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Virtual Water Conservation and Integrated Water-Resource Sustainability in Bahrain: A Modeling Framework and Case Study

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ABSTRACT: Bahrain is one of the most water-scarce countries in the world. Without permanent rivers, very little precipitation, heavily depleted aquifers and heavily dependent on energy-intensive desalination for drinking water. This research establishes and implements a unified framework of virtual water conservation and sustainable water management that integrates water footprint accounting, groundwater sustainability evaluation, desalination-energy-carbon relations, climate-adjusted demand modeling and digital water governance principles in a single indicator-based system. A national water-balance model includes virtual-water and water footprint accounting, groundwater mass-balance, specific energy and carbon intensity of desalination, and climate-adjusted demand model. Six sustainability metrics as Water Stress/Security Index, Groundwater Sustainability Index, Virtual Water Dependency Ratio, Carbon Intensity of Water Production, Net-Zero Water Index and Circular Water Index have been developed using the same framework and are evaluated in a representative reconstruction from 1990 to 2026 and a forecast from 2025 to 2050. Virtual-water imports are a critical component of the efficient water portfolio, much better than renewable domestic supplies, groundwater metrics show an oscillation from near-equilibrium to depletion and the carbon intensity depends on the energy source used for desalination. In five scenarios the net-zero and circular approach lead to the most positive impact on water security and decarbonization while the business-as-usual and climate-stress trajectories have an impact on groundwater sustainability. The strategy transforms virtual water from a trading concept to a water security tool and an easy to use, easily accessible way of accessing water for water-deficient Gulf economies looking to build climate-resilient, low-carbon water systems. unde omnis iste natus error sit voluptatem accusantium doloremque laudantium

1. INTRODUCTION

The lack of freshwater is one of the most crucial sustainability issues of the twenty-first century. Population growth, urbanization, industrialization, better living conditions, and climate change have increased the pressure on the limited resource-hungry world and over two billion people are now living in nations facing significant water scarcity**Error! Reference source not found.**. Water scarcity is especially acute in arid and semi-arid areas with little rainfall, high evaporation rates, and frequent droughts. The Gulf Cooperation Council (GCC) member countries - Bahrain, Saudi Arabia, Kuwait, Qatar, the United Arab Emirates, and Oman - have the lowest per-capita renewable freshwater supply worldwide, and meet their demands from groundwater extraction, desalination, wastewater recycling, and food import. Bahrain has particular challenges in this group as the GCC members, with its limited land surface area, lack of durable surface water supply, and over-dependent aquifers. Historically, the archipelago has been built on freshwater sources from the Dammam and Rus-Umm Er Radhuma systems**Error! Reference source not found.**. Increasing abstraction levels over recharge has led to a decrease in the water tables, intrusion of seawater, and high salinity. Bahrain has turned to unconventional water sources, with desalination as the main

source for drinking water and treated sewage effluent (TSE) for irrigation and landscaping. Desalination improves water security but also relates to energy usage, greenhouse gas emissions, operational expenses, and brine disposal; hence, sustainable planning will need to take water, energy, environmental, and economic factors into consideration**Error! Reference source not found.**.



Figure 1. Bahrain's water-resource management**Error! Reference source not found.**

Figure 1 illustrates Bahrain's water-resource management has evolved from groundwater abstraction to desalination, wastewater reuse, virtual water, and potentially artificial intelligence, digital twins, renewable-powered desalination, and circular, net-zero water systems between 1950 to 2050. A significant addition to tangible supply is virtual water; the amount of freshwater used in the creation of products and services. Allan proposed the concept in the 1990s in order to understand how water-deficient Middle Eastern countries remained food-secure since importing food or manufactured goods is essentially importing the water used in their production and therefore redistributes water over land rather than through physical transport**Error! Reference source not found.**. The idea is based on water-footprint accounting, which breaks consumption down into a blue area (surface and groundwater), green area (rainwater), and gray area assimilative). Virtual water imports are a supplementary resource that alleviates the pressure on aquifers and desalination facilities in Bahrain, but they are rarely taken into account in the context of the current indicator system. The water-energy-food (WEF) nexus considers these systems as mutually dependent: desalination transforms energy into water, agriculture uses both, and electricity production is made from water.

Climate change contributes to warming, evapotranspiration, and the necessity for cooling and irrigation, while the effects of rising sea levels increase as well. Digital technologies like smart metering, the Internet of Things (IoT), machine learning, and digital twins present new and innovative methods for predicting demand, identifying losses, and improving operations.**Error! Reference source not found.** As a result, the integration of these views with virtual water accounting still remains a neglected field in water-short countries. While Bahrain has a well-established water resource, there are four gaps. Most of the research is qualitative and not quantitative or prognostic. Second, there is a scarcity of frameworks that combine virtual-water commerce, water-footprint assessment, groundwater sustainability, desalination energy, and climate adaptation. Third, new technologies digital governance, artificial intelligence, and the circular water economy are rarely integrated in this effort. Fourth, it is not yet possible to develop quantitative measures for policy options.

Thus, the present research addresses these problems by assembling a coherent and indicator-driven framework and implementing it in Bahrain through a case study in 2050. Donations**Error! Reference source not found.**. (i) A detailed virtual water and water-footprint accounting framework in Bahrain is developed and integrated with groundwater mass-balance, desalination–energy–carbon, and climate-influenced demand models; (ii) a set of six sustainability indicators is laid out; (iii) five development scenarios up to 2050 are examined; (iv) digital water governance is considered in the national planning process; and (v) transferable policy advice is given to the GCC.

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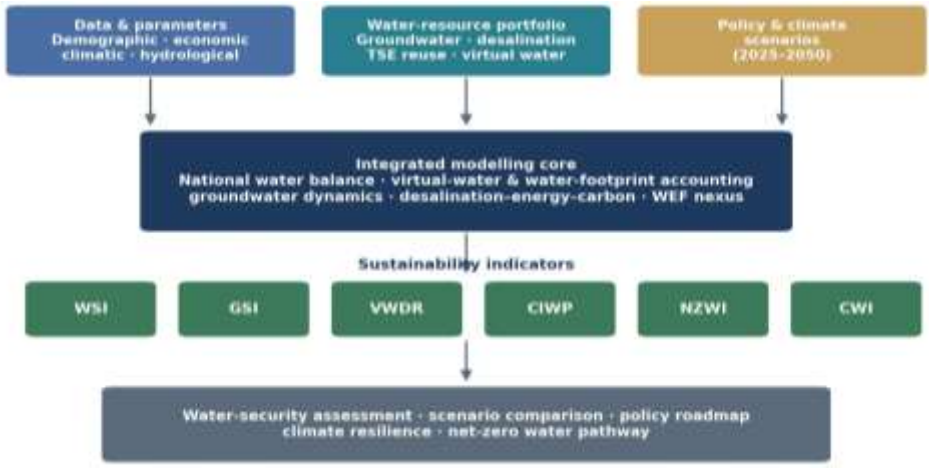


Figure 2. Framework of the integrated water sustainability assessment structure**Error! Reference source not found.**

Figure 2 summarizes the conceptual framework of the integrated water sustainability assessment model. It integrates data and parameters (demographic, economic, climatic, and hydrological), water-resource alternatives (groundwater, desalination, treated sewage effluent (TSE) reuse, virtual water), and policy and climate scenarios (2025 - 2050) into one global model. The model includes national water balance, virtual water and water footprint assessment, groundwater dynamics, desalination, energy and carbon interactions, and water-energy-food (WEF) relationship**Error! Reference source not found.**. The model generates sustainability measures WSI, Groundwater Sustainability Index (GSI), Virtual Water Dependency Ratio (VWDR), Carbon Intensity of Water Production (CIWP), Net-Zero Water Index (NZWI), and Circular Water Index (CWI) that underpin water security assessment, scenario analysis, policy formulation, climate resilience assessment, and the formulation of a net-zero water strategy.

The analysis is based on four interrelated research inquiries in relation to the essential aspects of Bahrain's water sustainability and security**Error! Reference source not found.**. What is the extent of virtual water in comparison with Bahrain's real water resources and how does it change with time? This question analyzes the effect of imported virtual water in food and other goods in relation to local freshwater resources and historical patterns and considers how international trade has been incorporated into Bahrain's water supply plan. What route will groundwater take and what is the risk of seawater intrusion in the form of extraction methods? This study examines the long-term water depletion trend of groundwater, aquifer depletion and coastal aquifers and how they cannot be protected from becoming inundated with seawater due to current extraction methods and determines the limits to which groundwater could become economically and ecologically unsustainable in the future. (RQ3) How does desalination energy supply and water production carbon intensity impact the environment and how can decarbonization be a net zero water sector?**Error! Reference source not found.**

The link between desalination technologies, electricity generation and greenhouse gas emissions and the transition to renewable energy, energy-efficient desalination and low-carbon technologies can reduce the carbon footprint of Bahrain's water sector and water supply and reliability to the extent that they are more reliable in the long term**Error! Reference source not found.**. (RQ4) How can supply generation, supply regulation, wastewater recycling, virtual water exchange and digital management in the future water security strategies and energy and carbon and groundwater cost recovery, in a way that is such that in the long term there is an overall sustainable water security in 2050 and where the water is not only safe but also affordable? This question applies a systems perspective to different policy portfolios and the future and seeks the best combination of technologies, institutions and management strategies for the water supply, groundwater conservation and energy and carbon efficiency and economic benefit for the future, in terms of sustainability.

All four research questions create the basis for a unified water sustainability model that integrates water management, climate and resilience in Bahrain and the need for evidence and to take action to ensure that Bahrain becomes a secure, circular and net zero water state by 2050.

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2. CONCEPTUAL BASIS AND RELEVANT STUDIES

2.1 Virtual Water and Water Footprint Measures

Virtual water has changed the way we look at water resources by expanding the accounting horizon beyond hydrology. The conventional approach was to look at only water that is available locally, but virtual water showed that trade carries water between countries; water-scarce importers protect their own water resources and exporters of water-heavy goods export freshwater. The idea had a great impact on agriculture, trade, and food safety policies. To illustrate, water footprint accounting has been used for a detailed analysis of freshwater consumption in production systems. The total footprint consists of the blue, green, and grey parts**Error! Reference source not found.**:

$$WF = WFblue + WFgreen + WFgray \quad (1)$$

The blue part shows the surface water and groundwater consumption, the green part rainwater that is taken out by evapotranspiration, and the grey portion water that is required to meet pollution for environmental requirements. Based on the research, the industry and energy sectors, urban systems, and national accounts were studied. It is related to carbon footprints and life cycle values, and it is a way to assess resource efficiency in the enterprise. Desert importers see such a point too.

2.2 Water Shortage and Virtual Water in The GCC

The GCC is one of the most water-scarce regions on the planet. In the region, annual rainfall is usually less than 100 mm, and evaporation is much more intensive, and few renewable resources exist, so it relies on groundwater, desalination, reuse, and imports. An observation that has been found in many GCC studies is that virtual-water imports are much greater at present than renewable domestic resources, and imported food is a hidden water source for growing populations**Error! Reference source not found.**. We are expecting virtual water imports to be the dominant part—and often greater than 70% of the actual water consumption in most countries in the GCC. Saudi Arabia's previous attempt to achieve cereal self-sufficiency by fossil groundwater irrigation, which was later shifted to strategic imports, illustrates the importance of domestic production and aquifer sustainability in the regional strategy which is now at the forefront.

2.3 The Relationship Between The Water-Energy-Food Nexus And Climate-Related Pressures

The WEF nexus tells us that how we optimize one system affects the others, and sector-specific optimization can simply transfer the pressure. In Bahrain, the connection is clear: desalination sacrifices energy for water; agriculture demands both water and energy; and if we don't acknowledge the third, we have a serious problem with total sustainability. Climate change intensifies these interactions. High temperatures will put more pressure on municipal, cooling, and irrigation systems and the need for desalination, but it will also increase the amount of seawater that is invading coastal aquifers. And as such, adaptive and integrated planning desalination, water reclamation, demand management, and virtual-water optimization must be integrated to achieve**Error! Reference source not found.**.

2.4 Digital Oversight Of Water Systems

Artificial intelligence, machine learning, and digital twin technologies have revolutionized water operations. Data-driven models based on artificial neural networks, random forests, gradient-boosted trees, support-vector machines, and long short-term memory networks have proven successful in estimating demand, leak detection, and desalination performance optimization. Digital twins generate real-world virtual models of physical systems, which are constantly updated based on sensor networks and SCADA data, so that predictive management is made possible. The combination of these technologies with virtual water accounting and sustainability analysis is a way to reduce costs, losses, and emissions and enhance reliability.

2.5 Strategic Positioning And Innovation

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So in this context, the current study contains a well-driven, indicator-based approach that considers virtual water as a key element in the national water balance alongside groundwater, desalination, and reuse; it also considers desalination in relation to its energy and carbon impact and uses a single, internally coherent set of indicators for transparent scenario evaluation through 2050**Error! Reference source not found.**. This synthesis, rather than any single factor, marks the innovation of the current study in comparison to other arid economies.

3. THE PRESENT CONDITION OF BAHRAIN'S WATER SECTOR

Bahrain is one of the world's most water-scarce nations. The availability of renewable freshwater is in short supply because of a lack of precipitation, high evaporation rates, low rainfall, few rivers, and limited replenishment; hence, national security is made possible by a combination of groundwater, desalination, water recycling, and virtual-water imports. Water resources are often divided into two categories due to the high-water scarcity in Bahrain. In the past 50 years, the system has transitioned from groundwater to desalination, with reuse and imports playing a more critical role. Natural sources of water are generally found in groundwater aquifers and ancient springs**Error! Reference source not found.**. Non-traditional resources include artificially produced or externally obtained supplies like desalinated ocean water, processed wastewater, reclaimed and runoff water, and virtual-water imports.

The rise in unconventional resources is an indicator of a transition from extraction to management and technology. A database of information for a typical baseline year shows that the total resources are 371 million cubic metres (MCM), with groundwater contributing about 54.6%, desalination about 35.6%, and treated wastewater about 9.7%. From this period, we can see that the total resources have increased from 83 MCM in the mid-1920s to 162 MCM by the late 1970s and further up to 331 MCM in the mid-1990s as non-conventional water resources become more developed**Error! Reference source not found.**. The path is characterized not just by volume but by structure: as we have increased the amount of natural groundwater, we are increasingly replacing it with manufactured and imported water, and this is the key change that defines the future and potential dangers to this country that we are dealing with.

Table 1. Representative composition of Bahrain's traditional water-resource supply at a baseline of around 371 MCM and the long-term expansion of total resources**Error! Reference source not found.**

Source / period	Value	Note
Groundwater (baseline share)	≈ 54.6%	Dammam and Rus–Umm Er Radhuma aquifers; stressed by over-abstraction
Desalination (baseline share)	≈ 35.6%	MSF, MED, RO; principal potable source, energy-intensive
Treated wastewater (baseline share)	≈ 9.7%	Irrigation and landscaping; fastest-growing conventional stream
Other (drainage, rainfall)	< 0.1%	Negligible in the national balance
Total resources, mid-1920s	≈ 83 MCM	Groundwater-dominated era
Total resources, late 1970s	≈ 162 MCM	Onset of desalination (first plant 1975)
Total resources, mid-1990s	≈ 331 MCM	Rapid non-conventional expansion

The water-resource development and structure in Bahrain's past is shown in Table 1. Groundwater became the main water source in the early stages of national water development and is about 54.6% of total water in Bahrain, with the Dammam and Rus-Umm Er Radhuma aquifers being heavily depleted from over extraction. Desalination is a major source of drinking water and has become the primary source of drinking water in spite of the high energy consumption. Treated wastewater accounts for about 9.7% of the national water supply and is the most rapidly expanding conventional water source, mainly used for irrigation and landscaping. Other sources, like drainage water and precipitation, are less than 0.1% of the water supply and thus Bahrain's natural freshwater resources are limited. The table also illustrates the rapid growth of total water resources for decades from about 83 million cubic metres (MCM) in the mid-1920s when groundwater was the source of water to about 162 MCM in the late 1970s after desalination was implemented and, by the mid-1990s, to nearly 331 MCM as non-conventional water resources began to grow quickly**Error! Reference source not found.**.

3.1 Subsurface Water

Aquifers remain strategic even as they are depleted. The Dammam aquifer has been able to cater to urban, agricultural, and industrial demand since the arrival of industrial expansion, but it is also being inundated with water which leads to pressure and salinity issues, as in the Rus-Umm Er Radhuma system**Error! Reference source not found.**. Storage develops with a mass balance between replenishment and extraction and sustainability means that at least some amount of replenishment must take place in order to compensate for extraction. As one example, abstraction has often been bigger than recharge in the past, and many aquifer units are unsustainable to be used at present.

3.2 Saline Water Conversion

Desalination is the primary source of drinking water. The main technologies used are multi-stage flash (MSF), multi-effect distillation (MED), and reverse osmosis (RO). RO is popular because it is cheaper and membrane expenses can be reduced, and current systems provide an energy consumption of about 2.5-4.5 kWh m^{-3} for feed salinity and recovery. Energy is the main input of operations and emissions, and as such, low-carbon energy sources are the key to sustainability**Error! Reference source not found.**.

3.3 Repurposing And Virtual Water

Sewage effluent is one of the rapidly growing resources, reducing groundwater extraction and contamination and supporting agriculture and landscape irrigation and circularity. Although virtual-water imports are not obvious in the infrastructure, they play a key role in the operational portfolio: since Bahrain imports huge amounts of food and industrial products and exports little agricultural products, the net virtual-water imports are positive and can be seen as a national water reserve that guarantees food security without further extraction from production in the country.

3.4 Requirements And Barriers

Demand is driven by three sectors: a growing and expanding municipal population; a growing city population and an increasing economy; agriculture, which is still in demand despite the decline in cultivated area and the increased reuse of water; and industry, which needs a reliable supply of cooling and processing of oil and petrochemicals**Error! Reference source not found.**. On the ground, the water is being depleted and invaded, with water being extracted and desalinated, and the use of desalination is an energy- and carbon-intensive process which, in turn, is in the way of changing the water industry, the growth of the population, food security, distribution and non-revenue problems, and the production of water. This is what sets in motion the development of a more integrated, indicator-based methodology and the shift towards a circular and digitally managed, low-carbon water economy.

4. THE UNIFIED MODELING FRAMEWORK

4.1 Summary and Data Foundation

Our framework shows Bahrain's water system through a series of interconnected balancing includes a national water balance, virtual-water (water footprint metrics), groundwater mass balance, desalination energy-carbon module and climate-adjusted demand model, from which we generate six sustainability indicators on a consolidated basis. The

application is used as an example: the parameter values are taken from the published GCC and Bahrain data, the national statistics, and the conventional water footprint, while the monthly reconstructions from 1990 to 2026 and the 2025 to 2050 are the model-generated sequences to show both the functionality of the framework and the direction and magnitude of the trends, not the real numbers.

4.2 National Water Balance

At the national level, the variation in the water storage over time is defined as the difference between the inflows and outflows:

$$\frac{dW}{dt} = I - O \quad (2)$$

It is called mass balance or conservation equation which describes a change in the amount of a substance kept inside a system in time. W is the quantity of the substance in the system (water in a reservoir or chemical in a tank) and dt/dW is the change of the quantity over time and I is the rate of inflow (input) into the system and O is the rate of outflow (output) from the system. The formula indicates that the accumulation rate of the material is equal to the intake less the outflow. If the input is higher than the outflow, then the amount of material in the system is higher (this is the outflow)**Error! Reference source not found.**. If the inflow is less than the outflow, then the amount of material in the system is lower (this is the inflow and outflow). If the inflow and outflow are equal, then the storage is also equal (the system is always balanced).

This basic yet important equation is employed in hydrology, environmental engineering, chemical engineering, and in many other fields to assess and predict the dynamics of systems related to mass transfer and retention. For example, we assume that a reservoir has 100 liters of water in it. The liquid flows in at the rate of 8 liters a minute (I=8) and exits at the rate of 5 liters per minute (O=5). Then dt/dW = 8 minus 5 which results in 3 L/min. This shows that the water level in the tank is rising at a rate of 3 liters per minute.

$$I = GW + D + TSE + VW + R \quad (3)$$

It represents the overall inflow (I) to a water system that is the sum of all main sources of water into the system. GW is the groundwater inflow, which is the water that comes from underground aquifers, D is the direct precipitation (rainfall) that falls directly on the aquatic environment or research area, TSE is treated sewage effluent, which is the treated wastewater that is released into the system and can be used as a water resource, VW is virtual water, which is the water associated with imported goods or the water that is transferred by humans, depending on the context, and R is surface runoff, which is water that enters the water system from the land surface after precipitation or snowmelt**Error! Reference source not found.**.

Together, these elements make up the entire water intake, rendering it an invaluable instrument for water balance assessments, hydrological evaluations, and water resource administration.

$$O = M + A + In + C \quad (4)$$

Where, the total outflow (O) of water from a hydrological system to represent the total quantity of outflow (O) from a hydrological system as the sum of all the main routes through which water exits the system. M denote the use of municipal water consumption, which includes water for drinking in the city, residential and commercial, and public, as well as agricultural water for irrigation and animal purposes, In represents the industrial water consumption, which includes water used for manufacturing, processing, and other industrial operations, and C the use of water in hotels, restaurants, offices, and retail facilities.

All these are the main sources of water discharge from the system and the main sectors that use or extract water from this water. This formula is used in water balance and resource management work to identify the total water demand of the system and the impact of various sectors on the total water discharge and plan for water supply and disposal and for planning sustainable use and conservation of water**Error! Reference source not found.**.

4.3 Virtual Water and Water Footprint Assessment

This equilibrium is the financial model in which virtual water is considered as a real resource. The total virtual-water imports and exports are calculated by multiplying the volumes of traded commodities by their water footprints:

$$VMimport = \Sigma iQiWFi, \qquad VWexport = \Sigma jQjWFj \tag{5}$$

It measures the virtual water that gets transferred through the trade of goods and commodities. Virtual water is the volume of water used in the production of a product in which it is not transferred physically. In these formulas, Qi and Qj are the amount of imported or exported goods, respectively, and WFi and WFj are the water footprint of each item that is the amount of water required to make a unit of that item. The sum symbol (Σ) is the virtual water transferred by all imported or exported products to calculate the total virtual water flow. VWimport indicates the total volume of virtual water entering a region through imported goods, and VWexport indicates the total virtual water that exits the region in terms of the total volume of virtual water from the export of non-native products**Error! Reference source not found.**. These equations are widely used in the management of water resources and sustainability research to investigate the hidden transfer of water from one country to another by trade and to help policymakers to understand water usage, water security, and how to make the best use of water that is sustainable.

So, the net balance is $VWnet = VMimport - VWexport.$ Positive values indicate net virtual-water increase. The examples of unit footprints shown correspond to typical values of about 1.3-1.8 m3 kg-1 for wheat, 2.5-3.5 for rice, 3.5-4.5 for chicken and 15-20 for beef, representing the high embodied water of animals.

The crop water footprints are calculated for each unit of yield:

$$WFblue = \frac{CWUblue}{Y} and \frac{WFgreen}{Y} \tag{6}$$

where CWU is crop water use and Y is yield (where the grey component corresponds to dilution requirement:

$$WFgrey = \frac{L}{Cmax - Cnat} \tag{7}$$

where pollutant load is L, maximum allowable concentration Cmax and natural concentration Cnat. The virtual water consumption of a country is represented by the Virtual Water Dependency Ratio (VWDR):

$$VWDR = \frac{VWimport}{VMimport + Wdomestic} \tag{8}$$

which is close to zero with minimal dependence and approaches one with significant reliance on imported virtual water.

4.4 Sustainability of Groundwater

Aquifer storage changes according to the disparity between replenishment and extraction:

$$\frac{dS}{dt} = (R + L) - (A + D) \tag{9}$$

where R is recharge, L is lateral inflow, A is abstraction and D is discharge. The equilibrium value is $R + L = A + D$. There are two non-dimensional indicators of the water quality, the Groundwater Sustainability Index and the Groundwater Depletion Index:

$$GSI = \frac{R}{A}, and\ GDI = \frac{A - R}{R} \tag{10}$$

where GSI > 1 and GDI < 0 indicates sustainability, GSI equal to 1 indicates balance and GSI below 1 indicates unsustainable use. The risk of intrusion is limited by the Ghyben–Herzberg equation z ≈ 40h (the depth z of freshwater below sea level for a head h above it), indicating that minor reductions in head can lead to significant saline encroachment.

4.5 Desalination, Energy and Carbon Emissions

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The efficiency of desalination is based on its energy consumption and the resulting emissions. Annual energy consumption and emissions are determined by:

$$SEC = \frac{E}{Q},\ E_D = SEC * Q_D, CO_2 = EF * E_D \quad (11)$$

where Q_D is the output per year and EF is the grid emission factor. The Carbon Intensity of Water Production (CIWP) standardizes emissions relative to production (kg CO_2 m^{-3}), facilitating technological comparisons. Advancements in decarbonization are represented by a Net-Zero Water Index:

$$NZWI = 1 - \frac{CO2}{CO2,max} \quad (12)$$

which nears one as emissions decrease towards zero. In the context of renewable integration, with renewable proportion $RF=E_R/E_T$, emissions are represented as CO_2 = (1 - RF) EF SEC Q_D, indicating that CO_2 approaches zero as RF approaches one.

4.6 Demand, Climate Adaptation, and Prediction

Baseline demand is anticipated using a compound-growth model and modified for temperature rise:

$$WD_t = WD_0(1 + r)^t(1 + \gamma\Delta T) \quad (13)$$

with growth rate r, climate-sensitivity coefficient γ, and temperature increment ΔT; population is represented as $P_t = P_0 e^{rt}$. A structural regression connects demand to its determinants.

4.7 Indicators of Sustainability and Its Incorporation

Six metrics, outlined in Table 2, convert model states into analogous, dimensionless performance measures encompassing water security, groundwater condition, trade reliance, carbon intensity, decarbonization, and circularity. A weighted composite amalgamates these elements for scenario evaluation:

$$IWSI = w_1GSI + w_2WSI + w_3(1 - VWDR) + w_4CWI + w_5NZWI, \Sigma w_i = 1 \quad (14)$$

where dependence is incorporated as (1 - VWDR) to ensure all components enhance with sustainability. Scenario formulation and policy enhancement reduce a cost function concerning supply, energy, and carbon while adhering to demand, sustainable yield, emissions, and budget limitations, with uncertainty examined using Monte Carlo sampling of growth, warming, and efficiency variables.

Table 2. Definitions and understanding of sustainability indicators for frameworks**Error! Reference source not found.**

Indicator	Definition	Interpretation
Water Security Index (WSI)	Effective supply relative to demand: $\frac{GW + D + TSE + VW}{WD}$	≥ 1 secure; < 1 deficit
Groundwater Sustainability Index (GSI)	Recharge over abstraction, $\frac{R}{A}$	> 1 sustainable; < 1 depleting
Virtual Water Dependency Ratio (VWDR)	Imported virtual water over effective demand	→ 0 low; → 1 high dependence
Carbon Intensity of Water Production (CIWP)	Emissions per unit water, $\frac{CO_2}{Q_D}$	Lower is better (kg CO_2 m^{-3})
Net-Zero Water Index (NZWI)	$1 - \frac{CO_2}{CO_{2,max}}$	→ 1 near carbon-neutral

Circular Water Index (CWI)	Reused water over total demand, $\frac{TSE + reuse}{WD}$	Higher indicates stronger circularity

5. EXEMPLARY RESULTS AND ANALYSIS

In this section we apply the framework to Bahrain. The temporal series, as stipulated are based on published parameters and are not actual observations.

5.1 Assessing Virtual-Water Equilibrium And Reliance

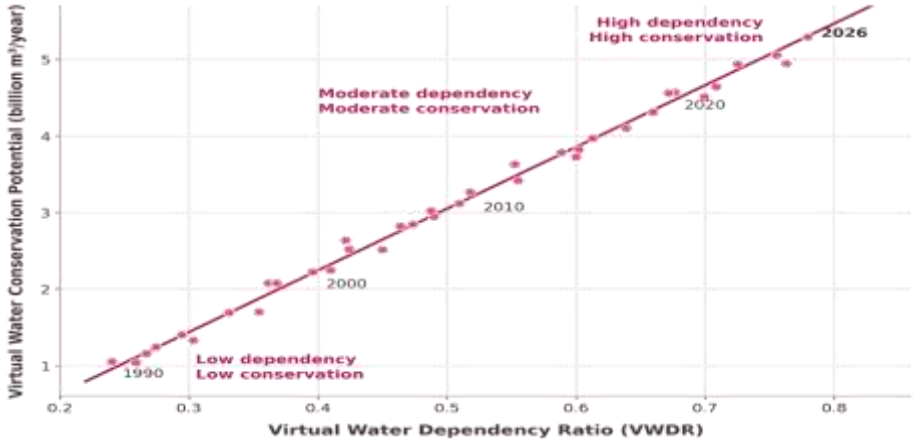
Due to substantial imports of food and industrial goods to Bahrain and very little agricultural exports, the net virtual-water imports are very positive, and, according to the GCC data, much higher than renewable domestic resources.**Error! Reference source not found.** This is in line with the embodied-water intensity of the traded commodities: livestock and processed commodities have the biggest footprints, and thus the sector is dominated by meat, dairy and cereals importing too much embodied water in terms of their weight in Table 3. Using the unit footprints on the import volumes, the total virtual-water flows are much higher than domestic renewable resources, in line with the regional data that we have seen that imported virtual water accounts for more than 70% of the effective consumption in many GCC countries.

Table 3. Virtual-water content of major imported commodities, showing the embodied water intensity used in our analysis

Commodity	Virtual-water content	Relative intensity
Wheat	≈ 1.3–1.8 m^3 kg^{-1}	Moderate
Rice	≈ 2.5–3.5 m^3 kg^{-1}	High
Poultry	≈ 3.5–4.5 m^3 kg^{-1}	High
Beef	≈ 15–20 m^3 kg^{-1}	Very high
Milk	≈ 0.9–1.2 m^3 L^{-1}	Moderate

The Virtual Water Dependency Ratio increases with the reconstruction period, rising from a low dependency in the early 1990s to a high dependency by the 2020s, due to population increase, a deteriorating groundwater quality and a lack of domestic agriculture. The conservation equivalent (the freshwater that local production would need) also correlates with dependency: higher reliance on imports leads to higher domestic conservation and reduced aquifer stress and delayed desalination development in Figure 3**Error! Reference source not found.**. This positive correlation helps to establish virtual water as a viable water-conservation strategy but also highlights the relevance of supply chain and price risks in food security policy. Viewing this ratio as a strategy and not just a result in Bahrain for the long run, the country can strategically build up its import portfolio, focusing on the most water-intensive goods that are most necessary for saving a lot of oil in order to manage the total market in a way that is more sustainable for the country.

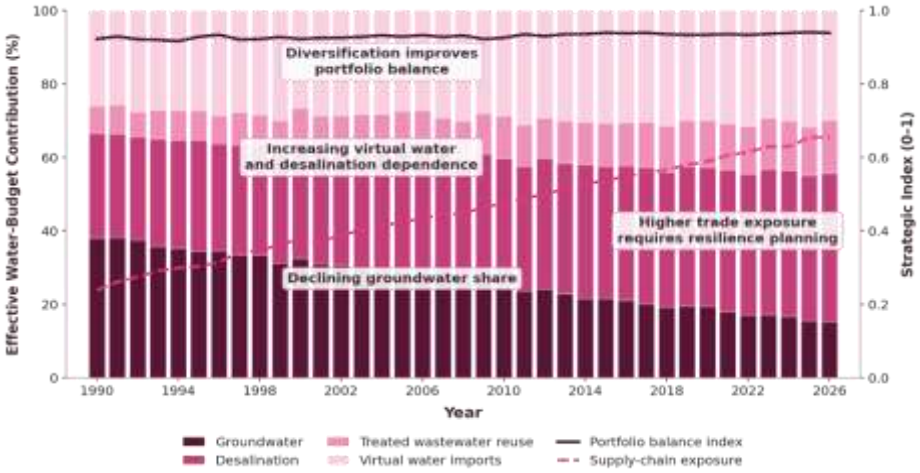
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Graph 1. Relationship between the Virtual Water Dependency Ratio (VWDR) and virtual-water conservation potential over the illustrative period

Increasing reliance on imported virtual water is associated with progressively larger domestic freshwater savings, indicating a transition from low-dependency, low-conservation conditions toward high-dependency, high-conservation conditions.

The evolving national water budget makes the same point at portfolio level: the groundwater share declines while desalination, reuse, and virtual water grow, shifting the system from groundwater dominance toward a diversified structure in Graph 1. Diversification improves reliability multiple independent pathways reduce the impact of any single disruption but raises supply-chain exposure as import dependence increases, underscoring that resilience is achieved by balancing pathways rather than maximizing any one of them.



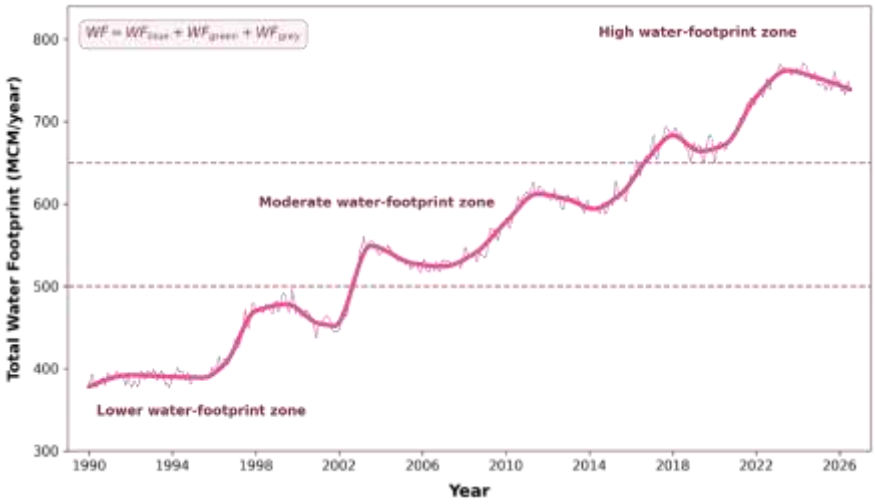
Graph 2. Bahrain's water-security portfolio including diversification and supply-chain indicators

Graph 2 shows how groundwater, desalination, treated wastewater reuse, and virtual water imports have evolved in Bahrain's overall water security model along with evidence of diversification and supply chain vulnerability. The system shifts from a groundwater-centric supply stream to being more dependent on desalination and imports.

5.2 Water Imprint Progression

The water footprint of the country increases from being virtually zero to maximum as population increases, urbanization, and living standards increase direct and embodied consumption in Figure 5. The rise in water footprint, fueled by local withdrawals and imported embodied water, indicates a need to increase efficiency, reuse, circular-economy initiatives, and virtual water optimization to mitigate the water footprint growth and still ensure service quality**Error! Reference source not found.**.

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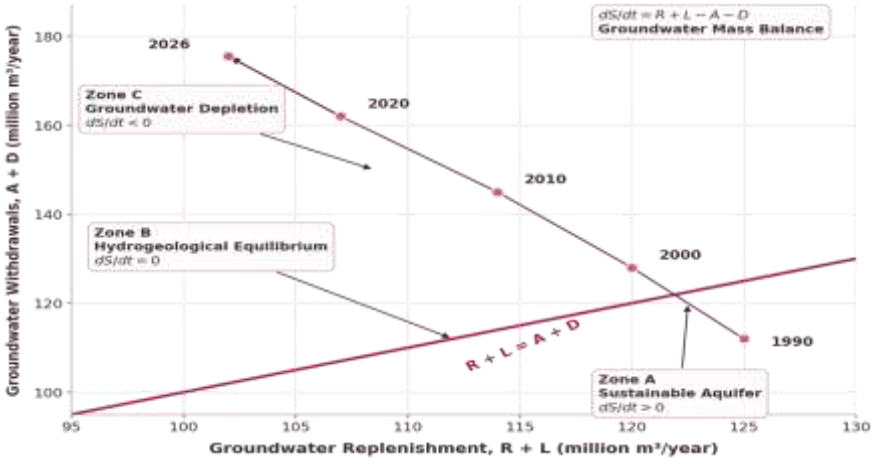
Graph 3. The evolution of Bahrain's overall water

Graph 3 shows the evolution of Bahrain's overall water footprint (blue + green + grey) and the moving average trend and utilization zones. The continuous increase indicates demographic and economic growth as well as growing dependency on locally and internationally supplied water.

5.3 The Sustainability of Groundwater and the Encroachment of Seawater

The balance of replenishment vs withdrawal as illustrated by the equilibrium line shows that the water balance has been shifted from almost balanced in the early 1990s to a situation where withdrawals are now exceeding replenishment.

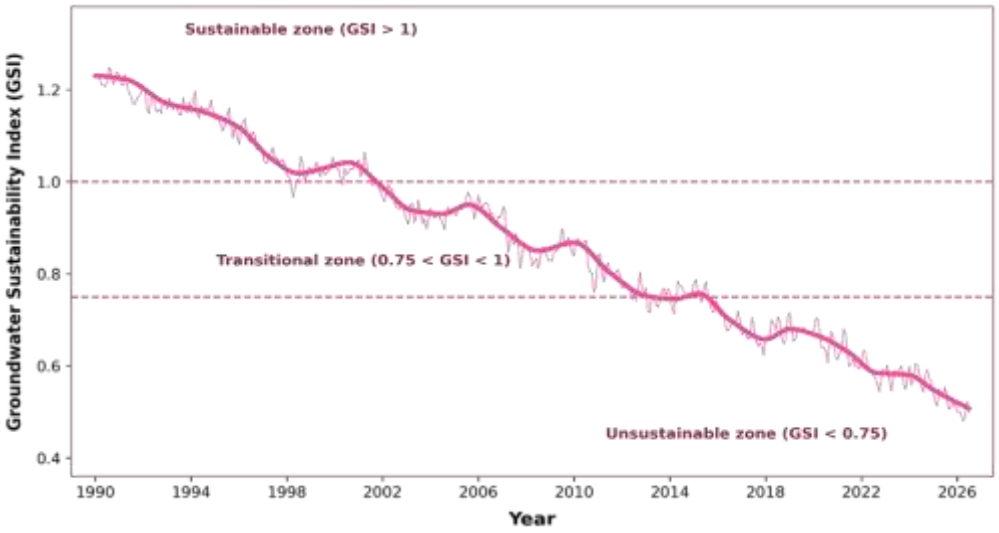
Due to a shrinking arid recharge and increased demand from population growth, urbanization, and industry, changes in storage are negative and the hydraulic heads are reduced, and pump energy is increased due to the Ghyben–Herzberg mechanism and intrusion**Error! Reference source not found.**. The Groundwater Sustainability Index is dropping towards the equilibrium value in a way that indicates a transition into unsustainable practices in Figure 6. These results indicate that groundwater alone cannot lead to long-term sustainability and regulated recharge, reuse, demand regulation, and virtual-water optimization are needed to stop depletion.



Graph 4. Groundwater Sustainability Assessment Framework

Graph 4 illustrate the groundwater replenishment (recharge + lateral inflow) against withdrawal (abstraction + natural discharge). Points below the equilibrium line indicate sustainable operation ($dS/dt > 0$), points above indicate depletion ($dS/dt < 0$). The track is away from near-equilibrium to depletion.

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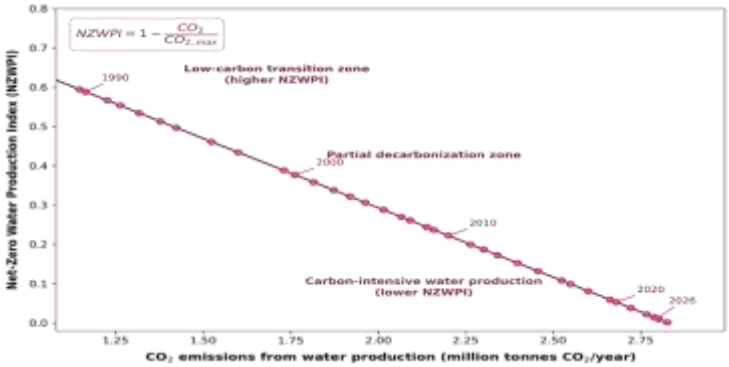


Graph 5 Representative development of the Groundwater Sustainability Index (GSI)

Graph 5 shows the development of the groundwater where, values greater than 1 indicate that recharge is more than abstraction and less than 1 means stress. The downward trend is a reflection of increasing abstraction to finite recharging.

5.4 Desalination, Energy and Carbon

As energy is the main input to desalination, where the intensity of the carbon is determined mainly by the energy source for fossil-based power, the increase in production is accompanied by a decrease in the Net-Zero Water Index, but for renewable fractions in terms of energy recovery, waste heat utilization and efficient membranes the index is increased to unity. To show the accounting with a real case, a maximum reference of 3.0 Mt CO2 yr^{-1} and current emissions of ~ 1.8 Mt yr-1 gives NZWI ≈ 0.40 which means that there is still a lot of decarbonization potential to be done. The negative relationship between the emissions and the index is a measure to be taken to track progress to the net-zero water sector**Error! Reference source not found.**.



Graph 6. Relationship between water-sector carbon emissions and the Net-Zero Water Index (NZWI)

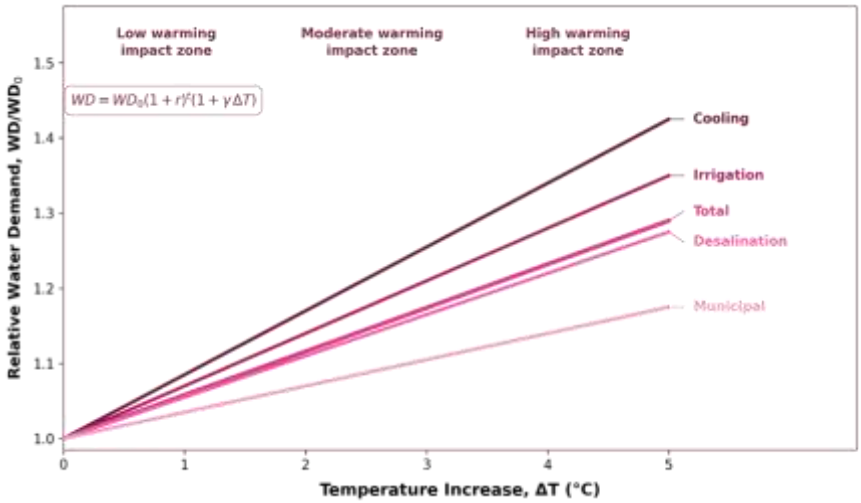
The relationship between carbon emissions from the water sector and the NZWI is shown in Graph 6. Higher emissions are associated with lower index values; decarbonization of desalination allows the index to be closer to unity and zones between carbon-intensive, transitional and low-carbon operations. The Net-Zero Water Index is normalized using the data shown in Table 4, which illustrates the levels of carbon emissions based on the desalination configuration.

Table 4. Levels of carbon emissions based on desalination configuration

Configuration	CO_2 (Mt yr^{-1})	Relative carbon intensity
Best available technology / renewable-powered	0.5	Lowest
Reverse osmosis (grid power)	1.5	Low–moderate
Multi-effect distillation	2.2	Moderate–high
Multi-stage flash	3.0	High
Worst-case reference	3.5	Reference maximum

5.5 Effects of Climate Change on Demand

The climate adjusted demand model shows that all sectors respond to increasing temperatures and cooling and irrigation are the ones with the highest sensitivity due to high thermal load and evapotranspiration. This is followed by desalination and municipal demand as demonstrated in figure 9. The increasing desalination output then increases energy consumption and, in the absence of decarbonization, emissions, and the WEF feedback that links temperature with water and energy strain is also in place**Error! Reference source not found.**. These results point to the need for demand management, recycling, efficient and renewable energy-driven desalination, and intelligent irrigation as the effective methods of adaptation.



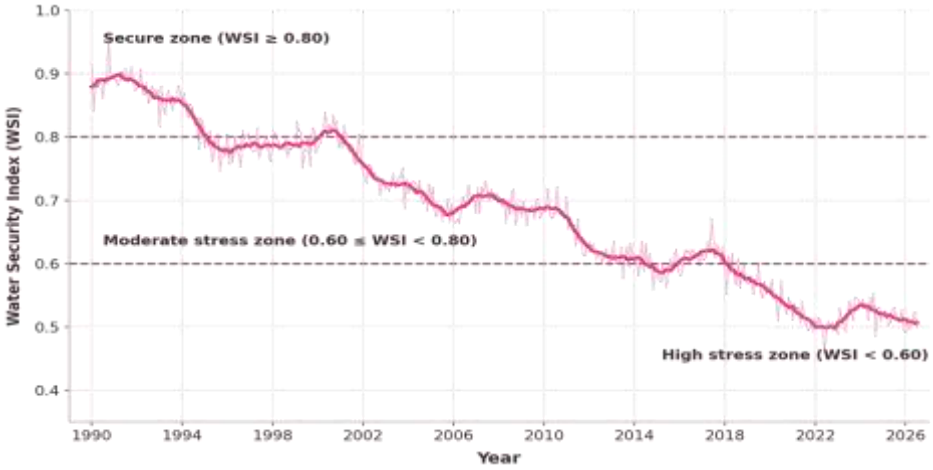
Graph 7. Climate Change Impact on Water Demand

Graph 7 displays the municipality, desalination, irrigation, cooling, and total water demand responses to in rease in temperature in climate-adjusted demand theory $WD = WD_0(1 + r)^t(1 + \gamma\Delta T)$. Cooling and irrigation are the most impactful.

5.6 Integrated Water Security

We include supply security in the Water Security Index. At reconstruction time, it diminishes when the demand from population growth, urbanization, groundwater depletion, and reliance on desalination increases and supply is not diversified enough, transitioning from secure to moderate and high-stress scenarios as shown in Figure 10. The trajectory points to the main planning question for the future: which solutions can guarantee security while also protecting energy, carbon, and groundwater.

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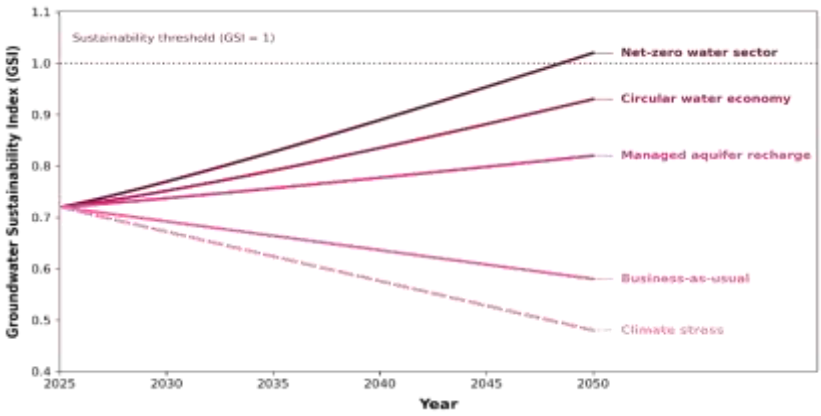
Graph 8. Water Security Index (WSI)

Graph 8 illustrates the evolution of the water security index (WSI) and the moving average and the thresholds for secure (≥ 0.80), medium-stress (0.60-0.80) and high-stress (< 0.60) water security. The decrease indicates increasing pressure on water supply.

6. FUTURE SCENARIOS AND SUSTAINABILITY EVALUATION (2025-2050)

There are five developmental trajectories compared to the 2025 benchmark, and we compare them using the indicators. (i) business-as-usual, keeping business as usual and not much change, with low reuse and no significant reform; (ii) climate stress as a result of the rapid warming and increased demand; (iii) renewable-powered desalination as renewable desalination based on solar reverse osmosis and energy recovery to increase the renewable share to unity; (iv) circular water economy with reuse and recovery of resources to improve the Circular Water Index; and (v) net-zero water sector (renewable desalination, digital optimization and low-carbon resources).

The comparison of scenarios of groundwater sustainability is the general trend shown in Graph 9. In a typical business scenario (and more significantly in case of climate stress) the Groundwater Sustainability Index is still outside the equilibrium and is showing a growing depletion and intrusion risk. With the management of recharge and circular water economy and net-zero solutions management, it can help to overcome the downturn or even reverse it, with the abstraction of water in the system and the withdrawal of water from the system and reclamation and reuse and import of water from the system. Using the same reasoning for the same values, net-zero and circular scenarios deliver the most beneficial overall water security and decarbonization, while supply expansion without diversity or decarbonization is the worst overall result. The general refrain is that resilience is a property of a portfolio: it comes from the management of the system at large—groundwater conservation, renewable desalination, recycling, virtual-water optimization, demand regulation, etc.



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Graph 9. Groundwater Sustainability Index (GSI)

As shown in Graph 9, the Groundwater Sustainability Index (GSI) provides scenario projections up until the year 2050. Climate stress and business as usual pathways are not sustainable because they are below the sustainability level (GSI = 1), while managed aquifer recharge, circular water economy, and net zero pathways are sustainable since they stabilize or restore sustainability. Table 5 shows the qualitative performance of the scenarios across the indicator set. The scenarios are shown to be improving, largely steady, or declining compared to the baseline.

Table 5. Qualitative performance of scenarios across the indicator set (↑ improving, → broadly stable, ↓ deteriorating relative to baseline).

Scenario	Water security (WSI)	Groundwater (GSI)	Carbon (NZWI)	Circularity (CWI)
Business-as-usual	→	↓	↓	→
Climate stress	↓	↓↓	↓	→
Renewable desalination	↑	→	↑↑	→
Circular water economy	↑	↑	↑	↑↑
Net-zero water sector	↑↑	↑	↑↑	↑

7. WATER GOVERNANCE IN THE DIGITAL WORLD

These multiple, low-carbon paths are increasingly dependent on digital capabilities. Artificial intelligence can turn various water-sector data into predictive analytics to predict demand, leak and failure detection, desalination efficiency, groundwater and water quality, and asset management**Error! Reference source not found.**. In the demand management, population, economic activity, temperature, humidity and urbanisation are related to demand through various models (from structural regression to neural and ensemble), such models are used to predict demand during different seasons and in the long run using RMSE, MAE, and R^2. Two additional layers in forecasting are added to the process. Smart water networks in IoT sensing, communication, analytics, automation in real time track flow, pressure and quality (pressure, quality, losses, etc).

This helps the system to detect leaks, failures and unauthorized connections early and the non-revenue water is less than billed volume divided by the production (the produced volume). Digital twins provide a continuous virtual version of the physical system that is integrated with SCADA and sensor feeds, which is able to analyse the scenario ahead of the physical action and provide predictive maintenance and maintenance of equipment health. For desalination applications, this can be done so that the total cost of energy, chemicals, and maintenance is reduced while maintaining the recovery and quality level. These are the same kinds of instruments and governance in the same regard as the tool itself.

Smart governance must integrate utilities, regulators, industries, farmers, research institutions, citizens and international partners to develop a common data and sustainability framework, where decisions are made transparent, responsive and evidence-based. An index of digital maturity (i.e., sensor coverage, data quality and analytical capability) can identify readiness and prioritize capital investment. Bahrain will adopt a cyber-physical water system that combines smart metering, IoT, artificial intelligence, digital twins, renewable energy-based desalination, virtual water optimization and circular economy to maximize efficiency, resilience and sustainability.

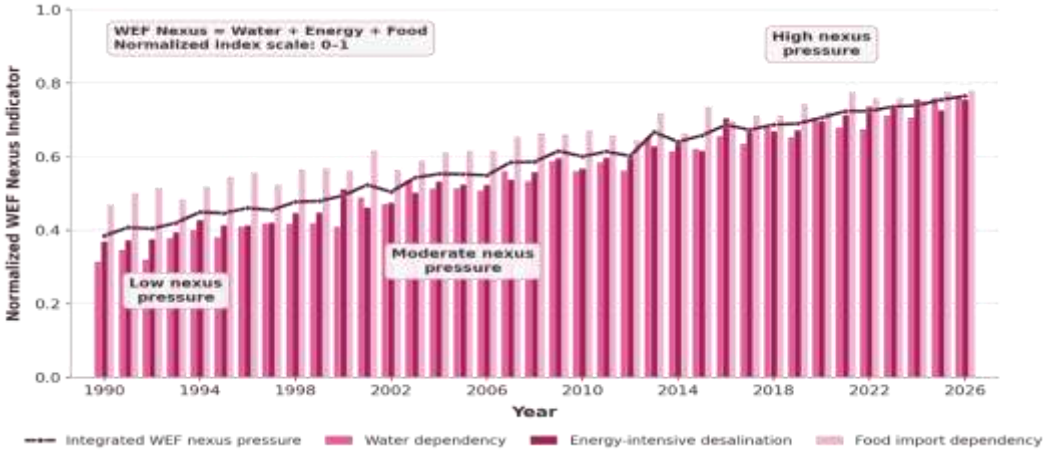
8. DISCUSSION

8.1 The Water-Energy-Food Relation in Bahrain and The Gulf Cooperation Council

It is confirm that Bahrain and the GCC are connected and that water, energy and food management need to be linked. The increase in water demand, energy-intensive desalination, and food imports are associated with the development of the system and the changes in one of them impact the other in Figure 12. This relationship is based

on the physical basis; desalination converts energy into water so a rise in water demand increases energy consumption and without decarbonisation emissions; food imports are water so a rise in imports increases virtual-water flows and reduces domestic withdrawals**Error! Reference source not found.**.

This suggests that sector-specific optimization may transfer rather than alleviate pressure and the growth of irrigated agriculture is threatening groundwater and the desalination increase may increase emissions, making it clear that good governance that is inter-related and based on the nexus is required for the sustainability of the country.



Graph 10. Water-Energy-Food Nexus Indicator

Graph 10 illustrates the depictive progression of water, energy and food nexus metrics of Bahrain and the GCC: water resources, energy-demanding desalination processes and food imports and a nexus-pressure index. They all show increasing trend over time and demonstrate an increasing interconnection of all the three systems. Geographical evaluation. Bahrain, Qatar, Kuwait and the UAE rely on virtual water, which is due to the resource deficit and the financial ability to import.

Saudi Arabia is a good example of the shift from cereal self-sufficiency to strategic imports, and the UAE and Qatar are aware of the limitations of local agriculture. Bahrain's limited land and poor groundwater quality means farming growth in the long run will be extremely limited and virtual water imports will be a key driver for long term food security, so food security and water security should be approached in a more cohesive manner.

8.2 Virtual Water as a Means for Water Security and Its Trade-Off

One thing we can take away from this is that virtual water should not be seen as a short-term anomaly but rather as an inter-governmental resource that will build up the national water budget and a strategic means of security. Imported goods are able to move highly water-intensive manufacturing to the water-rich areas, which means the water that is used in water production can be stored and the water used to fuel aquifers and desalination facilities can be created in the country. This conservation would be a matter of several times the renewable domestic supply**Error! Reference source not found.**. But this reliance also puts us at risk of fluctuations in the world economy, geopolitical instability and logistics problems. Virtual water should be part of a multi-pronged approach that includes groundwater conservation, renewable energy desalination, and recycling and not just a substitute for the local resources. From a reliability perspective, diversity allocates risk to autonomous channels and strengthens system resilience on the basis of supply chain resilience.

8.3 Desalination, Carbon Reduction and Circular Economy

Desalination will continue to be the basis of drinking water supply and therefore, sustainable water supply will depend on energy consumption. Since the amount of carbon in the water is indicative of the energy source, the focus must be on the reduction of these energy sources (e.g., efficient membranes, energy recovery, waste heat) as well as to increase the renewable portion to unity at which the production is already carbon neutral. Circularity is also beneficial: the reuse of treated wastewater and resource recovery reduces the demand for water and the energy

needed for those resources to be used. The scenario analysis shows that decarbonized desalination and circular reuse, enabled by digital tools, can be more effective than single-lever methods in the composite.

8.4 Policy Consequences and National Strategy Alignment

There are multiple policy trajectories that come directly from this. Virtual water must be officially incorporated into national water accounts and food security strategies so that our strategic reserve process and supply chain diversification is in place. Sustainable groundwater conservation must be integrated with abstraction regulation, the collection and treatment of wastewater and monitoring of water supply depletion and intrusion to be kept at an upper hand. Reuse should be expanded and included in agriculture and landscape development for circularity. Desalination should shift towards renewable energy sources and energy recovery to ensure lower carbon intensity through increased Net-Zero Water Index. The distribution efficiency should be increased via leak management and non-revenue water reduction by smart metering, IoT, artificial intelligence and national digital twin in order to enable governance to work with evidence. These guidelines are in line with Bahrain's long-term sustainability goals that are based on resource efficiency, environmental conservation, climate adaptation and technological development and are applicable to other GCC contexts.

8.5 Constraints and Future Activities

The research is a working theory, an example and not an empirical evaluation. The reconstructions from 1990 to 2026 and projections from 2025 to 2050 are derived from models based on published data. Future work objectives include calibrating and validating against high-resolution national data on trade flows, aquifer dynamics and desalination processes; using machine learning for long-term demand, groundwater and quality predictions; creating a national digital twin that integrates water and energy systems and green-hydrogen pathway for effective implementation, conducting comparative studies across countries to understand the scope of GCC cooperation in trade, reuse and climate adaptation; and a detailed economic impact and optimization analysis of the interventions. These enhancements would make the current framework a decision-making tool for operational planning.

9. CONCLUSION

It introduced a quantitative and indicator-based methodology to evaluate virtual-water conservation and sustainable water management in Bahrain and we have used this as a case study to make a future case study for the Kingdom of Bahrain in 2050. By taking virtual water into account as a central part of the national water balance along with groundwater, desalination and reuse and integrating it with groundwater mass balance, desalination energy-carbon module, climate-adjusted demand, and a set of six sustainability indicators, we have consolidated perspectives that are usually considered separately.

Three conclusions have emerged. First, virtual water imports are a key component of Bahrain's efficient water resources as they are likely to exceed renewable domestic water supply significantly and are a practical reserve that provides food security for the country while relieving pressure on aquifers and desalination sites - albeit with the trade-off of supply chain instability, which requires careful monitoring. Second, groundwater indicators are declining across all sectors and are more likely to be interlinked to the present water used, making it clear that water aquifers alone can never provide long-term sustainability and so require the management of recharge, reuse and demand. Third, because the carbon intensity depends on the energy used for desalination, decarbonization thus making the renewable proportion more balanced along with cyclical reuse can be the most effective way to a low-carbon, resilient water industry.

For the five prospective scenarios, the net-zero and circular strategies yielded the highest combined benefits in water security and decarbonization, whereas the business-as-usual and climate-stress approaches compromised groundwater sustainability. The main takeaway is that resilience is a portfolio: diversity, integration are the key elements, and a digitally enabled governance model that is more flexible and adaptable than a single source of water. The paradigm is open, replicable and adaptable, presenting GCC and other water-starved economies with a sound, business case model for climate-resilient, low-carbon water management. With national data as a reference, it can be used as a decision-support tool to help with water availability in a context of growing population, climate change and resource interdependence.

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AUTHOR CONTRIBUTIONS

Lorem A. Ipsum: Conceptualization, Investigation.

Dolor B. Sit: Methodology, Laboratory Analysis.

Amet C. Consectetur: Data Curation, Formal Analysis.

Adipiscing D. Elit: Supervision, Writing—Review & Editing.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ETHICS STATEMENT

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Ethical approval was not required for this study.

DATA AVAILABILITY STATEMENT

Lorem ipsum dolor sit amet, consectetur adipiscing elit. Data supporting the findings of this study are available from the corresponding author upon reasonable request.

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