCM)	Reduction in 2035 (%)	Total Cumulative Reduction (MCM)
Reducing discharge to sea through increasing volume of treated wastewater used in the agriculture sector (National Afforestation Strategy)	15.6	8.5	117
Reducing discharge to sea through increasing volume of treated wastewater used in the agriculture sector (Managed Aquifer Recharge)	74.8	54	119
All adaption measures combined	147.9	78	1871

5. Conclusions and Recommendations

The Kingdom of Bahrain faces severe water management challenges due to its arid climate, rising sectorial water demands, and lagging wastewater treatment capacities and reuse plans. The financial, economic, and environmental costs of the system are significant, including energy requirements, operational expenses, and environmental impacts manifested by desalination brine discharge to the marine environment, greenhouse gases emissions, and generated wastewater that are treated and are unused as well as the untreated volumes discharged to the marine environment due to overflow. The current conditions of the water management system could threaten the continuation of the water sector in serving the Kingdom's sustainable development.

In general, Bahrain's water management system experiences low efficiency, which is manifested in relatively high per capita water use and high levels of non-revenue water due to physical leakage in the municipal sector, low irrigation efficiency in the agricultural sector, and low reuse rates in treated municipal wastewater. The costs associated with the current water management system are expected to increase with population growth, continued consumption patterns, and will be compounded by the impacts of climate change.

In Bahrain, most of management efforts in the water sector in Bahrain have focused on supply-side engineering measures and improvements. These efforts are represented by the expansion in desalination, groundwater withdrawal, and limited reuse of treated wastewater. In fact, this has led to the emergence of many unsustainable water uses and conditions, particularly low water use efficiency, growing of both water demands and per capita water use, increasing cost of water production, deterioration of groundwater quality and land productivity. There has been limited emphasis on demand-side management and efficiency measures, which have been investigated in this study for their effectiveness in raising the sustainability levels of the water sector in Bahrain.

The current water management system in Bahrain is modeled using a dynamic mathematical model, WEAP, and is used to simulate the system under various demand management scenarios. These scenarios are: reducing per capita water consumption and physical leakage in the distribution network in the municipal sector; increasing irrigation efficiency and the reuse of tertiary treated wastewater in the agricultural sector; and using surplus tertiary treated wastewater in groundwater recharge. The results indicate that these management interventions, if implemented, could significantly enhance the sustainability of the water management system yielding major financial, economic, and environmental benefits.

Conserving water in the municipal sector, which depends almost entirely on desalinated water reduces supply costs, greenhouse gas emissions, brine discharge, as well as generated wastewater and hence its treatment costs. Properly treated wastewater could meet most of the agricultural demands and hence lower stress on groundwater resources and allow their recovery. Moreover, it will support the objectives of the National Afforestation Strategy an important component in Bahrain's commitments to achieve carbon neutrality by 2060. The study findings provide critical insights for policymakers to enhance Bahrain's water resource sustainability and meet long-term development goals.

This work has focused on the municipal sector, as it is the main water user in Bahrain and due to the availability of detailed temporal and spatial billing data on its subsector, provided by the Bahrain Electricity and Water Authority. However, similar data could not be obtained for the agricultural sector, the second-largest water user in the Kingdom, due to the absence of agricultural statistical records. The agricultural sector lacks comprehensive records on the number of farms, their crops, water use, and their dynamic changes over time. Conducting regular agricultural censuses is essential for improving data accuracy for modeling and long-term water resource planning.

Moreover, to improve modeling and analysis under uncertainty, it is recommended that a stochastic approach is adopted as opposed to the deterministic approach. The main uncertain modeling parameters are population growth rates for both Bahrainis and non-Bahrainis. In addition, it is essential to enhance data collection and monitoring by regularly gathering comprehensive water sector data, such as leakage percentages, brine outflows, and detailed municipal water subsector consumption, along with conducting regular agricultural censuses to improve data accuracy for modeling.

To enhance the sustainability of the water management system in Bahrain, it is recommended to focus on: 1) lowering per capita water consumption in the municipal sector; 2) improving irrigation efficiency in the agricultural sector; and 3) increasing treated wastewater reuse in all appropriate sector including irrigation, landscaping and groundwater recharge. Implementing economic tools (e.g., tariffs), structural tools (e.g., building codes and water saving devices), and sociopolitical tools (e.g., education and awareness) will significantly improve the sustainability and efficiency of Bahrain's water management system. The viability of these tools under Bahrain's socio-economic conditions and their cost-effectiveness in achieving the three focus areas is recommended to be investigated in future studies.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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