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A system dynamics approach to management of water resources in Qatar

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ABSTRACT

Rapid global population growth and extensive urbanization threaten water sustainability, hindering sustainable development. This issue is particularly acute in arid regions such as the Gulf Cooperation Council (GCC), where the scarce natural water resources are overexploited. Effective water resource management (WRM) is pivotal in overcoming this challenge. This holistic study presents an innovative approach to address water sustainability at a national scale by developing a WRM decision support system (DSS) leveraging system dynamics modeling (SDM). Employing a unique scenario design framework developed in this study, the DSS simulates Qatar's water resource system behavior for 2021 to 2070 according to nine clustered policy scenarios presenting different degrees of sustainability designed accounting for changes in physical, environmental, and socioeconomic patterns. Our results reveal that the "business-as-usual" (BAU) WRM policy can balance water supply and demand for only 32 years. According to the best policy scenario, the sustainability of the water supply could be ensured for up to 50 years by increasing the water supply by 10 % and reducing consumption by 10 %. Additionally, to aid policymakers in fostering water resource sustainability, groundwater conservation strategies are proposed using the unique scenario design framework by limiting the yield to the safe abstraction level and emphasizing the significance of preserving non-renewable groundwater resources as a "backstop" resource for the country. While marking the first holistic research study in Qatar by utilizing the SDM approach to tackle national-scale WRM challenges, the established WRM DSS model is equally applicable to other GCC countries and similar arid regions.

1. Introduction

Water is fundamental to life and serves as the backbone for societal development. Sustainable WRM is crucial for achieving stability between economic growth, environmental and human development (Xian et al., 2022). Furthermore, it is paramount to create a long-term equilibrium between supply and competing regional demand from different societal subsystems (Darbandsari et al., 2020). WRM fosters resilient communities and promotes equitable growth, involving effective planning, allocation and conservation of water resources (Cosgrove and Loucks, 2015). Successful WRM plays a crucial role in addressing numerous sustainable development goals (SDGs) altogether, in particular, clean water and sanitation (goal #6), zero hunger (goal #2), good health and well-being (goal #2), climate action (goal #13), sustainable cities and communities (goal #11) and responsible consumption and production (goal #12) (Lahlou et al., 2023; Salvia et al., 2019). Therefore, addressing water scarcity challenges using effective WRM strategies represents the way forward to achieving sustainable development (Al Khoury et al., 2023), especially in water-scarce regions and arid environments such as the GCC countries (Al Rashed et al., 2023). In the Arabian Peninsula, water scarcity issues are severe due to minimal precipitation, harsh weather, and high evaporation rates (Priyan, 2021). This makes surface freshwater resources scarce and scattered. Water demand mainly relies on nonconventional water sources since natural water resources are scarce (Alhaj et al., 2017; Moghaddasi et al., 2022) and overexploited and necessitates effective WRM policies for long-term water resource sustainability.

The WRM entails intricate and intertwined relationships among water resources, human activities and socioeconomic and

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Nomenclature

Abbreviations

ANN	Artificial Neural Network
BAU	Business-as-usual
BMED	Bipolar Membrane Electrodialysis
CLD	Causal Loop Diagram
DSS	Decision Support System
DW	Desalinated Water
FIFA	International Association Football Federation
GCC	Gulf Cooperation Council
GCM	Global Climate Models
GDP	Gross Domestic Product
GW	Groundwater
MAR	Managed Aquifer Recharge
RCM	Regional Climate Models
SA	Systems Approach
SDGs	Sustainable Development Goals
SDM	System Dynamics Modeling
SED	Selective Electrodialysis
SFD	Stock and Flow Diagram
SVM	Support Vector Machines
SW	Surface Water
TSE	Treated Sewage Effluent
UN	United Nations
WRM	Water Resource Management

Variables and symbols

AD	Agriculture water demand
CD	Commercial water demand
DD	Domestic water demand
ED	Environmental water demand
GD	Government water demand
i	Water supply type
ID	Industrial water demand
j	Water demand type
k	Water supply level
l	Water demand level
MCM	Million cubic meters
MRE	Maximum relative error
N	Total time
n	Time instance
RE	Relative error
RI	Reliability index
R^2	Coefficient of determination
S	Shortage
WD	Water demand
WS	Water supply
WSI	Water sustainability index
$Y_{actual,n}$	Actual historical value at time instance "n"
$\overline{Y}_{actual}$	Average of actual historical values
$Y_{simulated,n}$	Simulated value at time instance "n"

environmental subsystems (Freitas and Magrini, 2013; Makanda et al., 2022; Mott Lacroix and Megdal, 2016). These interconnected subsystems are complex, and a holistic analysis of a WRM is challenging (Al Khoury et al., 2023). Therefore, the systems approach is essential to analyze the water system holistically and devise effective WRM strategies that ensure harmony among all the interconnected subsystems of the society (Naeem et al., 2023; Saravanan, 2008).

SDM is a systems approach that facilitates researchers and decision-makers in holistic WRM system understanding by analyzing the long-term consequences of policies, recommendations, and regulations across connected subsystems. In water-related studies, SDM helps achieve a system's equilibrium by balancing the competing water needs and avoiding the unintended consequences regarding water resource sustainability (Pluchinotta et al., 2021; Zomorodian et al., 2018). The policy scenario analysis capability of SDM makes it an attractive tool for WRM decision-makers. It helps the analysts design and tests several policy scenarios using a simulation model and evaluate the system behavior over time (Zarghami and Akbariyeh, 2012; Zhang et al., 2008). This approach also simulates potential system disruptions, enabling the design and testing of adaptive WRM policy responses (Li et al., 2023; Mirchi et al., 2012). By adopting an SDM approach, WRM decision-makers can efficiently reduce system vulnerability, foster the sustainability of water resources, and make valuable contributions to societal sustainable development (Stojković et al., 2023).

Qatar represents a unique case study for WRM analysis within GCC, characterized by natural water scarcity, rapid urbanization, increasing water demand due to socioeconomic development, and high dependence on desalinated water (Saleem et al., 2023). In addition, over-extraction of groundwater is a pervasive issue in arid regions, as evidenced by previous studies (Ahmad and Prashar, 2010; Dawadi and Ahmad, 2013; Stave, 2003), with particularly dire consequences for the aquifers in Qatar as observed in the recent reviews (Abbas et al., 2023; Aloui et al., 2023; Lahlou et al., 2023). Similarly, the other GCC countries are also experiencing accelerated socioeconomic growth, lately centered on tourism, and developing as host countries for mega-sport events (Abbas et al., 2023), which adds a challenge for the WRM decision-makers to ensure a sustainable supply to meet the current and future water demand. While existing studies, such as those conducted by (Al Rashed et al., 2023; Aloui et al., 2023; Lahlou et al., 2023; Mohamed et al., 2020), have explored various aspects of WRM in GCC countries, they have often overlooked the intricate and dynamic feedback interactions among the subsystems, holistically. Additionally, most of the earlier research was concentrated on WRM policy analysis using SDM at the basin level (Dehghani et al., 2022; Gohari et al., 2013; Madani and Mariño, 2009), with limited attention given to policy analysis at the national level.

Furthermore, a systematic water supply and demand scenario design framework could not be found in the literature. To bridge these research gaps, this paper aims to devise resilient WRM strategies leveraging the SDM approach that enable Qatar and similar arid areas such as GCC countries to foster sustainable development by ensuring adequate water availability. Furthermore, the natural water scarcity and water storage limitation of the nonconventional water sources in arid regions, notably in GCC, necessitate adopting the WRM strategies that can foster groundwater conservation.

This study addresses the identified challenges and research gaps with the following objectives:

- **Holistic system understanding**: Devise a framework for comprehensively analyzing an arid region's complex water resource system using SDM, focusing on Qatar as a case study.
- **Decision support system**: Develop a DSS leveraging SDM to enhance stakeholder engagement and assist policymakers in determining the tipping points of various WRM strategies where the water demand in the system will exceed the supply.
- **Unique scenario design framework**: Design a scenario generation framework with the dual objectives of facilitating stakeholder engagement and aiding policymakers in formulating a range of water supply and design scenarios while systematically evaluating their impact on water resource sustainability.
- **Groundwater conservation policies**: Assist policymakers in formulating and integrating groundwater conservation strategies

that emulate real-life options for arid regions, applying to Qatar as a case study.

Following the introduction, a literature review on WRM using the SDM approach is presented in Section 2. Section 3 details the methodology highlighting SDM application for effective WRM using causal loop and stock-flow diagrams. Furthermore, a unique WRM scenario design framework formulated in this study is also illustrated in Section 3. Section 4 covers the results and discussions, including the policy implications and recommendations, whereas Section 5 concludes the research findings.

2. Literature review

Water scarcity due to climate change and increasing demand coupled with hydrological uncertainty and the risks of extreme weather events is already a reality in arid and hyper-arid environments, and strengthening water security is imperative against this issue. Institutional tools incorporating legal and regulatory frameworks and incentives are needed to allocate and preserve water resources. At the same time, the complexity and interconnectedness of systems, sectors, and actors in WRM require methodological approaches that account for complexity and can also integrate and emphasize feedback within the integrated system. The system dynamic model has been widely used to analyze the WRM aspects in several regions (Dehghani et al., 2022).

An investigation into WRM strategies in Shenzhen, China, was conducted using the SDM approach by Sun et al. (2017) to address the challenge of bridging the supply-demand gap. Given the steady growth in population and economic activity, the study emphasized prioritizing supply expansion projects. Furthermore, the study assumed a stable supply throughout the simulation, whereas analyzing disrupted supply scenarios is advised as possible future work. However, the research presented a substantive analysis addressing the equilibrium between supply and projected demand (Sun et al., 2017). Yet, the study did not address the impact of water conservation strategies. In contrast, the WRM policy, focusing exclusively on supply expansion while not addressing demand management, backfired in an arid region of Iran. Employing the SDM approach, (Gohari et al., 2013) have shown that increasing supply in the Zyandeh Rud basin using water diversion projects inadvertently led to a subsequent rise in per capita demand. Although expanding the supply strategy worked well in the short term, it was a less effective long-term WRM approach.

Moreover, estimating regional demand is imperative to ensure timely planning and investment in supply projects. The study by Qi and Chang (2011) has affirmed the appropriateness of SDM as the preferred tool for water demand estimation, in contrast to multivariate regression and time series analysis. The recommendation is attributed to the latter analytical techniques being ill-suited for capturing the intricate nonlinear dynamics inherent to the system.

The policy evaluation using the scenario analysis technique of the SDM approach proves to be highly effective for analyzing WRM strategies under uncertain future parameters. The study by Madani and Mariño (2009) used the SDM approach to conduct WRM policy scenario analysis in Iran's Zyandeh Rud river basin. The study found that water supply and demand balance in the basin can be achieved by population control coupled with the enhanced supply from the water diversion project. These research findings facilitated the regional WRM decision-makers to minimize the groundwater over abstraction. Analyzing the water scarcity issue using scenario analysis in Tabriz, Iran (Zarghami and Akbariyeh, 2012) has suggested enhancing supply through an inter-basin water transfer project, improving water availability by 45 % during the simulated time. Likewise, the study by Kotir et al. (2016) has identified that water infrastructure investment in Ghana's Volta River Basin is the desirable policy scenario to balance increasing regional demand compared to the cropland expansion policy. Scenario analysis complemented with the optimization approach is used by Li et al. (2018) to minimize the water shortage in China's Zhengzhou region. Additionally, Liu et al. (2022) have conducted an SDM-based policy scenario simulation of WRM strategies in China. In the analysis, the WRM system is evaluated using four development policy modes: economic development policy, sustainable development policy, environmental-focused policy, and business-as-usual policy. The system performance against each WRM policy is evaluated using the supply-demand ratio.

While useful, the methodology employed by previous studies exhibits limitations, as it proves challenging and occasionally unrealizable to shape national policies exclusively from the perspective of WRM. Prioritizing environmental sustainability and ecological protection, only a handful of nations might adopt WRM policies that constrain economic growth. For instance, adopting the economic development policy suggested by Liu et al. (2022) in China could potentially come at an environmental cost. To be more pragmatic, WRM strategies must be holistically analyzed and formulated to support societal growth, enabling sustainable development (Pahl-Wostl, 2007; Pahl-Wostl et al., 2007). WRM analysts must formulate strategies that harmonize societal and environmental sustainability while considering increasing socioeconomic growth rates (Fraser et al., 2006; Hashimoto et al., 1982). Subsequently, by demonstrating the tangible outcomes of timely decisions, decision-makers and stakeholders can be readily persuaded to allocate the required resources for critical WRM projects, which are pivotal for water resource sustainability and essential for fostering sustainable development.

In this context, unlike the previous research studies, where the WRM decision makers are suggested to adopt specific modes of development and limit the population growth rate (Liu et al., 2022), this unique research work defines several policy scenarios with increasing growth rates of the interconnected subsystems using SDM. It aids decision-makers in analyzing possible ways to achieve water supply sustainability for an arid region and foster sustainable development. Secondly, utilizing a uniquely developed policy scenario generation framework, this research study introduces policy scenarios for sustainable groundwater utilization within safe abstraction limits. The developed framework facilitates formulating and analyzing several policies to promote groundwater conservation in arid regions, facilitate stakeholder engagement, and establish robust WRM strategies. The WRM policy scenario design framework is a novel contribution to scientific literature, further enhancing the novelty of this research work. Third, unlike prior research, which predominantly focused on tackling WRM challenges within specific water basins (Kotir et al., 2016; Li et al., 2018; Madani and Mariño, 2009; Zarghami and Akbariyeh, 2012), this study addresses the research gap and presents a comprehensive SDM framework for conducting a national-level analysis of the WRM system for arid regions, specifically GCC countries. Moreover, the research objectives of this study facilitate the policymakers to realize the United Nations (UN) Sustainable Development Goals (SDGs), particularly SDG #11, focusing on developing sustainable cities and communities, and SDG #12, promoting responsible consumption and production.

3. Methods

3.1. Study area

Qatar, located on the eastern edge of the Arabian Peninsula, is a relatively small peninsula spanning approximately 11,600 km^2 (Fig. 1). Situated strategically within the GCC, it is bordered by the Persian Gulf on three sides, while its southern border is shared with Saudi Arabia. It is characterized by a desert climate with scant annual precipitation averaging 75 mm/year and notably high evaporation rates reaching 2200 mm/year (Abbas et al., 2023; Aloui et al., 2023; Lahlou et al., 2023). Consequently, the absence of surface water (SW) within Qatar leaves the country mainly reliant on groundwater, which exhibits a sustainable average yield of 50 million cubic meters per year (MCM/year). Nevertheless, the current rate of groundwater extraction stands significantly

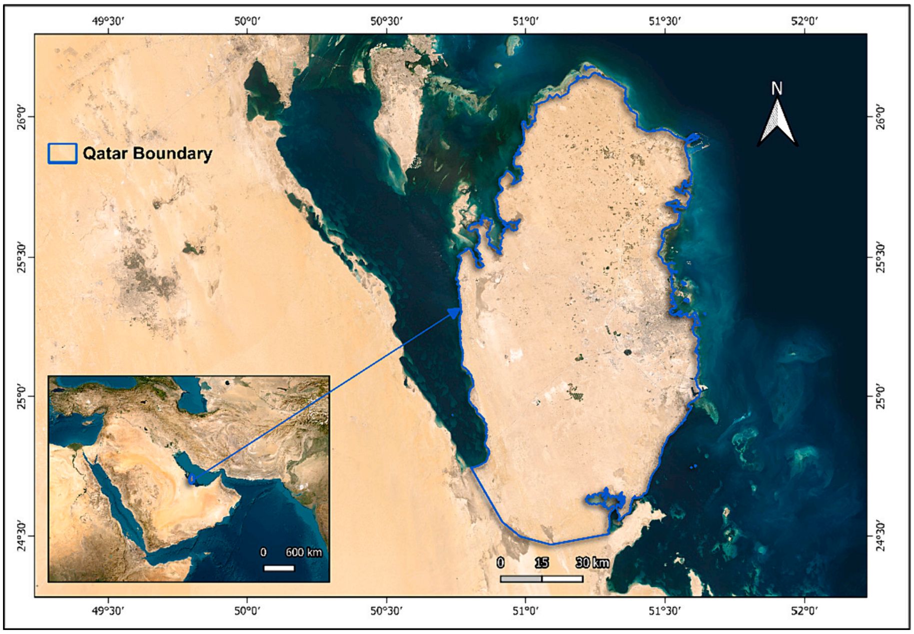


Fig. 1. Map of the state of Qatar.

higher, at 255 MCM/year (Aloui et al., 2023; Lahlou et al., 2023; PSA Qatar, 2021). Given Qatar's inherent water scarcity, the nation predominantly depends on nonconventional water sources, with desalinated water (DW) and treated sewage effluent (TSE) playing pivotal roles in meeting its water needs.

The Domestic water demand (DD) in Qatar represents the household water requirement by the citizens and accounts for 295 MCM/year (Fig. 2) (PSA Qatar, 2021). The Industrial water demand (ID), 29 MCM/year, represents the manufacturing, mining (including the oil and gas sector), electricity and air conditioning, and construction sector water usage. The commercial water demand (CD), 90 MCM/year, mainly represents the demand for hotels, accommodation, food services, wholesale, retail, and transportation sectors. The Environmental water demand (ED), 88.56 MCM/year, mainly represents the water requirement of green spaces. The government water demand (GD), 59 MCM/year, includes the public administration office, educational institutions, and healthcare water usage. Qatar's Agricultural water demand (AD) accounts for 311 MCM/year, representing the local food production of crops, fodder, meat, dairy, and poultry. The overall water demand amounted to a total of 873 MCM in 2020.

The primary water sources in Qatar include desalination, with a production capacity of 671 MCM/year, groundwater abstraction of 255 MCM/year, and TSE, with a maximum treatment capacity of 360 MCM/year (PSA Qatar, 2021).

The rapid expansion of the tourism and sports industry in the GCC, particularly in Qatar, which aims to become an international hub for mega-sports events and competitions, has significantly elevated the water demand. This surge in demand is particularly noteworthy when we consider that, during the FIFA World Cup of 2022 played in Qatar, the country hosted around 1.4 million international tourists while maintaining a resident population of 3.1 million during the same year (Qatar Tourism, 2022). This research introduces a distinctive dimension to WRM analysis by including the demand associated with the tourism and sports sectors.

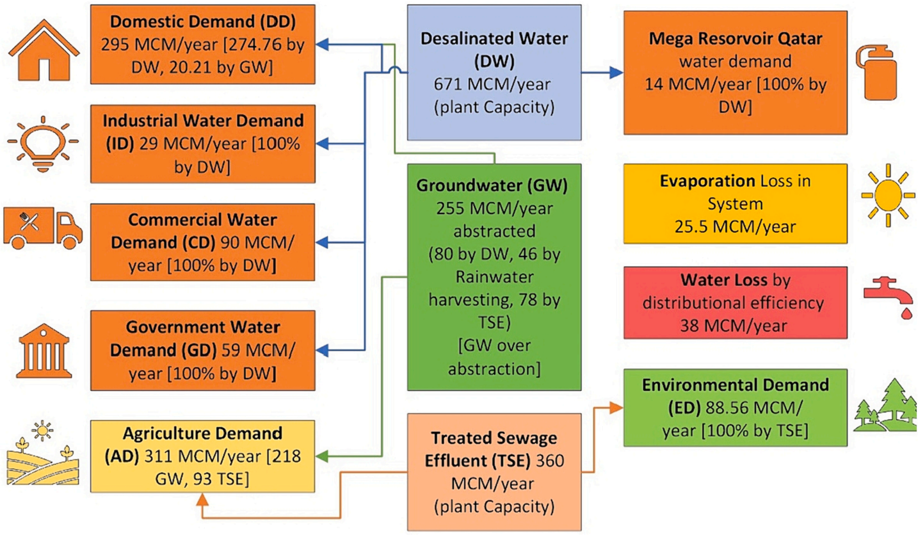


Fig. 2. Qatar's water balance, business-as-usual (BAU) case.

3.2. System dynamics modeling approach

This study integrates the SDM approach and a unique scenario-design methodology to develop a framework to assess the impact of various WRM policies on long-term water resource sustainability (Fig. 3). The analysis comprises the comprehensive mapping encompassing regional water supply and demand subsystems. This is achieved using a causal loop diagram (CLD) and detailed stock and flow diagram (SFD) development. The modeling progressed by employing policy scenario analysis, systematically adjusting system parameters, and adopting a long-term SFD-based simulation model with a 50-year run time while keeping 2020 as the baseline year. The scenario analysis research aims to rigorously assess the resilience of various WRM policies, focusing on balancing the interplay between regional water supply and demand.

3.2.1. Causal loop diagram

Causal relations among the model elements are established using a qualitative tool of the SDM approach called CLD (Madani and Mariño, 2009). Using CLD (Fig. 4) this work developed the WRM system structure and established the interaction of the socioeconomic subsystem with the water resource subsystem. In the GCC, the population growth rate is usually related to economic development and the availability of nonconventional water (Odhiambo, 2017), which is mainly desalinated. In arid regions, including Qatar, the population growth rate is a function of economic development complemented by the sustainable water supply for the residents (Abbas et al., 2023).

Consequently, with sufficient desalination capacity, the region's economic growth instills confidence in the citizens regarding water services, which brings the concept of residential utility to WRM (Madani and Mariño, 2009). Residential utility is a dimensionless indicator used to capture the satisfaction level of water users in the region. It is contingent upon the rate of economic development and the per capita water consumption, as illustrated in the studies by (Gohari et al., 2017; Madani and Mariño, 2009). This implies that a region experiencing an improvement in residential utility will consequently experience a corresponding increasing trend in population growth and per-capita water demand (Madani and Mariño, 2009), depicted as a positive sign (+) in Fig. 4. This kind of WRM system structure is well suited for water-scarce arid regions, based upon the SDM approach, as demonstrated by Madani and Mariño (2009), while addressing the WRM challenges of Zayandeh Rud basin, Iran.

Additionally, this study uses a water sustainability index (WSI) to examine the long-term performance of various water policies in terms of resilience, as employed by Li et al. (2019). The WSI is the water supply to demand ratio (Li et al., 2018; Sun et al., 2017). An increase in demand has an inverse relationship to WSI, which is depicted by a negative (-) sign in Fig. 4. In contrast, an increase in supply has a positive (+) direct effect on WSI. According to the literature, a stable water resource system must have at least a water WSI ratio equal to 1, while a ratio equal to or higher than 1.2 is desirable (Li et al., 2019; Sun et al., 2017).

The prime objective of a CLD is to establish a holistic system understanding and problem scoping, as shown in step 2 in Fig. 3; nevertheless, it is not possible to depict the system's behavior over time quantitatively. To complement the CLD, a quantitative system analysis is performed using the stock and flow diagram (SFD) described in the subsequent section.

3.2.2. Decision support system development using stock-and-flow diagram

An SFD is a quantitative tool of the SDM approach that models and analyzes system behavior over time (Datola et al., 2022). In this study, a DSS simulation model based on SFD is developed (Fig. 5) for Qatar's WRM policy analysis using STELLA (version 3.4.1) (ISEE Systems, 2023). The SFD quantifies the system using the concept of stocks and

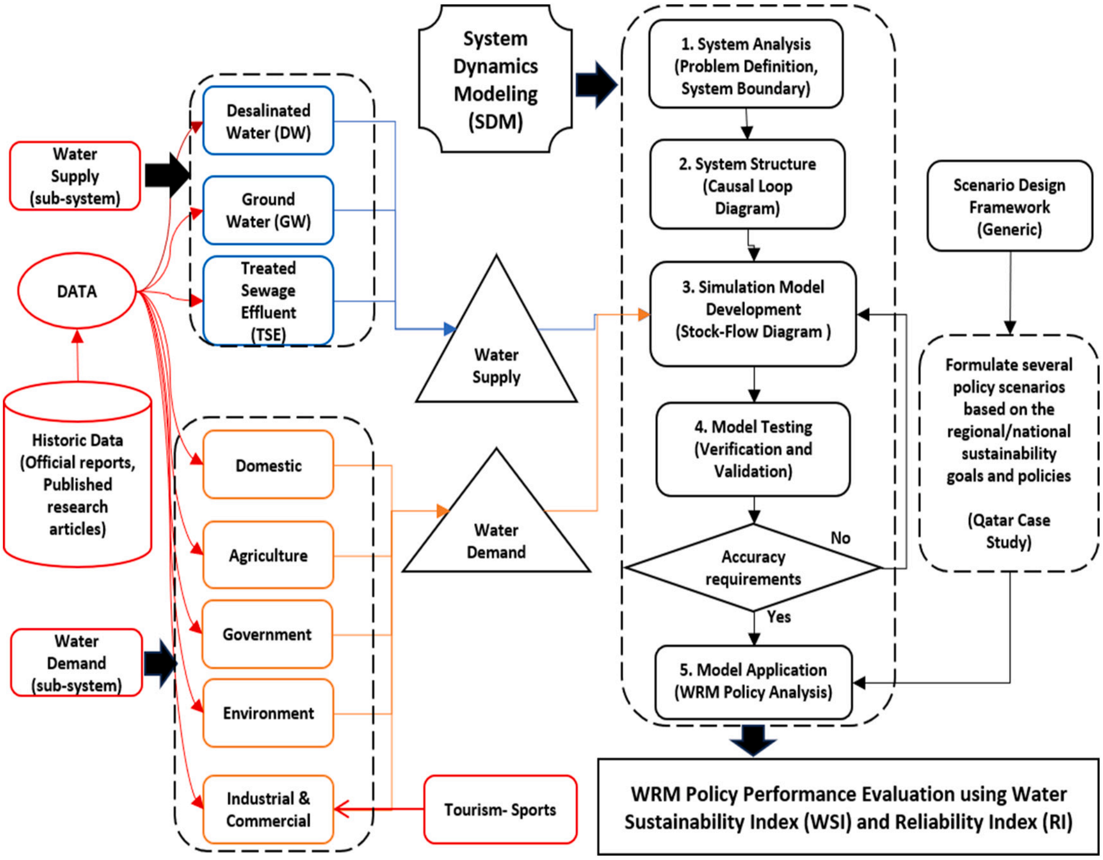


Fig. 3. Schematic diagram of the developed framework used for effective WRM policy analysis.

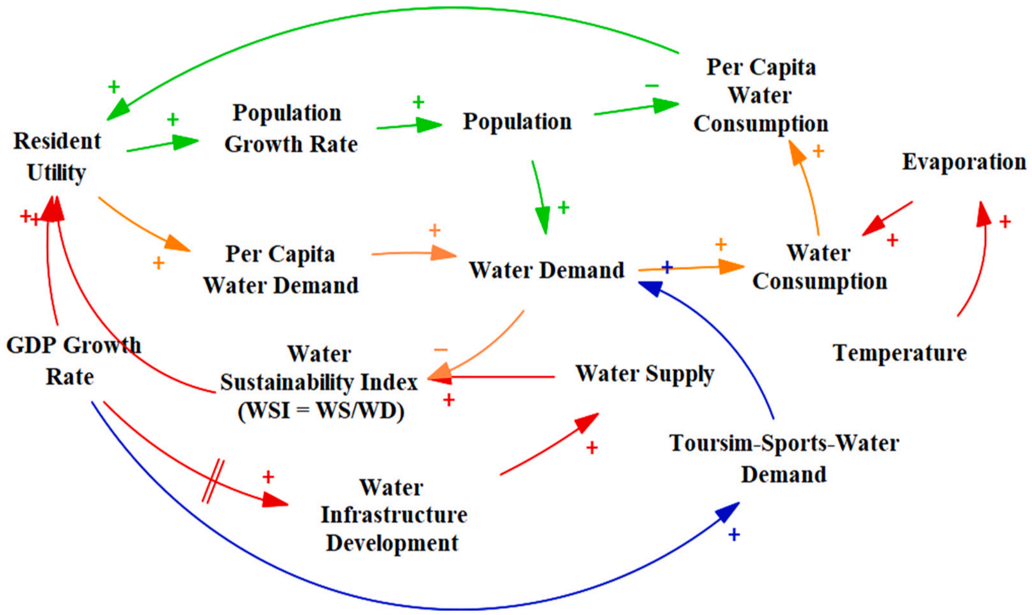


Fig. 4. Causal loop diagram.

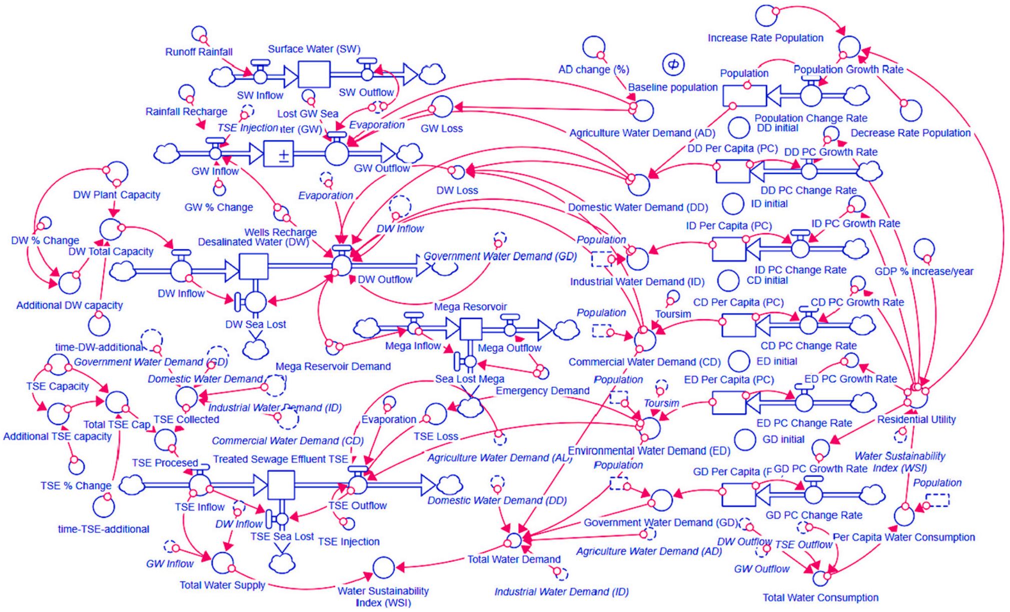


Fig. 5. Qatar's WRM SFD model was developed leveraging the SDM approach.

flows. Stocks represent the accumulation of a quantity over time, and flows represent the inflow or outflow of an amount into the stock over time (Zare et al., 2019). The time unit used in this study is "year". The SFD model is developed based on the interaction of the water resource system and the socioeconomic subsystem, denoting water demand. The rationale is that with increasing socioeconomic development, water demand will increase over time, putting pressure on the water resource supply.

The primary water resources in Qatar consist of groundwater, desalinated water and TSE (PSA Qatar, 2021), as presented in Fig. 2. There is minimal average rainfall per annum (75 mm/year), while the region experiences extensive evaporation (as high as 2200 mm/year). This makes Qatar a hot, arid region with no surface water available (Abbas et al., 2023; Aloui et al., 2023; Lahlou et al., 2023).

The groundwater inflow consists of mainly artificial recharging in the form of TSE (78 MCM/year), rainfall recharge (46 MCM/year) and recharging wells (80 MCM/year) using desalinated water (PSA Qatar, 2021), as illustrated in Fig. 2. The groundwater outflow is in the form of agricultural demand (90 %, 230 MCM/year) and domestic demand (10 %, 25.5 MCM/year). The aquifers in Qatar are over-exploited, as the average safe abstraction limit is 50 MCM/year, while the current practice of abstraction is 255 MCM/year (Abbas et al., 2023; Cochrane and Al-Hababi, 2023).

The desalinated water inflow is based on the plant capacity. Currently, the maximum desalination capacity in Qatar is 671 MCM/year (PSA Qatar, 2021). The desalination outflow constitutes demand of industrial (29 MCM/year), domestic (274.76 MCM/year), commercial (90 MCM/year), government (59 MCM/year), and the aquifer recharge wells (80 MCM/year), as shown in Fig. 2. Furthermore, Qatar's mega water storage project demand consists of storing 14 MCM/year for emergency use, also covered by desalinated water (Abbas et al., 2023). This project is known as the “Qatar Water Security Mega Reservoirs Project”. It aims to enhance the water resource system resilience by providing an emergency water resource backup of seven days (Cochrane and Al-Hababi, 2023).

The inflow to TSE plants is based on the collected wastewater from domestic, commercial, government and industrial consumers (Abbas et al., 2023; Lahlou et al., 2023; PSA Qatar, 2021). The maximum processing capacity of the TSE plants in Qatar is 360 MCM/year. The outflow of TSE consists of the demand for green spaces modeled as environmental demand (88.56 MCM/year), agricultural demand (93 MCM/year, fodder crops only), and TSE injection into the aquifers (78 MCM/year) (Abbas et al., 2023; PSA Qatar, 2021), as highlighted in Fig. 2.

The WRM DSS model developed in this study also encompasses the water demand originating from tourism and sports activities, which couldn't be found in the past literature (Gohari et al., 2017, 2013; Liu et al., 2022; Madani and Mariño, 2009). The impact of this demand is significant in arid regions, primarily those with low populations (Gonzalez-Perez et al., 2023). In 2019, there was a substantial influx of 2.13 million tourists in Qatar (Qatar Tourism, 2022). The developed DSS in this study also captures the water demand associated with this influx (Fig. 5).

The developed WRM decision support system provides a comprehensive macrolevel analysis of the socioeconomic factors that shape regional WRM strategies, leveraging the SDM approach. The key variables and subsystems employed in the developed SFD simulation model are presented in Table 1. Additional details, such as variable types, units, equations, and data sources, are included in the supplementary information as an appendix, Table A1.

3.2.3. *Performance indices*

The performance indices of a system help the decision-makers to analyze and rank different policies quantitatively. Perturbation in the system variables is induced by generating different scenarios altering the simulation model's supply and demand levels while testing several WRM policies. Two performance indices are used to test WRM policies, namely the water sustainability index (WSI) (Li et al., 2019; Milano et al., 2013; Naeem et al., 2023; Pedro-Monzonís et al., 2015) and the reliability index (RI) (Li et al., 2019; McMahon et al., 2006).

$$\text{Water Sustainability Index} = \frac{\text{Water Supply}}{\text{Water Demand}} \tag{1}$$

Eq. (1) evaluates the system's resilience under varying water supply and demand scenarios. The system's ability to ensure sustainable supply under varying scenarios is evaluated. When the WSI value is greater than or equal to one, the time is considered a sustainable WSI period (Li et al., 2019; Pedro-Monzonís et al., 2015). During this time, the water supply is sufficient to meet the water demand of the system.

The RI is the second performance indicator used in this study (McMahon et al., 2006). As presented in Eq. (2), the RI is the likelihood that the water system can adequately meet the demand. In WRM, the equation for calculating the RI is as follows:

$$\text{Reliability Index} = \frac{(n \mid S = 0)}{N} \tag{2}$$

Where “S” denotes water shortage, “n” represents the time (years) with no shortage and “N” indicates total simulation time. In this research study on Qatar's WRM DSS, the temporal increment utilized is a “year”, with the simulation model encompassing the period from 2021 to 2070. The RI is quantified on a scale from 0 to 1 and can be presented as a percentage (Hashimoto et al., 1982). The RI value assesses the robustness of a water supply system in meeting the total demand under varying scenarios and uncertainties (McMahon et al., 2006). A higher RI value represents a robust WRM system and vice versa. The desirable RI value for a WRM system is a policymaker's decision (Pedro-Monzonís et al., 2015).

Table 1
Key variables used in Qatar's dynamic WRM model development.

Subsystem	Stock	Key variables
Water supply	Groundwater (GW)	DW plant capacity (MCM/year)
	Surface Water (SW)	TSE plant capacity (MCM/year)
	Desalinated Water (DW)	TSE injection into GW (MCM/year)
	Treated Sewage Effluent (TSE)	GW lost into the sea (MCM/year)
	Mega Reservoir	Precipitation (mm/year)
		evaporation (mm/year)
Water demand	Domestic water demand per capita	Total water supply (MCM/year)
	Industrial water demand per capita	Total water demand (MCM/year)
	Commercial water demand per capita	Water sustainability index (Dimensionless)
	Environmental water demand per capita	Annual GDP percent change (%)
	Government water demand per capita	Population growth rate (%)
	Population	Tourists (people/year)
		Leakage in the distribution system (MCM/year)
		Agriculture water demand (MCM/year)
		Domestic water demand (MCM/year)
		Industrial water demand (MCM/year)
		Commercial water demand (MCM/year)
		Environmental water demand (MCM/year)
		Government water demand (MCM/year)

3.3. *Scenario design framework*

In the realm of WRM, a standardized framework for designing scenario-based decision-making models has been notably scarce in existing literature. Traditionally, such frameworks have relied mainly on expert knowledge and judgments (Kotir et al., 2016; Li et al., 2018; Liu et al., 2022; Naeem et al., 2023). A unique framework for scenario design and the WRM policy analysis is proposed to address this research gap (Figs. 6, 7). The developed approach empowers WRM decision-makers to evaluate the ramifications of various policies and make informed choices. In this framework, (i) represents the water supply type, (j) denotes the water demand type, (k) represents the supply level, and (l) denotes the demand level.

The developed WRM framework, as outlined in Fig. 6, is generic and can be used to generate various WRM policy scenarios. The framework accommodates the variability and uncertainty inherent in the system parameters by employing the abovementioned principle. This is achieved by systematically adjusting system parameters to a possible and pragmatic range by altering water supply and demand levels from a baseline value. Moreover, this process can be utilized to generate potential policy scenarios.

By employing the proposed framework (Fig. 6), the possible scenarios for the Qatar WRM case study are formulated and presented in Fig. 7.

The notation $[i, j, k, l]$ denotes a specific cell within the context of scenario generation.

- i is the water supply set, with $i = [1,2,3] = [\text{GW, DW, TSE}]$.
- j is the water demand set, with $j = [1, 2, 3, 4, 5, 6] = [\text{DD, ID, CD, AD, ED, GD}]$.

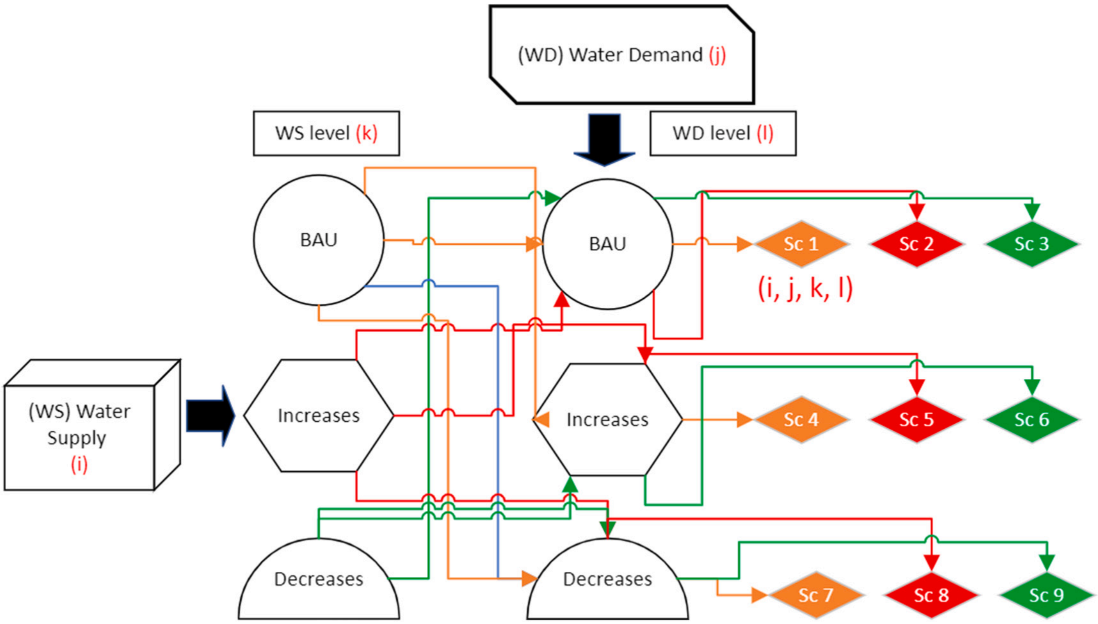
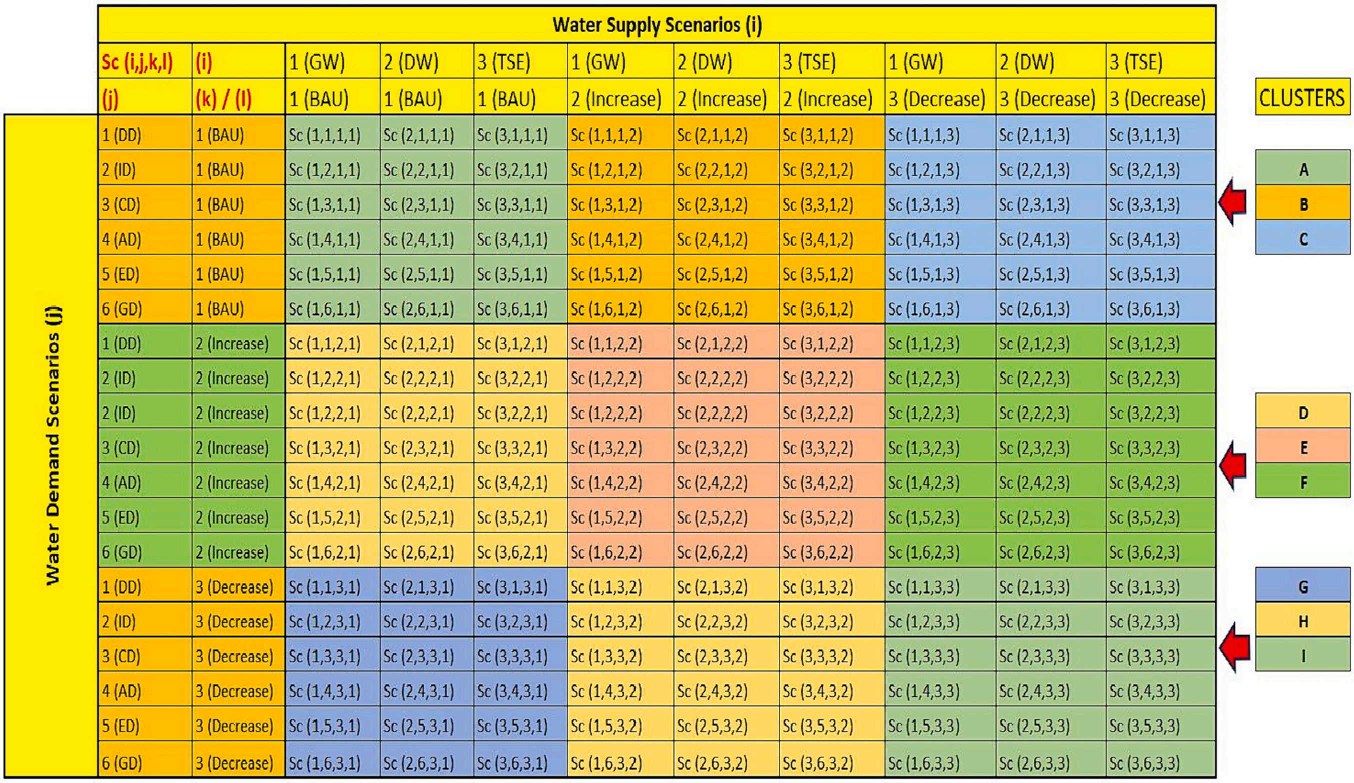


Fig. 6. Scenario design framework developed for WRM, where “Sc” represents a scenario.



		Water Supply Scenarios (i)								
Sc (i,j,k,l)	(i)	1 (GW)	2 (DW)	3 (TSE)	1 (GW)	2 (DW)	3 (TSE)	1 (GW)	2 (DW)	3 (TSE)
(j)	(k) / (l)	1 (BAU)	1 (BAU)	1 (BAU)	2 (Increase)	2 (Increase)	2 (Increase)	3 (Decrease)	3 (Decrease)	3 (Decrease)
1 (DD)	1 (BAU)	Sc (1,1,1,1)	Sc (2,1,1,1)	Sc (3,1,1,1)	Sc (1,1,1,2)	Sc (2,1,1,2)	Sc (3,1,1,2)	Sc (1,1,1,3)	Sc (2,1,1,3)	Sc (3,1,1,3)
2 (ID)	1 (BAU)	Sc (1,2,1,1)	Sc (2,2,1,1)	Sc (3,2,1,1)	Sc (1,2,1,2)	Sc (2,2,1,2)	Sc (3,2,1,2)	Sc (1,2,1,3)	Sc (2,2,1,3)	Sc (3,2,1,3)
3 (CD)	1 (BAU)	Sc (1,3,1,1)	Sc (2,3,1,1)	Sc (3,3,1,1)	Sc (1,3,1,2)	Sc (2,3,1,2)	Sc (3,3,1,2)	Sc (1,3,1,3)	Sc (2,3,1,3)	Sc (3,3,1,3)
4 (AD)	1 (BAU)	Sc (1,4,1,1)	Sc (2,4,1,1)	Sc (3,4,1,1)	Sc (1,4,1,2)	Sc (2,4,1,2)	Sc (3,4,1,2)	Sc (1,4,1,3)	Sc (2,4,1,3)	Sc (3,4,1,3)
5 (ED)	1 (BAU)	Sc (1,5,1,1)	Sc (2,5,1,1)	Sc (3,5,1,1)	Sc (1,5,1,2)	Sc (2,5,1,2)	Sc (3,5,1,2)	Sc (1,5,1,3)	Sc (2,5,1,3)	Sc (3,5,1,3)
6 (GD)	1 (BAU)	Sc (1,6,1,1)	Sc (2,6,1,1)	Sc (3,6,1,1)	Sc (1,6,1,2)	Sc (2,6,1,2)	Sc (3,6,1,2)	Sc (1,6,1,3)	Sc (2,6,1,3)	Sc (3,6,1,3)
1 (DD)	2 (Increase)	Sc (1,1,2,1)	Sc (2,1,2,1)	Sc (3,1,2,1)	Sc (1,1,2,2)	Sc (2,1,2,2)	Sc (3,1,2,2)	Sc (1,1,2,3)	Sc (2,1,2,3)	Sc (3,1,2,3)
2 (ID)	2 (Increase)	Sc (1,2,2,1)	Sc (2,2,2,1)	Sc (3,2,2,1)	Sc (1,2,2,2)	Sc (2,2,2,2)	Sc (3,2,2,2)	Sc (1,2,2,3)	Sc (2,2,2,3)	Sc (3,2,2,3)
2 (ID)	2 (Increase)	Sc (1,2,2,1)	Sc (2,2,2,1)	Sc (3,2,2,1)	Sc (1,2,2,2)	Sc (2,2,2,2)	Sc (3,2,2,2)	Sc (1,2,2,3)	Sc (2,2,2,3)	Sc (3,2,2,3)
3 (CD)	2 (Increase)	Sc (1,3,2,1)	Sc (2,3,2,1)	Sc (3,3,2,1)	Sc (1,3,2,2)	Sc (2,3,2,2)	Sc (3,3,2,2)	Sc (1,3,2,3)	Sc (2,3,2,3)	Sc (3,3,2,3)
4 (AD)	2 (Increase)	Sc (1,4,2,1)	Sc (2,4,2,1)	Sc (3,4,2,1)	Sc (1,4,2,2)	Sc (2,4,2,2)	Sc (3,4,2,2)	Sc (1,4,2,3)	Sc (2,4,2,3)	Sc (3,4,2,3)
5 (ED)	2 (Increase)	Sc (1,5,2,1)	Sc (2,5,2,1)	Sc (3,5,2,1)	Sc (1,5,2,2)	Sc (2,5,2,2)	Sc (3,5,2,2)	Sc (1,5,2,3)	Sc (2,5,2,3)	Sc (3,5,2,3)
6 (GD)	2 (Increase)	Sc (1,6,2,1)	Sc (2,6,2,1)	Sc (3,6,2,1)	Sc (1,6,2,2)	Sc (2,6,2,2)	Sc (3,6,2,2)	Sc (1,6,2,3)	Sc (2,6,2,3)	Sc (3,6,2,3)
1 (DD)	3 (Decrease)	Sc (1,1,3,1)	Sc (2,1,3,1)	Sc (3,1,3,1)	Sc (1,1,3,2)	Sc (2,1,3,2)	Sc (3,1,3,2)	Sc (1,1,3,3)	Sc (2,1,3,3)	Sc (3,1,3,3)
2 (ID)	3 (Decrease)	Sc (1,2,3,1)	Sc (2,2,3,1)	Sc (3,2,3,1)	Sc (1,2,3,2)	Sc (2,2,3,2)	Sc (3,2,3,2)	Sc (1,2,3,3)	Sc (2,2,3,3)	Sc (3,2,3,3)
3 (CD)	3 (Decrease)	Sc (1,3,3,1)	Sc (2,3,3,1)	Sc (3,3,3,1)	Sc (1,3,3,2)	Sc (2,3,3,2)	Sc (3,3,3,2)	Sc (1,3,3,3)	Sc (2,3,3,3)	Sc (3,3,3,3)
4 (AD)	3 (Decrease)	Sc (1,4,3,1)	Sc (2,4,3,1)	Sc (3,4,3,1)	Sc (1,4,3,2)	Sc (2,4,3,2)	Sc (3,4,3,2)	Sc (1,4,3,3)	Sc (2,4,3,3)	Sc (3,4,3,3)
5 (ED)	3 (Decrease)	Sc (1,5,3,1)	Sc (2,5,3,1)	Sc (3,5,3,1)	Sc (1,5,3,2)	Sc (2,5,3,2)	Sc (3,5,3,2)	Sc (1,5,3,3)	Sc (2,5,3,3)	Sc (3,5,3,3)
6 (GD)	3 (Decrease)	Sc (1,6,3,1)	Sc (2,6,3,1)	Sc (3,6,3,1)	Sc (1,6,3,2)	Sc (2,6,3,2)	Sc (3,6,3,2)	Sc (1,6,3,3)	Sc (2,6,3,3)	Sc (3,6,3,3)

Fig. 7. Possible WRM scenarios for Qatar. Clustered policy “A” to “I”.

- k is the water supply level set, k = [1, 2, 3] = [BAU, Increase, Decrease].
- l is the water demand level set, where l = [1, 2, 3] = [BAU, Increase, Decrease].

In this study, the total number of possible scenarios is 162 [($i = 3$) * ($j = 6$) * ($k = 3$) * ($l = 3$)]. To simplify the analysis, the “Nine Clusters” are referred to by the letters “A” to “I” (Fig. 7). These clusters represent the grouping of cells (where a cell represents an individual scenario), categorized as per the color of the groups. Taking the example of cluster “A”, it includes all the scenarios (cells) represented by the same color “green”, and where all the supply types and demand types are set at the same level, “BAU”. The color assigned to each “cluster” is selected randomly and only used to distinguish different clusters.

The same generic methodology could be used to systematically generate and test several possible policy scenarios for a selected region with varying supply and demand conditions (Fig. 8). To include the policy aspects and stakeholders' ability to govern actions and policies; we have included the possibility of calculating the value for the WSI and the RI for each cluster. Provided stakeholders acknowledge the possible outcome, the policy outlined in the scenario could be implemented; otherwise, alternative scenarios can be explored (Fig. 8). In this developed SDM simulation model, the BAU represents the system's existing water supply and demand pattern, considering no rise in water supply resources. The "increase" and "decrease" scenario represent a 10 % change from the baseline value. The system also allows for a combination of all three options. The choice of a 10 % variation in the water demand aligns with Qatar's Tarsheed initiative, which is part of a national conservation plan for sustainable development (Abbas et al., 2023; Lahlou et al., 2023).

3.4. Model validation

Model validation is crucial to establish confidence in the simulation model's performance. We tested the developed SDM simulation model for 2010–2020, utilizing the publicly available statistics sourced from official reports to validate it. Specifically, we relied on data from the "Water Statistics in the state of Qatar 2021", published in 2023 by the "Planning and Statistics Authority, State of Qatar" (PSA Qatar, 2023, 2021). Relative error (RE), maximum relative error (MRE) and the coefficient of determination (R^2) are the statistical metrics used for model validation.

The RE analyzes the percent difference between the simulated and actual value, with a <15% value deemed acceptable (Wen et al., 2022). RE is calculated based on the Eq. (3).

$$\text{RE} = \left| \frac{\left(\text{Y}_{simulated,n} - \text{Y}_{actual,n}\right)}{\left(\text{Y}_{actual,n}\right)} \right| \times 100\% \tag{3}$$

where $\text{Y}_{simulated,n}$ represents the simulated value at time instance "n", while $\text{Y}_{actual,n}$ represents the actual historical value of the parameter under consideration at the time "*n*". MRE denotes the largest error value inside the dataset and serves as the upper bound of the error between the simulated and historical data. MRE is calculated as shown in Eq. (4).

$$\text{MRE} = max\left(\left| \frac{\left(\text{Y}_{simulated,n} - \text{Y}_{actual,n}\right)}{\left(\text{Y}_{actual,n}\right)} \right| \times 100\%\right) \tag{4}$$

The model's ability to simulate the system in relation to its actual past behavior is shown by R^2. A perfect match is marked by a maximum value of 1, and a poor model fit is represented by 0. R^2 is calculated as shown in Eq. (5).

$$R^2 = 1 - \frac{\sum_{n=1}^{N} \left(\text{Y}_{actual,n} - \text{Y}_{simulated,n}\right)^2}{\sum_{n=1}^{N} \left(\text{Y}_{actual,n} - \overline{\text{Y}}_{actual}\right)^2} \tag{5}$$

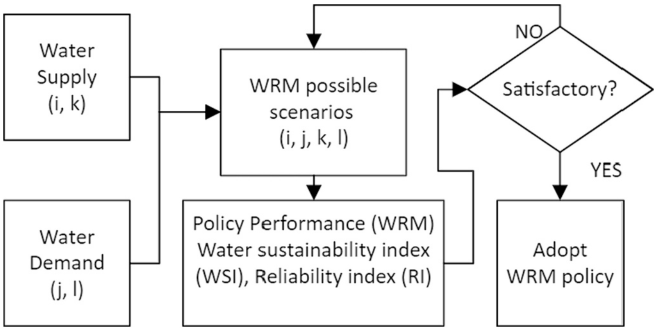


Fig. 8. Policy analysis using performance indices.

In Eq. (5), "N" represents the total time. The simulated value at time "*n*" is denoted by $\text{Y}_{simulated,n}$, whereas its actual historic value at time "*n*" is represented by $\text{Y}_{actual,n}$. Moreover, $\overline{\text{Y}}_{actual}$ represents the dataset's average of actual historical values.

4. Results and discussion

4.1. Model validation results

The significant variables for model validation included industrial water demand, commercial water demand, government water demand, domestic water demand, environmental water demand and total population. A good model fit is indicated by the R^2 (>80 %) and MRE (<15 %) (Dehghani et al., 2022). The utility of an SDM simulation is to analyze persisting systemic issues and predict forthcoming trends based on the interplay of various system parameters. SDM analysis emphasizes identifying the overarching trends with less focus on isolated data points and specific values (Madani and Mariño, 2009). These projections allow the system analysts and decision-makers to devise the best possible mitigation policies.

As an essential social driver affecting water demand, the "population" is a critical variable in WRM Qatar's simulation model. Its MRE value is 7.62 %, and its R^2 value was estimated to be 91.59 % (Fig. 9). Given the inherent parametric uncertainty in SDM investigations, including environmental and social systems, a RE value of up to 15 % is acceptable (Kotir et al., 2016; Wen et al., 2022). The population growth continued from 2.17 million people in 2010 to 2.8 million in 2019, decreasing to 2.76 million people in 2020 (PSA Population, 2021). This peculiarity is because most of Qatar's mega-infrastructure, including stadiums, transportation systems, and a brand-new city called Lusail, was built with the FIFA 2022 football World Cup as the target. Most of these development operations were finished by 2020, although they required a sizable labor force (PSA Construction, 2021). Furthermore, the year 2020 emerged to be crucial in the COVID-19 pandemic, which accounts for the declining population statistics in Qatar, given that immigrants comprise most of the nation's population.

The industrial water demand (ID) increased from 7.76 MCM in 2010 to 34 MCM in 2019. Still, it dropped to 29 MCM in 2020, following the completion of various construction projects in Qatar (PSA Construction, 2021; PSA Population, 2021), as demonstrated in (Fig. 10). The ID MRE value is 10.80 %, with an estimated R^2 value of 90.39 %. In Qatar, ID considers the demand from manufacturing, construction, mining (oil and gas) industries, and air conditioning (PSA Qatar, 2021).

Qatar's domestic water demand (DD), which primarily represents household water usage, reduced from 301 MCM in 2019 to 288 MCM in 2020 amid the COVID-19 pandemic (PSA Qatar, 2021). In addition, comparing the historical values and simulated findings, the DD MRE value is 2.91 %, with an estimated R^2 value of 91.41 % (Fig. 11).

The water needs of public administration, healthcare, and educational institutions are captured by the government water demand (GD) in Qatar. As illustrated in Fig. 12, the GD's MRE was determined to be 9.248 % with a R^2 of 90.62 % and a peaked water demand of 80 MCM in 2019. The water demand was reduced to 59 MCM in 2020 due to decreased educational activities and online education (PSA Qatar, 2021).

Environmental water demand (ED) in the developed WRM DSS model is ascribed to the green spaces in Qatar, including parks and stadiums. From 2010 (18.63 MCM) to 2020 (88.56 MCM) (PSA Qatar, 2021), ED increased substantially with a MRE value of 7.56 % and 92.33 % R^2 (Fig. 13). Green spaces, parks, and stadiums have been progressively constructed to host the FIFA 2022 tournament and address the demands of these establishments (PSA Construction, 2021); a significant and sustainable water supply is necessitated. It is imperative to maintain these constructed infrastructures, such as the stadiums and green areas, even in the event of a population drop, as in Qatar.

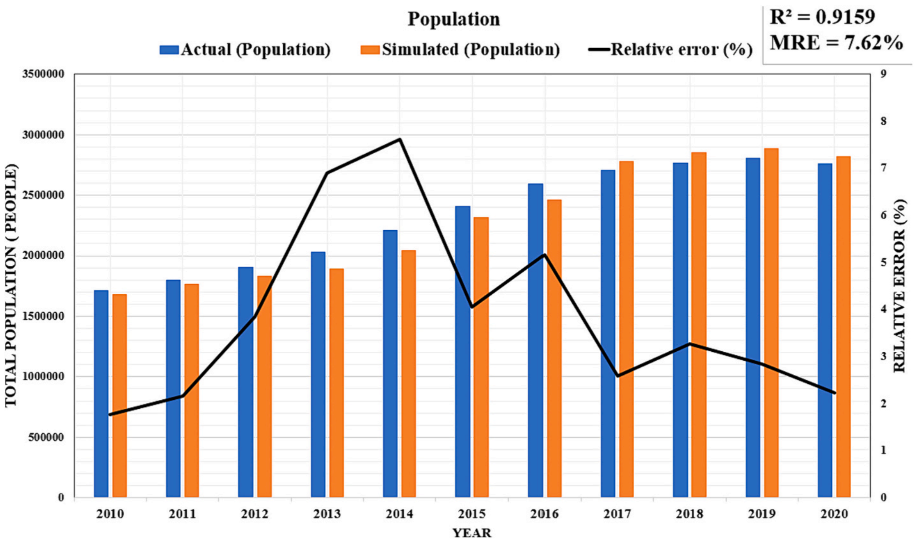


Fig. 9. Comparative statistics of the population with respective RE (%) values.

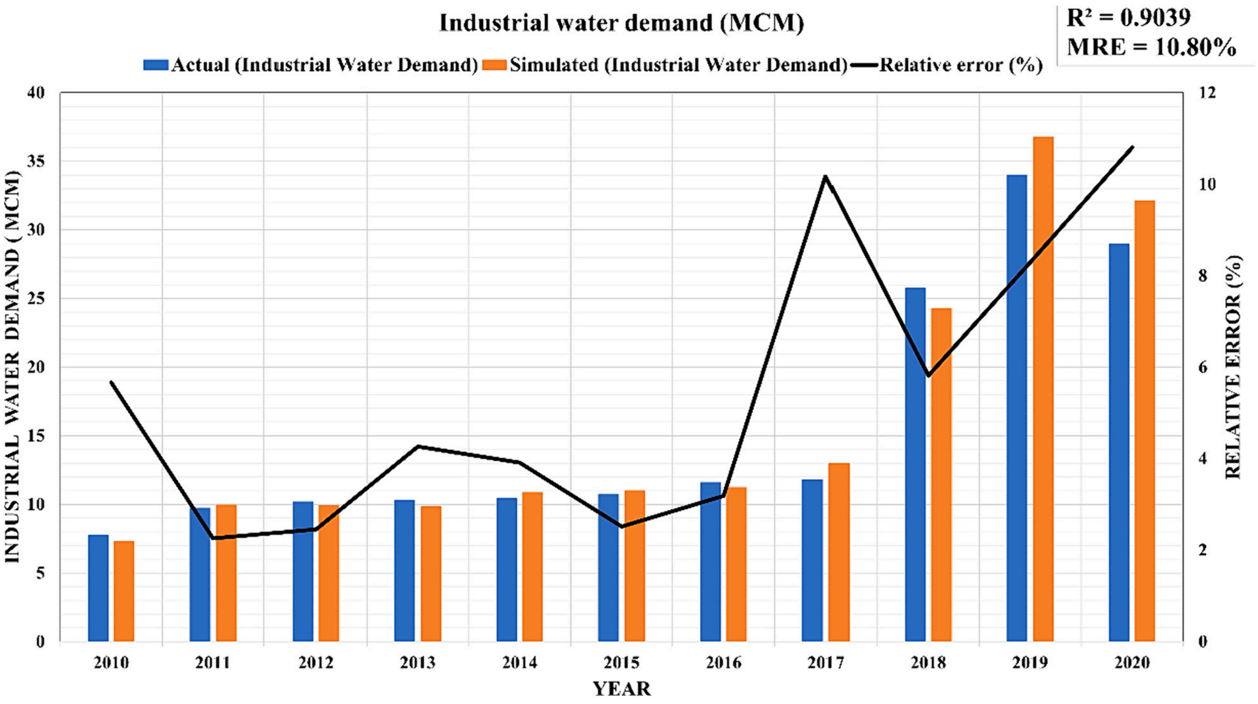


Fig. 10. Comparative statistics of the industrial water demand.

Commercial water demand (CD) in Qatar comprises transportation, hoteling, food services, households with working personnel, and retail trade operations (PSA Qatar, 2021). As depicted in Fig. 14, there was a significant decline in CD in 2018, with a value of 25.8 MCM, compared to 57.7 MCM in 2017. This was linked to the GCC countries' boycott of Qatar in the middle of 2017. The transportation, tourist, and hospitality industries were severely impacted by this embargo, which had a detrimental economic impact on the commercial sector. Nonetheless, from 2019 onward, the situation exhibited improvement (Selmi and Bouoiyour, 2020) as the commercial activities regained momentum. This is just one of the peculiar examples that highlight how important it is to look at WRM alongside the political and socioeconomic realities of the region. Additionally, this illustrates that real-world water policy management requires more than only hydrological modeling and analysis (Simonović, 2012). An integral aspect of WRM lies in adopting a holistic SDM approach to devise pragmatic policies (Barati et al., 2023).

4.2. Sensitivity analysis

Sensitivity analysis is essential for analyzing the impact of varying multiple parameters on the model's dynamic behavior (Rodrigues et al., 2023). In WRM DSS, most of the parameters used become challenging to estimate, which leads to modeling uncertainty. The sensitivity analysis is performed by varying a single parameter's value within a specified range while keeping the other parameters at baseline values. Occasionally, the impact of extreme values is analyzed (Gohari et al., 2017; Menendez et al., 2023). The resulting behavior of the simulation model, in the form of changing trends under these parameter variations, is compared with the expected real-world scenarios. Their alignment is a critical indicator in validating the system's dynamic behavior (Nouri

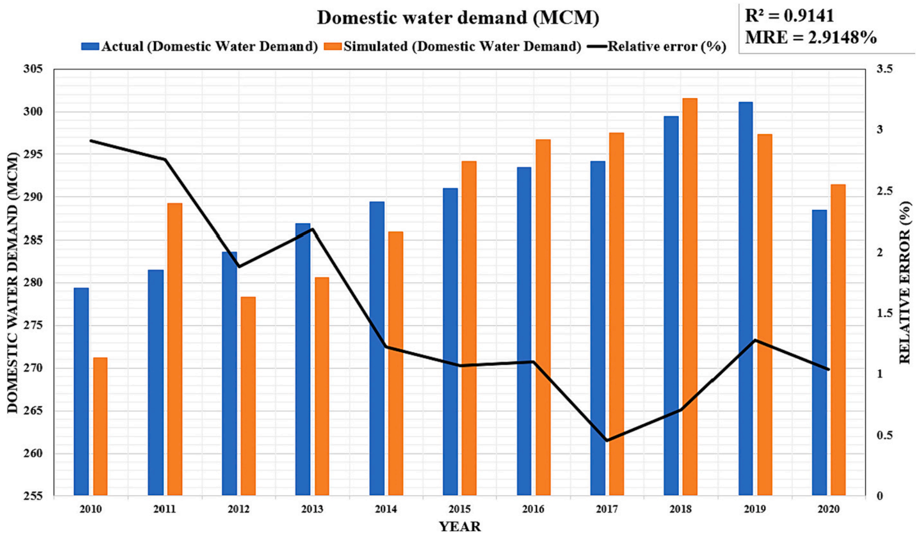


Fig. 11. Comparative statistics of the domestic water demand.

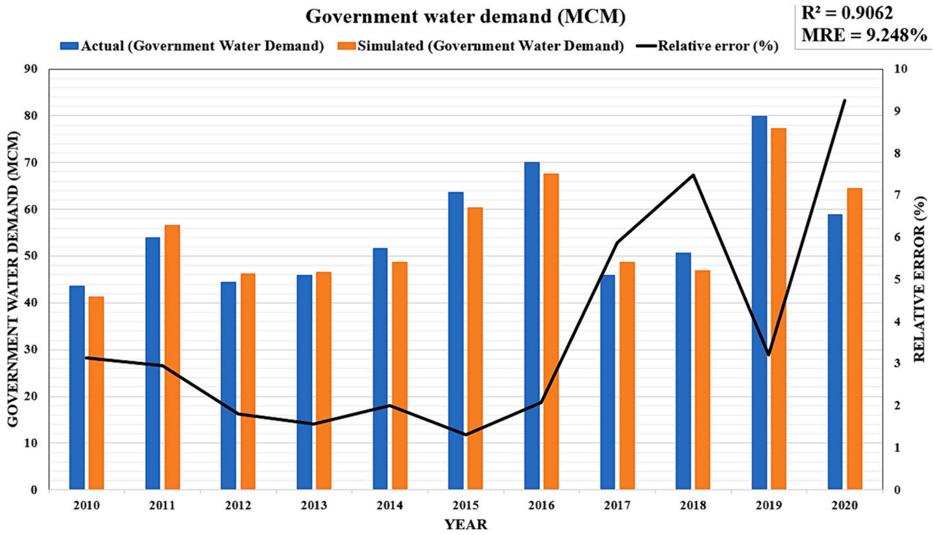


Fig. 12. Comparative statistics of the government's water demand.

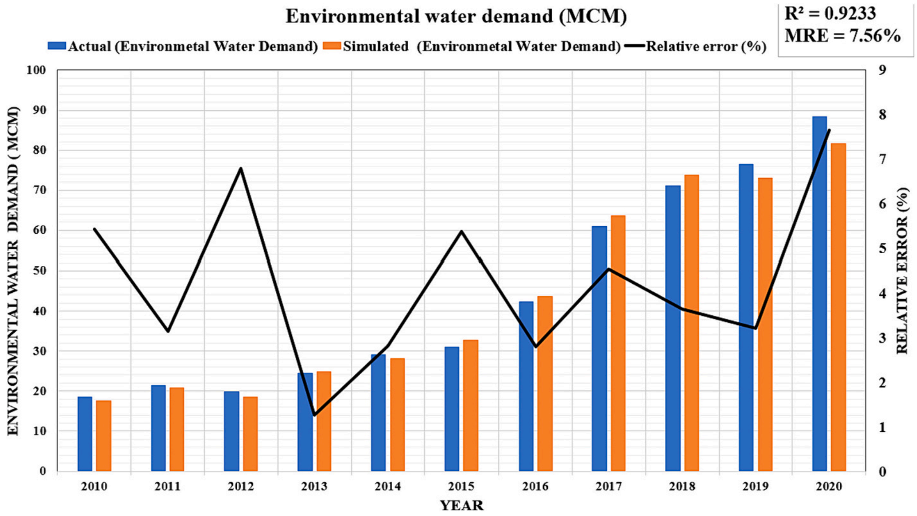


Fig. 13. Comparative statistics of the environmental water demand.

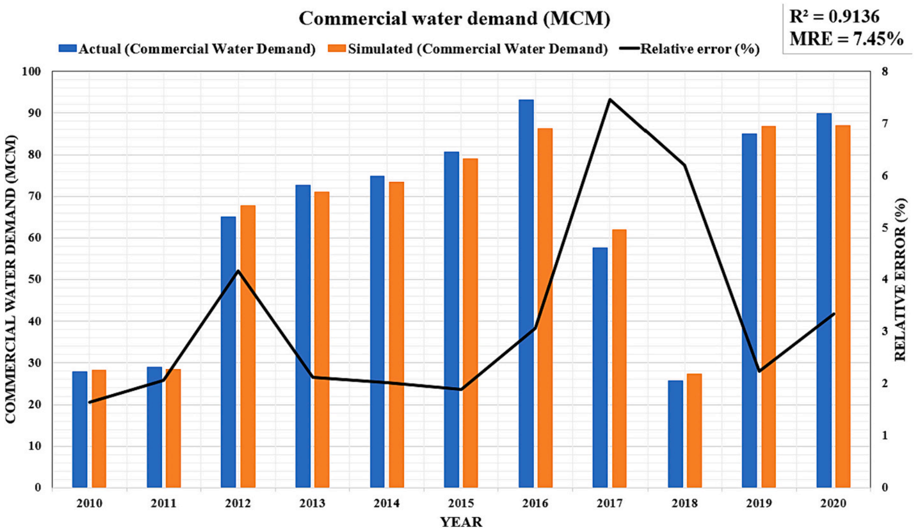


Fig. 14. Comparative statistics of the commercial water demand.

et al., 2023).

The impact of two supply and seven demand parameters on WSI is analyzed using STELLA (Version: 3.4.1) (ISEE Systems, 2023), as presented in Table 2. A system state with a WSI equal to or >1 signifies its ability to effectively meet water demand, reflecting the resilience of water resource management policies. By varying the parameter values to extreme limits (−/+ 20 %), the resulting system capability as the number of years where WSI ≥1 is analyzed and presented as a boxplot in Figs. 15, 16. Moreover, the parameters with comparatively larger boxplot variations from the mean value represent a noteworthy impact on the system.

The sensitivity analysis for the supply system in Fig. 15 indicates that the desalination supply impact is more significant than the TSE—an increase in the desalination plant capacity by 20 % results in the water supply sustainability of 38.5 years. In comparison, it results in 35.5 years for a similar rise in TSE plant capacity. This result also helps decision-makers prioritize infrastructure decisions between the two. The model is more sensitive in terms of WSI for DW plant capacity and mimics the actual system behavior; hence, the findings strengthen model validation.

The water demand parameters influencing the WRM system regarding WSI include changes in population, agriculture, industrial, commercial, domestic, environmental and government demand, as presented in Table 2. It can be noticed in Fig. 16 that varying the population (+/− 20 %) has the highest impact on WSI, resulting in WSI ≥1 for 19 years (+20 %) and 42 years (−20 %), respectively (range equals 23 years). This significant finding is critical, as it shows the pressure on the water resource system to fulfill the demand due to the increasing population.

Table 2
WRM system parameters are analyzed using sensitivity analysis.

Parameters	Initial value	Unit	Range [−20 %, +20 %]	Sustainable WSI (year)
DW plant capacity	671	MCM/ year	[537–805]	[21–38.5]
TSE plant capacity	360	MCM/ year	[288–432]	[25.24–35.5]
Baseline population	2.76	Million People	[2.208–3.312]	[42–19]
Domestic water demand	295	MCM/ year	[235.99–353.99]	[37–24.25]
Agriculture water demand	311	MCM/ year	[248.8–373.9]	[34.75–25.75]
Industrial water demand	28.99	MCM/ year	[23.19–34.79]	[35.5–25.25]
Commercial water demand	90	MCM/ year	[72–108]	[32.25–28.5]
Environmental water demand	88.56	MCM/ year	[70.84–106.27]	[32.25–29.75]
Government water demand	59.04	MCM/ year	[47.23–70.85]	[31.5–29.25]

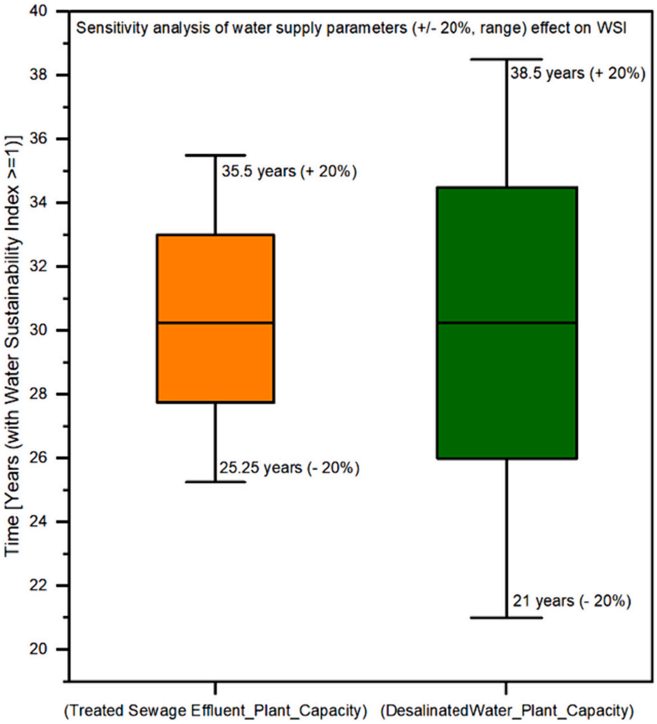


Fig. 15. Sensitivity analysis of water supply.

Analyzing the agricultural water demand, a 20 % variation in the baseline consumption value of 311 MCM/year, presented in Table 2, results in WSI ≥1 for 25.75 years and 34.75 years, respectively (Fig. 16). The finding highlights the significance of reducing the demand using advanced irrigation methods and greenhouse production. The 20 % variation in domestic demand from the baseline value of 294.99 MCM/year results in WSI ≥1 for 24.25 years and 37 years, respectively (Fig. 16).

The other water demand parameters, including industrial,

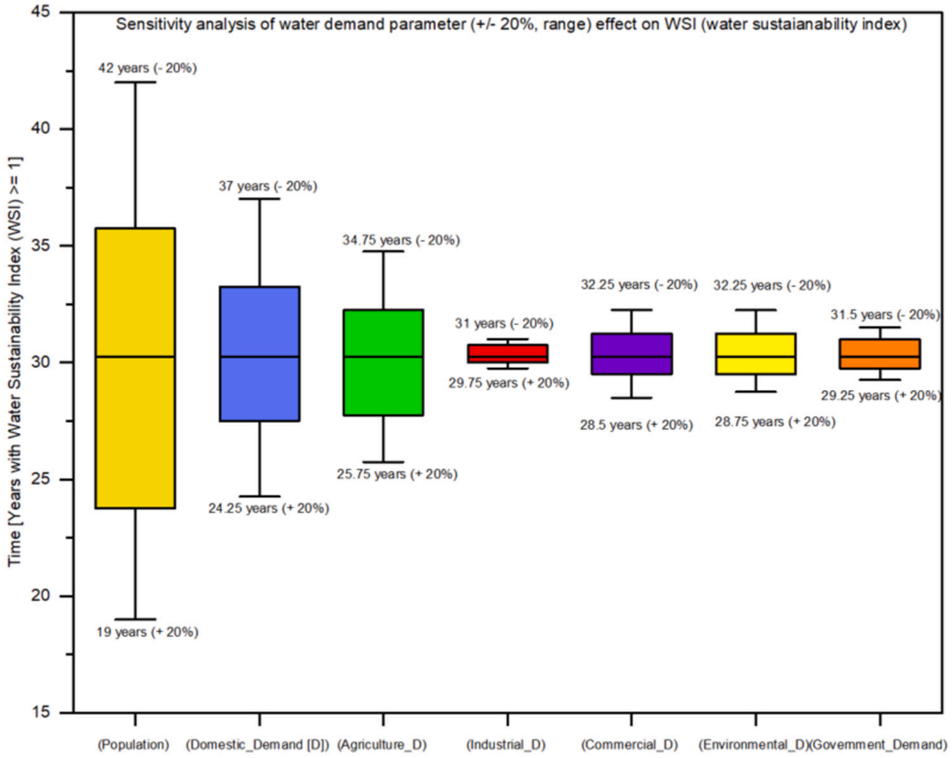


Fig. 16. Sensitivity analysis of water demand.

commercial, environmental and government demand, were the least sensitive (Fig. 16). The induced variation of 20 % among the parameters resulted in the sustainable water supply range that remained closer to the BAU value of 32 years.

The outcome of sensitivity analysis is closely aligned with observed system behavior. Notably, desalinated water accounts for around 52 % of the total water supply in the system, as reported by (PSA Qatar, 2021). Consequently, variations in its capacity range significantly impact the overall system. Similarly, the outcome of the water demand subsystem analysis is consistent with official water statistics of Qatar (PSA Qatar, 2021) and additionally reinforced by previous regional studies such as (Abbas et al., 2023; Ahmad and Al-Ghouti, 2020; Saleem et al., 2023).

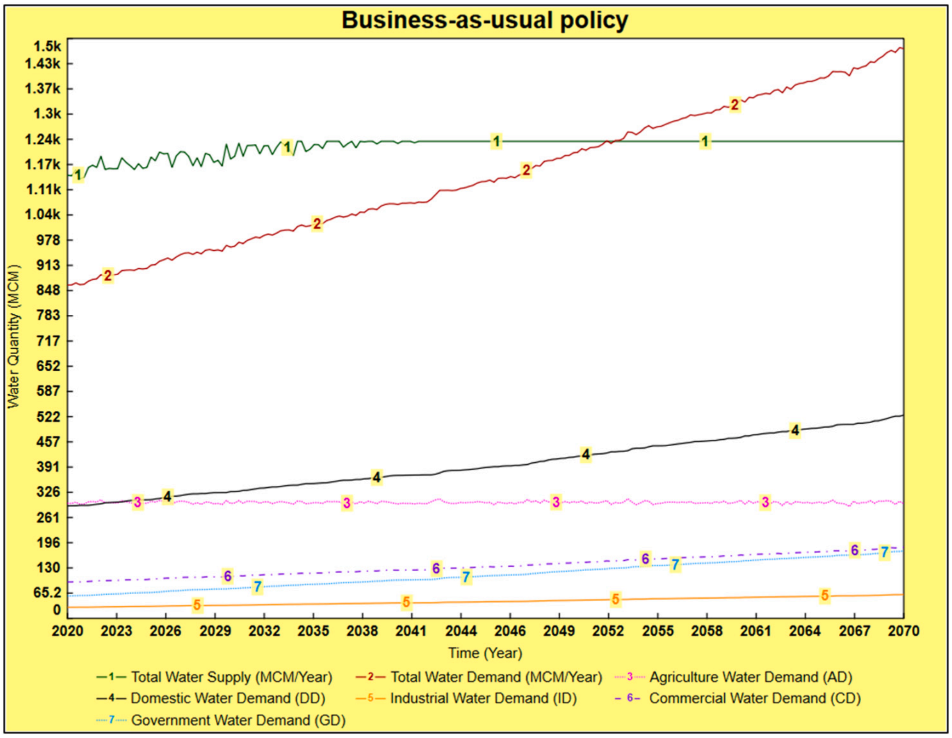


Fig. 17. Business-as-usual (BAU) WRM policy.

However, it is noteworthy that prior research primarily focused on specific demand subsystems and did not encompass the comprehensive dynamics of the entire system (Lahlou et al., 2023). Significantly, this study distinguishes itself as the first to comprehensively model and analyze all water supply and demand subsystems, encompassing their dynamic interactions. This approach enables the comprehensive assessment of the system's capacity to adequately satisfy Qatar's water requirements. To the best of the author's knowledge, this work represents an innovative and pioneering effort in conducting both sensitivity analysis and a holistic regional water resource system resilience analysis in Qatar.

4.3. *Policy implications*

4.3.1. *Business-as-usual (BAU) policy*

This study indicates a notable increase in the country's total water demand from 884 MCM/year in 2021 to roughly 1476 MCM/year by 2070 (Fig. 17). This is achieved by analyzing Qatar's existing WRM strategy using an SDM-based DSS under the BAU conditions, referred to as policy scenario "A" in Table 3. On the other hand, the system receives a consistent water supply at 1235 MCM annually. As illustrated in Fig. 17, the impulsive supply pattern from 2021 (1143 MCM) to 2038 (1235 MCM) is ascribed to the variation in TSE supply in the system until it reaches its maximum capacity of 360 MCM/year (Fig. 18). From 2038 onwards, the collected TSE exceeds the TSE plant capacity, indicating that the TSE processing is restricted to the maximum plant capacity level. Consequently, the water supply will remain stable at 1235 MCM/year from 2040 onwards. This also indicates the requirement for additional TSE processing plant capacity to satisfy increasing system demand while safeguarding the environment from unintended repercussions.

Additionally, it becomes evident that under policy scenario "A", the water demand could be met by 2052 (Fig. 17). Nevertheless, it is noteworthy that 2052 might also be regarded as a tipping point for WRM policy "A". Following this period, the WSI value drops below one, signaling an imbalance between supply and demand within the system. This BAU WRM strategy ensures a sustainable supply for 64 % of the time (32 years), while 36 % of the time (18 years), the region may experience water scarcity. Hence, adopting this strategy results in a reliability index (RI) of 64 % (32/50), as presented in Table 3.

4.3.2. *Tourism impact*

To illustrate the influence of tourism on the national water resource balance, policy scenario "A" was simulated without taking the tourism industry's demand into account, denoted as policy scenario "A_2" in Table 3. Consequently, the overall water demand decreased to 1461 MCM by 2070, maintaining supply for 34 years and resulting in an RI of 68 % (34/50), compared to the 64 % RI observed under the BAU WRM policy. This observation underscores the significance of accounting for tourist influx in national WRM policies. Failing to do so could inadvertently exert unforeseen pressure on the overall system. Moreover, the outcome highlights the importance of integrating the water demand from the tourism sector into these policies. Additionally, it underscores the importance of fostering stakeholder engagement across integrated sub-sectors to formulate effective regional WRM policies. The key findings and performance of various WRM policy scenarios evaluation using the DSS are summarized in Table 3. These WRM policy scenarios were formulated using the scenario-generation framework previously discussed in the Section. 3.3. Fig. 19 depicts the performance indicators result for all the assessed WRM policies.

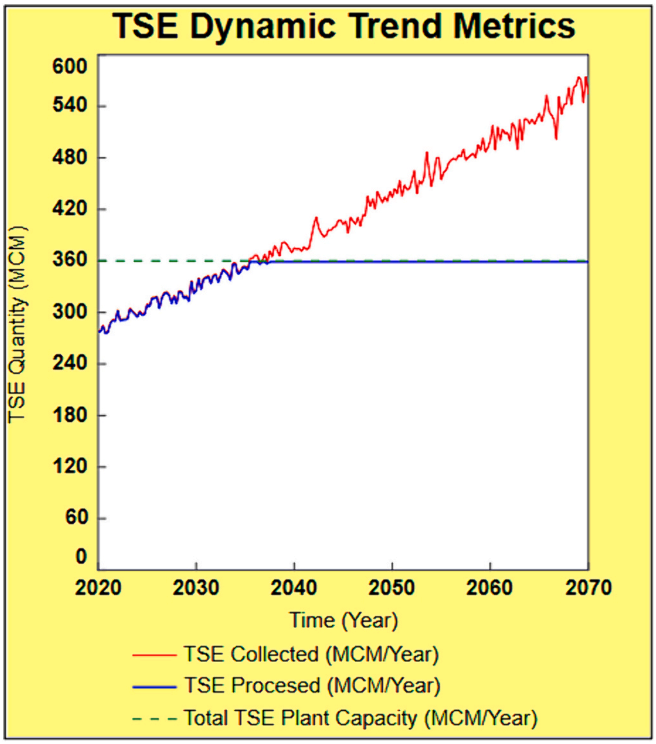


Fig. 18. TSE trends dynamics (2020–2070).

4.3.3. *Reduced water demand policy impact*

The strategic sustainability objective in Qatar, as part of the

Table 3
Water resource management policy scenario results.

WRM policy scenario	Water supply	Water demand	Years with WSI ≥ 1 (system's resilience)	RI (%)	Total water supply in year 2070 (MCM)	Total water demand in year 2070 (MCM)
Policy "A"	BAU	BAU	32 years (2021–2052)	64	1235	1476
Policy "A_2"	BAU	BAU –Tourism WD	34 years (2021–2054)	68	1235	1461
Policy "B"	10 % increase	BAU	40 years (2021–2060)	80	1358	1502
Policy "C"	10 % decrease	BAU	24 years (2021–2044)	48	1111	1449
Policy "D"	BAU	10 % increase	23 years (2021–2043)	46	1235	1616
Policy "E"	10 % increase	10 % increase	33 years (2021–2053)	66	1358	1624
Policy "F"	10 % decrease	10 % increase	14 years (2021–2034)	28	1111	1586
Policy "G"	BAU	10 % decrease	42 years (2021–2062)	84	1235	1334
Policy "H"	10 % increase	10 % decrease	50 years (2021–2070)	100	1358	1357
Policy "I"	10 % decrease	10 % decrease	34 years (2021–2054)	68	1111	1310

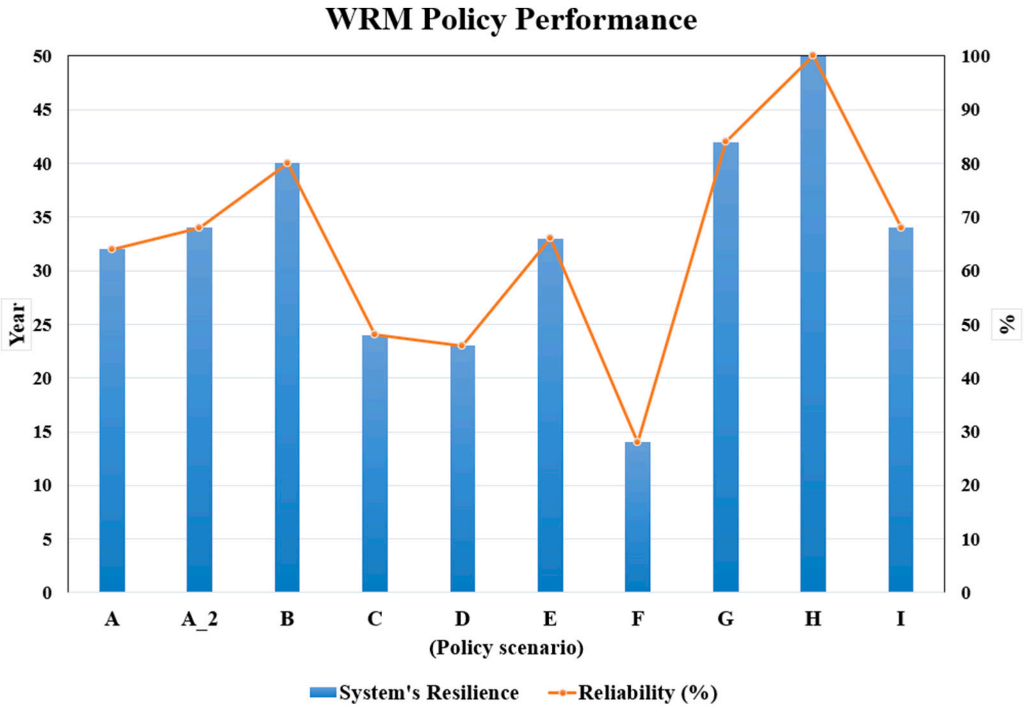


Fig. 19. WRM policies assessment using resilience and reliability indicators.

"Tarsheed program", is formulated to achieve a minimum 10 % reduction in water demand, as discussed earlier in the Section 3.3. In this research study, we investigate the impact of WRM policies that aim to achieve this 10 % reduction in water demand using the developed DSS. Several WRM scenarios with reduced water demand are generated using the unique scenario generation framework proposed in Section 3.3. Analyzing scenario "G", where the water supply capacity is kept at BAU level while the demand is reduced by 10 %, as stated in Table 3. This WRM policy results in supply sustainability till 2062, with an RI of 84 %.

Furthermore, insight emerges when we delve into policy scenario "I", characterized by a simultaneous 10 % reduction in supply and demand within the simulation model. This policy yields a noteworthy outcome, ensuring a sustainable water supply in the region for 34 years. Despite the reduction in water supply, the outcome remains commendable. Resulting in a noteworthy RI value of 68 %, the WRM policy surpasses the BAU policy by two years, marking a 6 % improvement over the BAU scenario. Policy "I" once again underscores the importance of devising effective strategies for mitigating water demand and its positive impact on water resource sustainability and improved system resilience.

4.3.4. *Increased water supply policy impact*

The enhanced supply scenarios in the water resource system are assessed by incorporating a 10 % capacity expansion of desalinated and TSE plants into the water supply system employing the developed DSS. The capacity expansion is a strategic outcome aligned with the national objective of bolstering regional water resilience through proactive investment in the strategic infrastructure, as outlined in Qatar's National Vision (QNV Committee, 2008). This results in a total system capacity of 1358 MCM/year. Under this policy, the water demand is maintained at its BAU level, denoted as scenario "B", concurrently with implementing a 10 % increase in water supply, as outlined in Table 3. Implementing policy "B" using the WRM DSS simulation model, it can be noticed that the regional water availability can be ensured till 2060, with an RI of 80 %, representing a 25 % improvement compared to BAU (Policy "A"). Despite maintaining the demand level at BAU in policy "B", a marginal increase in total demand was observed, reaching 1502 MCM in 2070. This represents a 1.76 % increment compared to the BAU scenario (Policy "A"). This is attributed to the fact that the enhanced water supply results in an improved WSI, which positively affects the regional residential utility. This subsequently influenced the per-capita water demand and ultimately contributed to an overall increase in the total water demand within the region. A similar finding was also reported by (Gohari et al., 2013), where the policy of increasing water supply alone without effective demand management in the Zayandeh-Rud basin of Iran resulted in unintended side effects of long-term increase in water demand. This policy exemplified the "Fixes that Backfire" system archetype, as stated by Gohari et al. (2013), highlighting system parameters' intricate and dynamic interplay in WRM policymaking. This further emphasizes the significance of SDM-based WRM DSS simulation research studies, which enable a comprehensive system analysis by considering feedback loops and complex interactions within the subsystems.

Notably, employing policy "E", regional water availability can be ensured for only 33 years. This scenario results in the context of enhanced water supply levels with an increase of 10 % concurrently with a 10 % rise in the demand of associated sub-sectors due to the absence of effective demand management initiatives, as illustrated in Table 3 and Fig. 19. The RI value in this scenario is 66 %, representing a modest 3.1 % improvement over the BAU scenario.

The WRM policy "E" again reinforces the pressing need for effective water demand management strategies. Compared to BAU policy "A" (ensuring water sustainability for 32 years), failing to invest in demand control initiatives leads to a marginal one-year extension of water availability, even with a 10 % increase in water supply.

In addition, policy "H", which advocates for a simultaneous 10 % increase in supply and a 10 % drop in demand through active demand management measures, results in a sustainable water supply until 2070. As evident in Fig. 19 and Table. 3, with considerable gains in the WSI and RI for the Qatar case study, policy "H" stands out as the most significant WRM strategy.

4.3.5. *Least desirable policy scenarios*

The least desirable WRM policy scenarios encompass situations where a decline in water supply occurs, potentially due to the partial closure of desalination and TSE facilities. The lack of active demand control strategies exacerbates these issues and increases water demand.

Under these conditions, a sustainable water supply can be ensured until 2044, given that the system supply drops by 10 % (policy “C”). This policy scenario is associated with an RI value of 48 %, as shown in Table 3. Conversely, if the supply is maintained at the BAU level with a potential demand increase of 10 % (policy “D”), a sustainable water supply can be upheld until 2054, yielding a reduced RI value of 58 %, which is 28 % lower than the BAU scenario. Moreover, when examining the scenario characterized by a 10 % increase in water demand coupled with a simultaneous 10 % decrease in supply (policy “F”), as illustrated in Table 3, the findings indicate that the water supply sustainability in the region can only be assured until 2034, with an associated RI of 28 %. Consequently, policy “F” is identified as one of the least desirable WRM strategies.

4.3.6. *Groundwater conservation policies*

Qatar's desert climate, marked by minimal annual rainfall of around 75 mm and high evaporation rates of up to 2200 mm (Ahmad and Al-Ghouti, 2020; Bilal et al., 2021; PSA Qatar, 2021), leads to a lack of surface water. Subsequently, the primary natural resource in Qatar is groundwater, with a limited sustainable yearly yield of about 50 MCM. However, Qatar's annual groundwater extraction rate, approximately 255 MCM, is much higher. The higher abstraction rate is a significant cause of seawater intrusion and elevated saline levels. These conditions, exacerbated by climate change, highlight the significance of sustainable water management strategies in arid regions like Qatar.

Additionally, it is widely acknowledged that declining groundwater levels across numerous arid regions are primarily caused by climate change, characterized by decreased precipitation and rising evapotranspiration (Abou Zaki et al., 2019; Gonzalez et al., 2016; Othman and Abotalib, 2019). Notably, within Qatar, a comprehensive investigation conducted by Bilal et al. (2021) harnessed Gravity Recovery and Climate Experiment (GRACE) satellite-derived historical data spanning from 2002 to 2019. The research found that average groundwater thickness decreased by 0.24 ± 0.20 cm yearly. This decline is predominantly ascribed to the excessive exploitation of aquifers, primarily for regional agricultural activities. An imbalance exists between the natural recharge of aquifers, hindered by the arid climate, and excessive groundwater extraction. This imbalance is expected to worsen due to rising water needs from a growing population and increased agriculture driven by higher food demand. Effective use of desalinated water and TSE for irrigation and industry is advised as a practical strategy to ease the burden on groundwater reserves.

It is critical to recognize that the adverse effects of declining groundwater levels can be mitigated if the abstraction is managed and kept within safe limits. Groundwater emerges as a crucial and scarce natural resource in arid regions, particularly in GCC countries, which underscores the imperative need to prioritize conservation. Overuse of aquifers poses serious issues, including saltwater intrusion and the salinity of the water. The groundwater conservation policies are formulated using the unique scenario generation framework developed to mitigate these issues, as presented in Fig. 6, Section 3.3. These WRM policies prioritize implementing measures to control groundwater outflow within a safe abstraction limit. While these policies are tailored to the Qatar case study, the generic approach can be extended to other arid regions promoting natural water conservation.

Nine groundwater conservation policy scenarios (R1, R2, …, R9) were formulated and analyzed based on performance indicators defined in Section 3.2.3. The key findings of this analysis are highlighted in Figs. 20 and 21. These figures illustrate the groundwater conservation policy scenarios evaluated using WSI and RI performance indicators. Furthermore, in the developed WRM DSS, a strategic approach to groundwater conservation has been adopted, prioritizing groundwater resource conservation by allocating only 10 % (32 MCM/year) for agricultural use and 5 % (15 MCM/year) for domestic needs. A 3 MCM/year contingency is also reserved for possible water losses. By incorporating these measures, the yearly groundwater extraction in Qatar can be effectively capped at a maximum of 50 MCM/year. This DSS model constraint, imposing an upper limit on groundwater utilization, follows the established safe abstraction threshold for the region, as advocated by recent studies on sustainable groundwater management in Qatar (Ahmad and Al-Ghouti, 2020; Aloui et al., 2023; Lahlou et al., 2023; PSA Qatar, 2021). The remaining water demand is met through nonconventional water sources. Specifically, 60 % (187 MCM/year) of the agricultural demand is fulfilled by DW, while 30 % (93 MCM/year) is sourced from TSE. Employing the conservation policies, the average groundwater conserved will be approximately 154 MCM/year. The conservation estimate is based on an average aquifer inflow of 204 MCM/year, combined with a strategic approach to limit the outflow to a

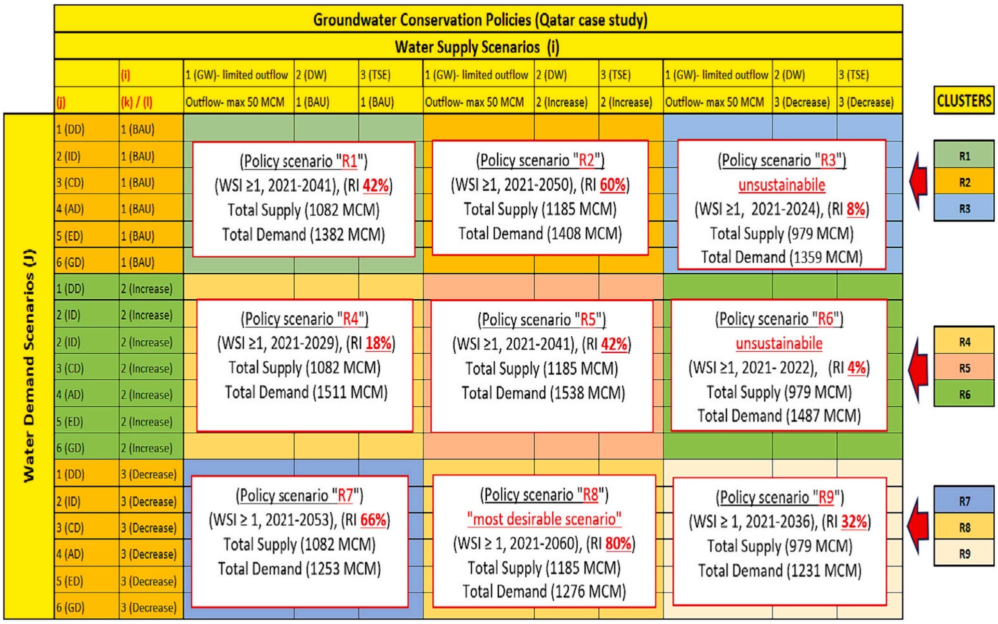


Fig. 20. Groundwater conservation policy scenario outcomes in Qatar.

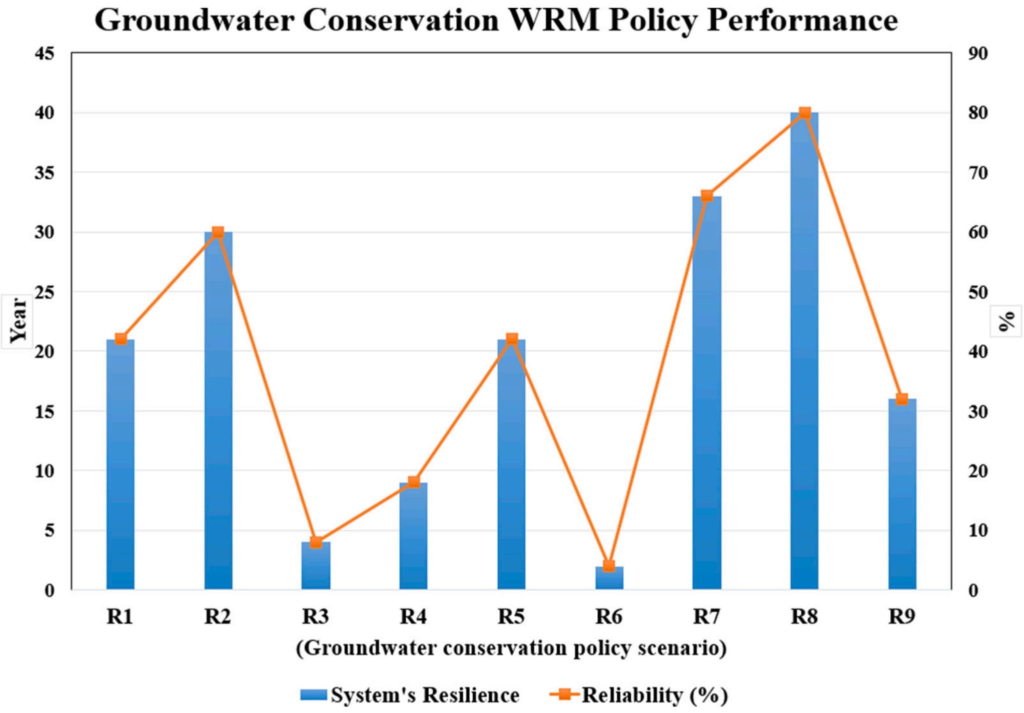


Fig. 21. Groundwater conservation WRM policies assessment using resilience and reliability indicators.

maximum of 50 MCM/year. The cumulative inflow to the aquifer comprises three key components: 78 MCM/year from TSE recharge, 46 MCM/year attributable to rainwater harvesting wells, and 80 MCM/year deriving from DW recharge wells. The aquifer inflow data is sourced from the national report on water statistics in Qatar published by (PSA Qatar, 2021). This approach aligns with Qatar's broader WRM strategies, prioritizing the efficient utilization of nonconventional water sources to meet growing demands while addressing groundwater sustainability concerns.

In the BAU groundwater conservation policy (policy “R1”), a maximum limit of 50 MCM/year is set for groundwater abstraction. The water demand level is also kept in line with the current rate, while the capacities for DW and TSE remain unchanged. In policy “R1”, a sustainable water supply can be ensured from 2021 until 2041 (21 years). This scenario is characterized by an RI of 42 % (Figs. 20, 21).

In the “R2” WRM policy, the strategy involves maintaining demand at the BAU level, with a 10 % increase in DW and TSE capacities. This strategy is estimated to maintain a sustainable water supply until 2050 (30 years), achieving an RI of 60 % (Figs. 20, 21). In contrast, the “R3” policy scenario entails a 10 % reduction in DW and TSE capacities. This reduction may result from a lack of investment in infrastructure maintenance or partial plant breakdowns due to unforeseen events or natural hazards, such as floods. Such a reduction would significantly limit the duration of a sustainable water supply to only four years, resulting in a significantly lower RI of 8 %. This makes the “R3” policy among the least favorable scenarios in terms of long-term water sustainability.

In the analysis of the “R4” policy scenario, characterized by a 10 % increase in water demand, it is estimated that a sustainable water supply can be maintained until 2029 (9 years), with an associated RI of 18 % (Figs. 20, 21). In contrast, the “R5” policy scenario demonstrates the potential to extend supply sustainability until 2041 (21 years). This is achieved through a 10 % increase in DW and TSE plant capacities. However, the “R6” policy scenario poses a considerable challenge, characterized by a combination of reduced DW and TSE supply (decrease of 10 %) and increased demand (rise of 10 %). This combination leads to a highly unfavorable and unsustainable policy scenario, with the RI dropping significantly to 4 %. The policy “R6” thus represents an extreme case, being the least desirable in terms of long-term water supply sustainability.

This research study indicates and quantifies that significant advancements in groundwater conservation and regional supply sustainability can be achieved by implementing water demand reduction strategies. In the “R7” policy, where both DW and TSE supply is retained at the BAU level, and the water demand is curtailed by 10 %, supply sustainability is estimated to be extended to 33 years. This WRM conservation policy is associated with an RI of 66 % (Fig. 20). On the other hand, policy “R9” is marked by a simultaneous 10 % decrease in supply and demand. This policy results in comparatively less favorable sustainability prospects for the system. With an associated RI of 32 %, this strategy limits the supply sustainability period to 16 years.

The outcomes indicate that the “R8” policy scenario is the most effective and robust WRM strategy. This policy primarily emphasizes groundwater conservation while enhancing system resilience to meet water demand. In this scenario, a strategic implementation of a 10 % reduction in water demand coupled with a 10 % increase in supply is simulated using the developed WRM DSS model. Such a combination is instrumental in enhancing the system's water supply sustainability and potentially improving it to 40 years. An additional indication of the effectiveness of this WRM strategy is its RI of 80 % (Figs. 20, 21). These findings highlight the significance of water demand reduction strategies and their positive effects on groundwater conservation. These outcomes also highlight the water resource system's increased resilience in meeting water demand while simultaneously conserving scarce groundwater resources.

4.4. *Policy recommendations*

To ensure sustainable development, it is crucial to strike a balance between water demand and supply levels. As outlined in the preceding section, various WRM policies underscore the necessity of implementing both water conservation and water supply enhancement strategies in Qatar. Relying solely on water infrastructure development while neglecting water conservation measures is not a viable long-term solution. Such an approach often leads to the “Fixes that Backfire” phenomenon, wherein short-term fixes increase consumption behaviors over time. Furthermore, contemporary WRM policies have heavily relied on the overexploitation of groundwater aquifers, aggravating environmental issues such as seawater intrusion and salinity. These challenges are exacerbated by the anticipated impacts of climate change, such as reduced precipitation and increased evapotranspiration rates, leading to decreased natural groundwater recharge.

Given the policy implications discussed, the key recommendations aimed at addressing these pressing concerns are presented as follows:

1. Groundwater conservation:

- Limit groundwater abstraction to the safe yield of 50 MCM per year and fulfill the demand gap using nonconventional water resources.
- Disseminate scientific studies to farmers, affirming the safety and sustainability of employing desalinated water and TSE, supplemented with a suitable blend of necessary nutrients, for irrigation. This measure is particularly pertinent considering that the agricultural sector accounts for the primary demand for groundwater.
- The government must incentivize farmers by providing them with nonconventional water resources at subsidized rates. In exchange, the government may request data on water consumption patterns from the respective farms. This will enhance system visibility and ensure long-term water resource sustainability.
- Incentivize the adoption of modern irrigation practices in the agricultural sector to reduce its overall water demand.

2. Water infrastructure development:

- Invest in nonconventional water resource infrastructure, including desalination and TSE plants, to address regional water needs and ensure long-term water availability.
- The enhanced supply level will meet the demand for agricultural water while facilitating the recharge of deep aquifers, which are currently being overexploited.
- Moreover, the increased capacity will bolster the overall resilience of the national water resource system.

3. Strategic water reserves:

- Considering the political and regional uncertainties, it is imperative for the government to concurrently establish Managed Aquifer Recharge (MAR) projects alongside the strategic Mega Reservoir project in Qatar.
- The enhanced capacity of nonconventional water sources will facilitate the provision of water for the recharge of aquifers.
- These projects will function as natural water reservoirs, providing stored water during emergencies or in the event of potential disruptions to the supply system.

4. Effective water conservation campaigns and strategies:

- Gamify water conservation efforts by creating mobile applications and games in regional languages. This approach may bolster societal awareness and engagement by introducing an entertaining element to capture attention.
- Subsequently, it will facilitate active stakeholder engagement, which is essential for devising pragmatic WRM strategies that consider the challenges faced by all stakeholders.
- Incentivize citizens to adopt conservation practices through two approaches: organizing social events to recognize their positive contributions and providing them with token gift credits that can be redeemed within government departments for paying fees or bills, etc.

5. Capture water demand comprehensively:

- Given the limitation of data regarding regional water demand, implementing IoT devices connected to a centralized data center will help effectively capture water demand from various subsectors.
- Considering the increasing tourism in the region, it is essential to assess the implications of this sector and prioritize it as a primary factor while developing regional WRM policies.

4.5. *Limitations and recommendations for future work*

It is essential to state the limitations of the SDM-based DSS simulation model, as they facilitate the pragmatic interpretation of outcomes. The study employed an average annual value of 311 MCM for the agricultural water demand (PSA Qatar, 2021); however, the subsector could not be further investigated since the necessary data were unavailable. Furthermore, this study has addressed the impact of climate change in the form of groundwater depletion utilizing the findings of a regional study (Bilal et al., 2021). Notably, Qatar's unique water resource context, characterized by the absence of surface water, highlights the significance of mitigating groundwater depletion through effective conservation strategies. In addition to the groundwater conservation strategies outlined in Section 4.3.6, the integration of comprehensive climatic data from Regional Climate Models (RCM) or Global Climate Models (GCM) might be investigated in further studies. Furthermore, it is essential to acknowledge that the unavailability of these climate projections for Qatar is a limitation of this study. This data scarcity hindered the incorporation of the temperature-evaporation dynamic relationship, although the aggregated impact of climatic factors, including precipitation and evaporation, using the findings of (Bilal et al., 2021; PSA Qatar, 2021) is included in the developed DSS model (Figs. 2, 5). In addition, the present research analysis investigated deterministic policy scenarios while acknowledging this constraint. Future research utilizing probabilistic scenario analysis could broaden the conclusions and build upon the research framework established in this study. Addressing these research gaps in future work could contribute significantly towards formulating effective WRM strategies under the impact of climate change.

Moreover, the pivotal role of desalinated water is emphasized in this study. The importance of associated infrastructure development in addressing the growing demand for water in arid regions, including GCC countries, is highlighted. Advocating for increased investment to boost production capacity, it is essential to acknowledge the significant environmental concerns associated with desalination (Elsaid et al., 2020). These include brine discharge and the emission of hazardous gases, which contribute to global warming. To address these challenges, policymakers must implement effective measures (Panagopoulos and Haralambous, 2020).

Several studies and practical techniques have been published to address these challenges (Felix et al., 2024; Giwa et al., 2017; Kabir et al., 2024; Mavukkandy et al., 2019; Morillo et al., 2014). A notable recent contribution by (Mustafa et al., 2024) offers a unique strategy that simultaneously addresses emissions and brine issues. The study integrates selective electrodialysis (SED) to treat the rejected brine and bipolar membrane electrodialysis (BMED) to address the hazardous flue gases emitted from desalination facilities. Valuable industrial products include hydrochloric acid, bicarbonate and carbonate salts, irrigation-grade water, and high-purity sodium chloride, which are extractable using the suggested valorization method. Active commercialization, the development of public-private industrial partnerships and strict legal enforcement of these approaches will facilitate addressing the environmental issues associated with desalination. Additionally, it will assist in turning desalination plant waste materials into valuable byproducts. Furthermore, it is crucial to tackle environmental challenges associated with desalination, encompassing sophisticated brine management strategies that were beyond the scope of this research. These measures, in conjunction with the current study's findings, which developed several WRM policy scenarios and assessed their impact on water resource system resilience, will assist policymakers in formulating strategic WRM policies that align with Qatar's commitment to environmental sustainability.

Furthermore, it is imperative to recognize that SDM models are designed primarily for long-term strategic decision-making and trend forecasting rather than precise point predictions. To enhance the precision of specific value predictions, the integration of advanced machine learning models, such as Artificial Neural Networks (ANN) and Support Vector Machines (SVM), has demonstrated significant potential (Fu et al., 2022; Pu et al., 2023). Moreover, applying optimization techniques for operational decisions related to optimal water resource allocation can substantially augment the model's capacity to bolster effective WRM policies (Naghdi et al., 2021). Investigating these avenues, particularly concerning improved prediction accuracy and refined operational decision support, contingent upon the availability of requisite data, represents a promising direction for future research.

5. Conclusions

This study achieves its primary objectives by establishing an SDM-based framework for understanding and managing the complex water resource system in arid regions, focusing on Qatar as a case study. Additionally, this study advanced the literature by establishing a novel framework for generating WRM policy scenarios specifically tailored to understand the intricacies of policymaking and a systematic policy analysis method. Furthermore, emphasizing the distinctive characteristics of the arid water system, the findings established in this study provide the foundation for future contributions.

Foremost among the contributions includes the development of a DSS using STELLA, integrated within the SDM framework. The developed simulation-based DSS model represents a significant stride forward in engaging stakeholders and supporting strategic decision-making processes. Its significance extends beyond Qatar, offering valuable insights and applications for the GCC countries and similar arid regions. In this study, the water supply and demand drivers were calibrated for 2010–2020, and system behavior was simulated for 2021–2070.

Additionally, a unique contribution of this research study includes an innovative scenario-generation framework designed to achieve dual objectives. Enhancing stakeholder participation through pragmatic and participatory scenario design is the first goal that was accomplished. The second objective was achieved by assisting policymakers in formulating various water supply and design scenarios.

Our findings underscore the critical importance of balancing water demand and supply levels to ensure sustainable development. Policy recommendations include:

- Prioritizing groundwater conservation measures.
- Investing in nonconventional water resource infrastructure.
- Establishing strategic water reserves.
- Implementing effective water conservation campaigns.
- Incorporating regional tourist influx considerations into water resource management policies.

These recommendations address pressing issues such as over-exploitation of groundwater, environmental degradation, and the need for comprehensive water demand capture. By adopting these measures, decision-makers can pave the way for more informed, strategic, and sustainable water resource management practices in arid regions, facilitating long-term resilience and sustainable development.

Future research opportunities encompass developing and analyzing water demand reduction strategies. These include examining customized water pricing schemes tailored to address domestic and commercial demand subsystems, serving as promising areas for further exploration and investigation.

CRediT authorship contribution statement

Khawar Naeem: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing – original draft. **Sarra Aloui:** Formal analysis, Methodology, Validation, Writing – original draft. **Adel Zghibi:** Conceptualization, Supervision, Writing – review & editing. **Annamaria Mazzoni:** Formal analysis, Supervision, Writing – original draft. **Chefi Triki:** Conceptualization, Supervision, Writing – review & editing. **Adel Elomri:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.spc.2024.03.024.

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