Dynamic Modeling of Water Consumption Management in the Khuzestan Plain

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Received: 2025-02-06 **Reviewed:** 2025-04-24 **Revised:** 2025-05-01 **Accepted:** 2025-05-08 **Published:** 2025-08-20

Abstract

The purpose of the present article is to develop a dynamic model for water consumption management in the Khuzestan Plain. Data collection was conducted through both library-based and field-based methods, employing a field analysis approach. Data analysis was performed using Vensim software. One of the prominent approaches in water resource allocation is the use of system dynamics methodology. Predicting behavioral changes in water resource systems under the influence of scenario-based and integrated policy interventions can support the optimal utilization of these resources. The system dynamics approach to water resource management in the agricultural sector of the Khuzestan Plain suggests short-, medium-, and long-term water consumption management strategies after examining current conditions. Under drought conditions, a shift in cropping patterns should be prioritized by planning authorities in responsible organizations. Accordingly, in recent years, a substantial portion of the land previously allocated to sugar beet and rapeseed—crops known for high water consumption—should be reduced. In collaboration with agricultural cooperatives, farmers should be encouraged to increase wheat cultivation. Changing cropping patterns across various cities can improve water demand in the agricultural sector. Given the rainfall levels in the province, farmers can replace high-water-demand crops with wheat to optimize water savings. Altering the cropping pattern not only increases wheat production in the province but also curbs excessive water use in this sector. In the industrial sector, the system dynamics approach to water resource management in the Khuzestan Plain identifies the direct use of potable water by industries as a major challenge for responsible organizations. Many of these industries have been established at high costs, yet initial planning for their water supply was inadequate. As a result, citizens frequently face shortages of drinking water. In the domestic sector, applying the system dynamics approach to water resource management in the Khuzestan Plain suggests that appropriate management and planning—along with promoting a water-saving culture—can largely alleviate citizens' deprivation from potable water. For instance, public education and awareness campaigns regarding efficient water use, planting drought-resistant and climate-compatible vegetation, detecting and repairing leaks in faucets and plumbing fixtures, utilizing unused water sources, employing water-retaining irrigation gels, reducing shower time, avoiding car washing with water hoses, and preventing the hosing down of streets and sidewalks can significantly minimize household water consumption.

Keywords: *Water consumption management, Khuzestan Plain, system dynamics modeling.*

How to cite this article:

Zeidvand, G., Hashemzadeh Khorasgani, G. R., & Alirezaei, A. (2025). Dynamic Modeling of Water Consumption Management in the Khuzestan Plain. Management Strategies and Engineering Sciences, 8(1), 1-12.

1. Introduction

Water, as an essential natural resource, plays a fundamental role in sustainable development, national security, and the preservation of ecosystems. In arid and semi-arid regions such as Iran, where the average annual precipitation is considerably lower than the global average, the importance of efficient water resource management is elevated to a strategic priority. The increasing frequency of droughts, overexploitation of surface and groundwater, and deteriorating quality of water reserves have collectively intensified the urgency for systemic reform in water consumption patterns [1, 2]. According to research, Iran faces one of the most acute water stress conditions globally, with certain regions like Khuzestan being particularly vulnerable due to high evaporation rates, inefficient irrigation systems, and unregulated urban expansion [3, 4]. These environmental pressures have not only impacted the physical availability of water but also exacerbated socio-economic vulnerabilities among agricultural, industrial, and residential communities.

The misalignment between supply and demand in Iran's water management system has reached a critical threshold. A significant contributor to this imbalance is the fragmented and reactive nature of existing water governance policies that fail to integrate scientific modeling and stakeholder-based approaches [5]. In response to this challenge, system dynamics modeling has emerged as a robust tool to simulate complex interactions within water resource systems and evaluate policy impacts under varying conditions. System dynamics, which emphasizes feedback loops, causal relationships, and time-dependent variables, enables a predictive understanding of how water demand in agriculture, industry, and domestic use evolves over time in response to policy interventions or environmental shifts [6, 7]. This methodological framework is particularly suited for managing multidimensional phenomena such as water scarcity, which involve ecological, economic, infrastructural, and behavioral dimensions.

The agricultural sector in Iran accounts for more than 90% of total water consumption, making it both the largest and most inefficient consumer of water. Outdated irrigation systems, excessive cultivation of water-intensive crops like rice and sugarcane in arid regions, and lack of economic incentives for conservation contribute to enormous water loss in this sector [8, 9]. Despite technological advancements and the introduction of modern irrigation methods, widespread adoption remains limited due to institutional inertia and inadequate training programs. As highlighted by Barzegari Benadkoki et al. (2021), the scientific development of sustainable water resource management in various countries has consistently relied on integrated policy design and participatory governance, elements still insufficiently embedded in Iran's water policies [10]. Moreover, the pricing mechanisms for water, particularly in agriculture, do not reflect its true economic value, leading to overuse and wastage. Addressing these structural inefficiencies necessitates not only technical innovation but also reforms in pricing strategies and subsidy allocations [11, 12].

Urban and industrial water consumption, while comparatively smaller in volume, pose equally significant management challenges. Rapid urbanization, infrastructural limitations, and increasing demand for industrial production in provinces like Khuzestan have created a situation where potable water access for households is often compromised [13, 14]. In many cases, untreated wastewater from industrial zones contaminates adjacent agricultural lands and aquifers, undermining both environmental and public health objectives. Effective risk assessment models, including those that integrate fuzzy logic and public-private partnership frameworks, are essential for mitigating such hazards and enhancing resilience in water infrastructure projects [14]. Furthermore, the use of alternative water sources such as treated wastewater—now a cornerstone of sustainable water strategies globally—remains largely untapped in Iran despite its proven effectiveness in international contexts [15].

Public awareness and behavioral change are also critical components of demand-side water management. Studies indicate that educational interventions, particularly those targeting school-aged children and local communities, can significantly improve water-saving behaviors and enhance long-term conservation outcomes [16, 17]. Initiatives that leverage culturally tailored content and cognitive behavioral strategies have demonstrated high effectiveness in fostering water-conscious habits, particularly when institutionalized through school curricula and municipal campaigns. For instance, the design of educational toys and interactive modules for preschool children has shown promise in internalizing sustainable consumption values from an early age [17]. Similarly, training courses based on flipped learning models have been successful in elevating knowledge levels about water conservation practices in middle school students [6].

Another important aspect is the role of digital governance and data-driven decision-making in water management. As Parsakia (2024) notes, balancing sustainability with operational efficiency in resource-intensive sectors, such as hospitality and utilities, requires strategic data integration and scenario planning to align resource availability with consumer demand [18]. Such approaches can be scaled to public water management through centralized monitoring systems, geospatial mapping of water use patterns, and predictive analytics. In Khuzestan, for instance, system dynamics modeling has helped reveal the intricate feedback loops between population growth, industrialization, and water shortages, thus offering actionable insights for infrastructure planning and investment prioritization [3].

It is also vital to recognize the geopolitical dimensions of water scarcity in the region. Transboundary water disputes, such as those in the Helmand River Basin, demonstrate how inadequate water governance can inflame regional tensions and reduce cooperation between neighboring states [5]. Iran's internal water challenges are not isolated from its external water diplomacy; both require coherent and integrated frameworks that consider hydrological, economic, legal, and socio-political factors. Strengthening institutional coordination across ministries, provinces, and water basins is imperative to ensure that national strategies are effectively localized and implemented.

Within this broader context, the Khuzestan Plain serves as a critical case study for analyzing the multifaceted dimensions of water stress. Known for its strategic importance in agriculture, energy production, and industrial development, Khuzestan faces compounded challenges due to its climatic conditions, overdependence on surface water sources, and lack of adaptive infrastructure. Droughts have become more frequent and intense, and water demand in the agriculture and industry sectors continues to outpace supply [2, 4]. In some areas, potable water shortages have reached crisis levels, with tankers being used for emergency water delivery to remote villages [9]. In this setting, any policy intervention that fails to consider the feedback dynamics between demographic trends, water pricing, agricultural incentives, and environmental degradation is unlikely to yield sustainable results.

In light of these complexities, this study seeks to apply the system dynamics approach to model the interplay between supply and demand across various water-consuming sectors in the Khuzestan region.

2. Methodology

Water resource management requires forward-looking decision-making based on a comprehensive approach. System dynamics is a management tool founded on such an approach. This scientific method enables the simulation of complex water resource systems to support decision-making. Through simulation, the uncertain outcomes of various decisions are revealed. The primary objective of this simulation method is to accelerate and facilitate the learning of system behaviors under current and future conditions. Data analysis was carried out using Vensim software.

Rate and State Variables

1. **State Variable**: Also referred to as a stock or level variable, state variables represent the condition of a system at a specific point in time. They remain definable even if time is paused. In this study, the volume of water consumption in the industrial, agricultural, services, and potable sectors is considered a state variable. These variables reflect the system's dynamics.
2. **Flow Variable**: These variables are time-dependent and cannot be defined when time is paused. State variables change as a result of flow variables. In this study, water consumption across agricultural, service, and industrial sub-sectors and other areas in Khuzestan Province is defined as a flow variable. In effect, increased consumption in different sectors reveals their contribution to total water usage.

Sub-Model Analysis in the Dynamic Model

This model begins with a supply-demand framework. On the demand side, population level, industrial growth, and agricultural growth determine total water demand. On the supply side, surface and groundwater resources meet the needs of household, industrial, and agricultural consumption.

1. **Groundwater Aquifer System**: This includes recharge sources such as rainfall infiltration, inflow, surface water infiltration, and return flows from domestic, industrial, and agricultural sectors. Depletion factors include aquifer evaporation, outflow, drainage, spring discharge, and groundwater extraction.
2. **Population System**: Population is one of the most significant and influential factors affecting the water cycle. The population variable reflects human influence on the water cycle and is a function of birth rate, migration, and mortality rate. It is itself affected by various social, cultural, educational, and other factors.
3. **Water Demand System**: This includes potable water, industrial, and agricultural demand. Industrial demand is a function of the number of industrial units and the average water requirement per unit. Agricultural demand includes cultivated land area and water usage per hectare. Water demand in all three sectors is met from both surface and groundwater sources. With population growth, potable water demand rises, and industrial and

agricultural water demand increases at a growth rate, leading to a growing negative gap between water supply and demand.

3. Findings and Results

Figure 1 illustrates the causal loop diagram related to the system dynamics model of water consumption management in the Khuzestan Plain. This model displays the region's hydrological components. The main elements include water demand in agriculture, industry, and domestic use, surface water levels, water deficit, water transfer, and groundwater.

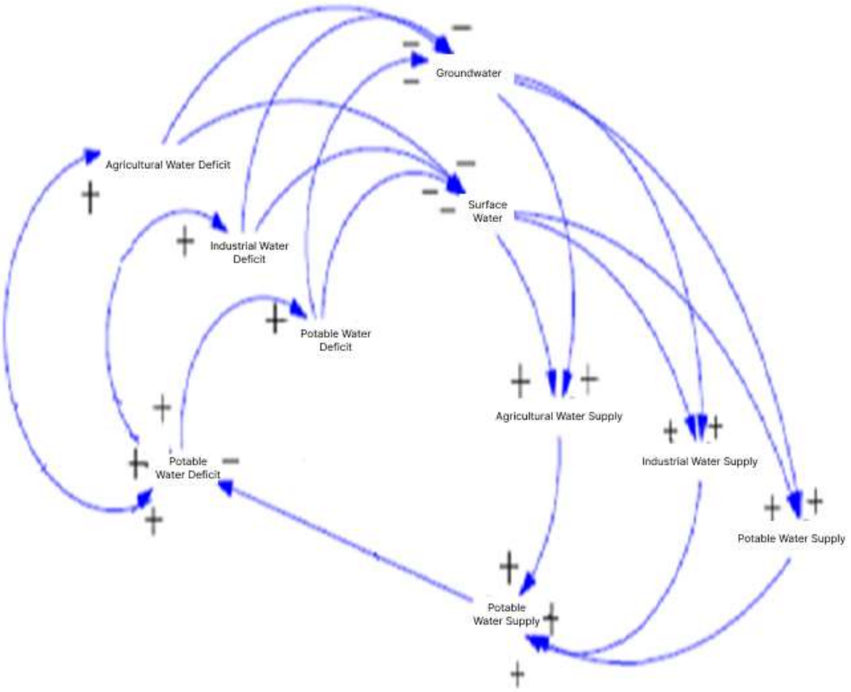

Figure 1. Effect Diagram

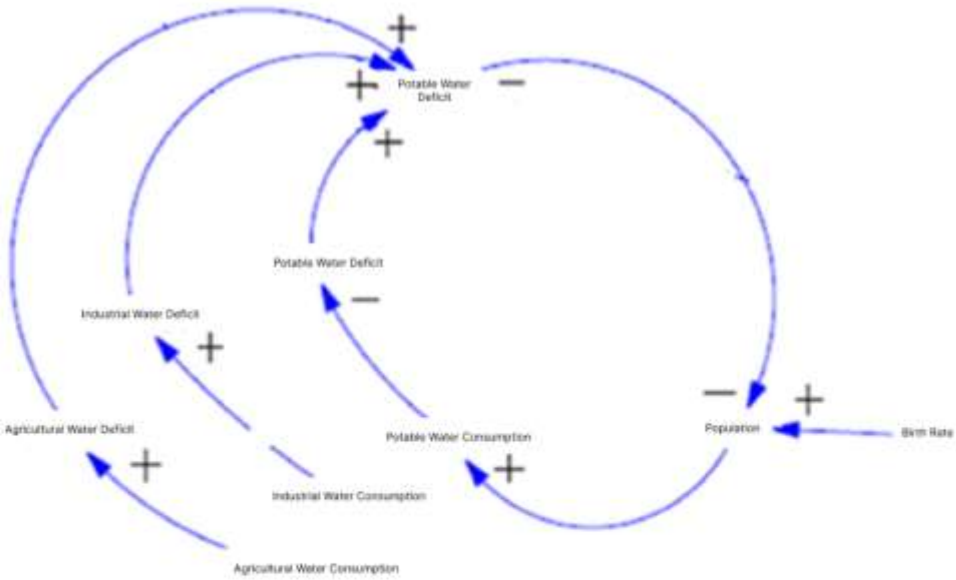

Figure 2. Cause Diagram

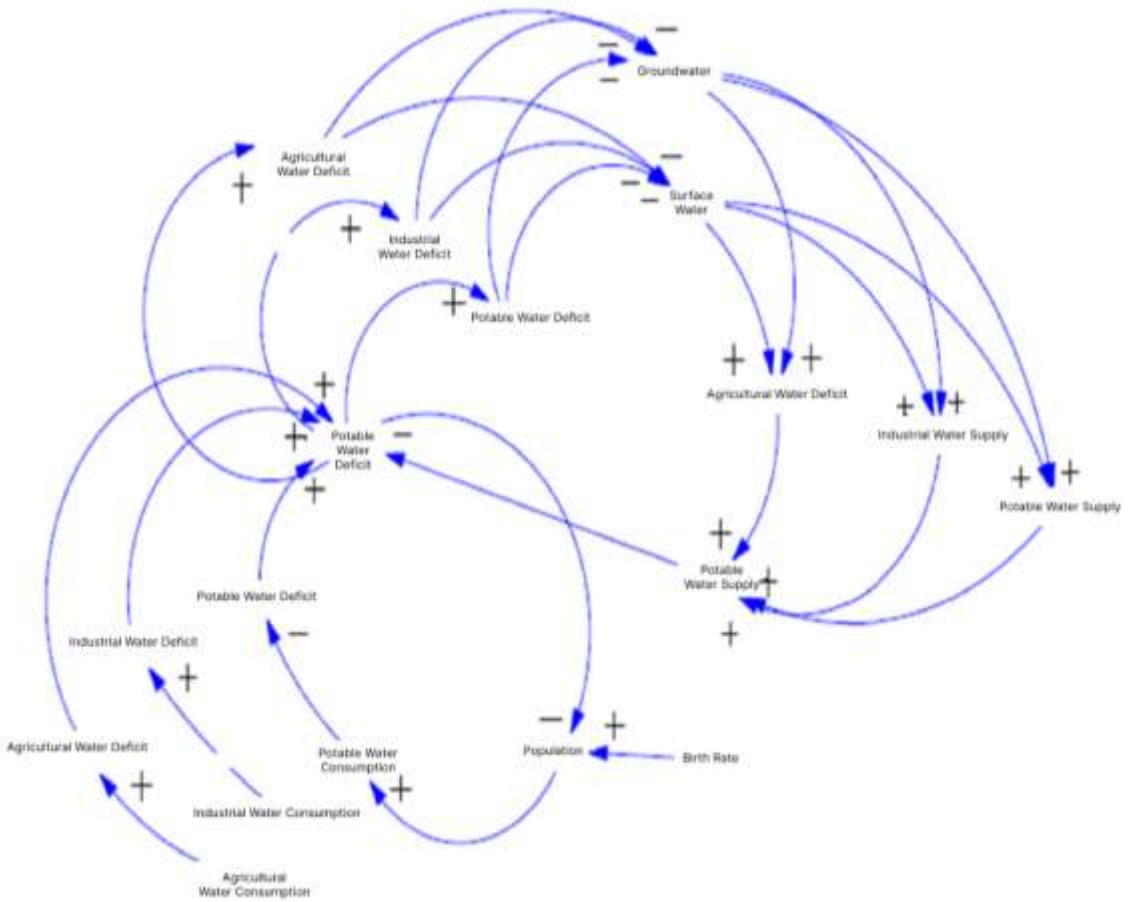

Figure 3. Combined Causal Loop Diagram

Causal loop diagrams provide a visual understanding of the model structure. To comprehend system behavior, the relationships among system variables must be developed and simulated over time using computer tools. A closed-loop water system is shown in Figure 4, which presents the stock-and-flow diagram created for the Khuzestan Plain. This figure illustrates the key stocks and flows. The stock-and-flow diagram is essentially a composite system composed of stocks, rate variables, and their interrelationships.

The stock-and-flow diagram for the Khuzestan Plain model, encompassing all variables identified in the causal loop diagram, was drawn using the Vensim software environment and used for system dynamics-based simulation.

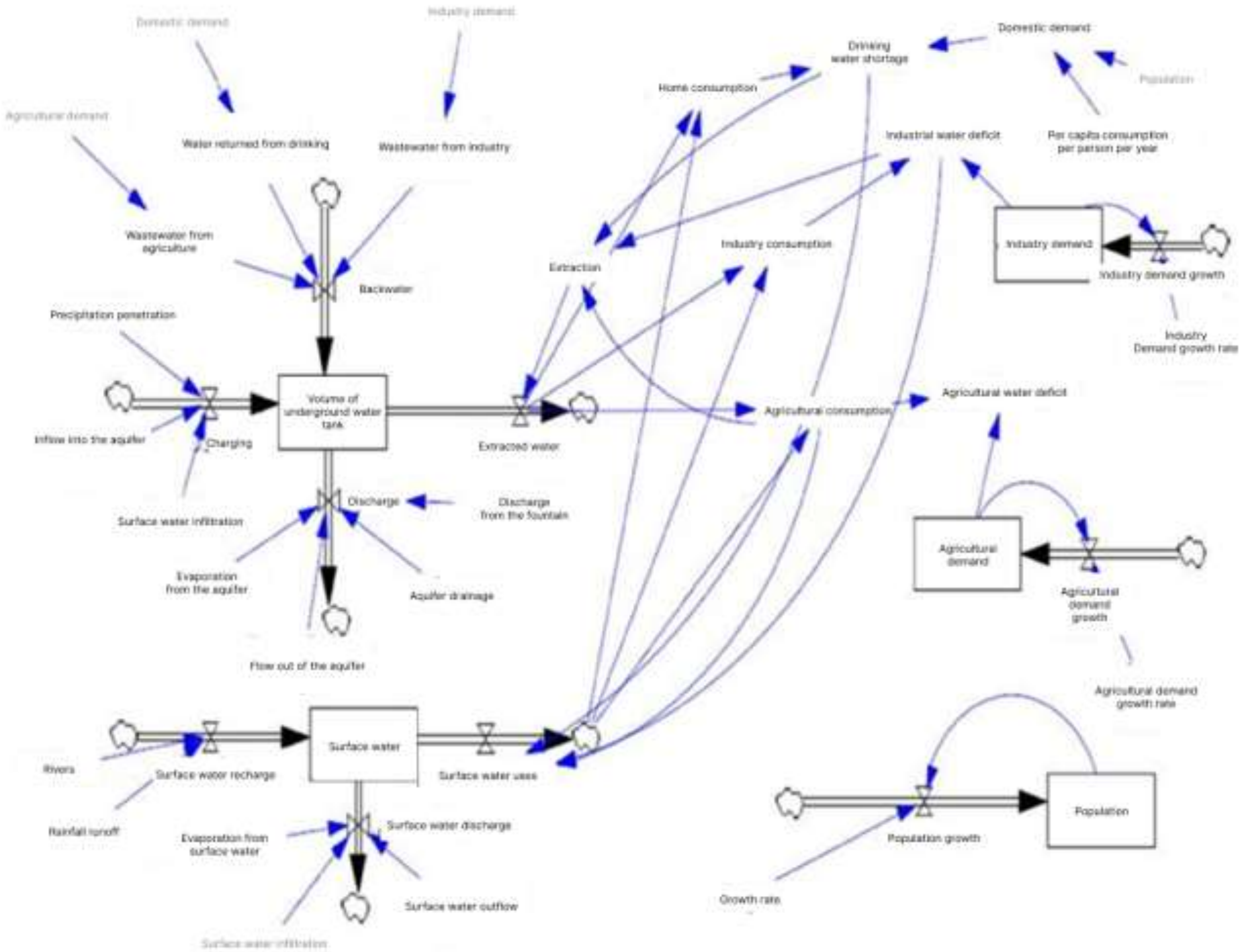

Figure 4. Flow Diagram of the Water System Dynamics Model.

Policy 1: Policies in Response to Increasing Domestic Water Consumption Demand: The rise in domestic potable water consumption demand is addressed as a strategic policy. Specifically, a 20% increase in domestic water demand triggers changes in the model's state variables. In Khuzestan Province, household water consumption is significantly above average or normative levels, resulting in persistent pressure on potable water demand. If domestic consumption increases, appropriate policies must be implemented to address this rise. The most critical policy in this sector is consumption pattern reform and water demand management. As illustrated in Figure 5, with population growth, the demand for potable water increases, leading to a narrowing gap between supply and demand, eventually reaching a point where supply can no longer meet demand. In Figure 5, the trajectory of potable water demand from 2016 to 2023 shows a consistent upward trend. This indicates that effective water demand management must be informed by expert-determined strategies and components.

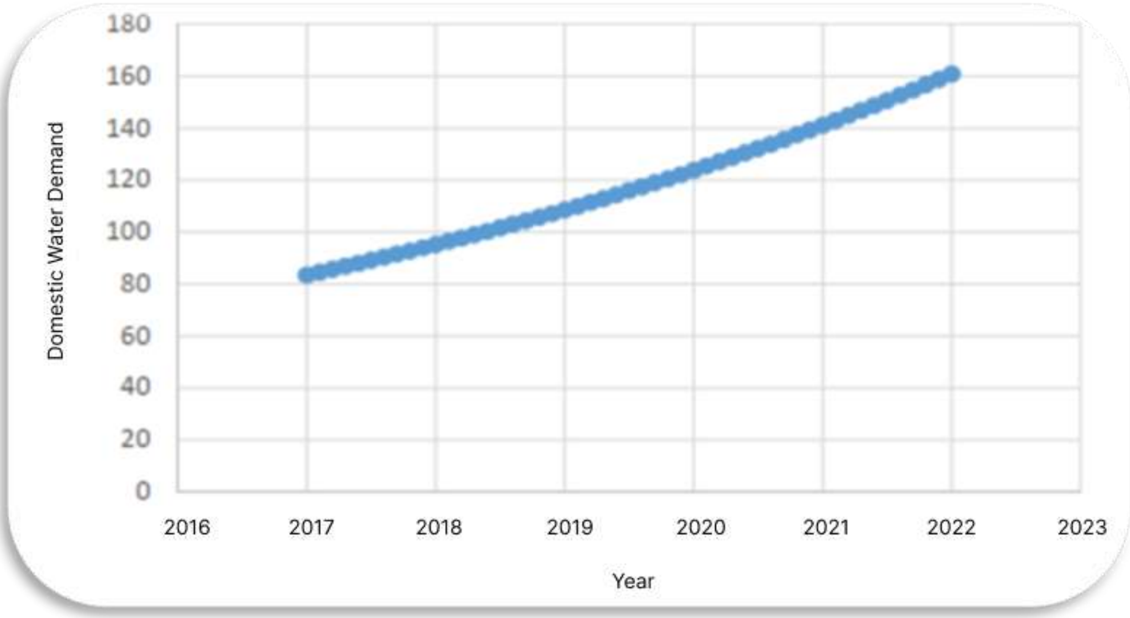

Figure 5. Domestic Water Demand – Scenario 1

This figure illustrates the gap between potable water supply and demand. According to Figure 6, this gap progressively narrows until it reaches zero. A zero value indicates that the entire volume of water extracted for domestic use is fully consumed. When the value becomes negative, it signifies a potable water shortage.

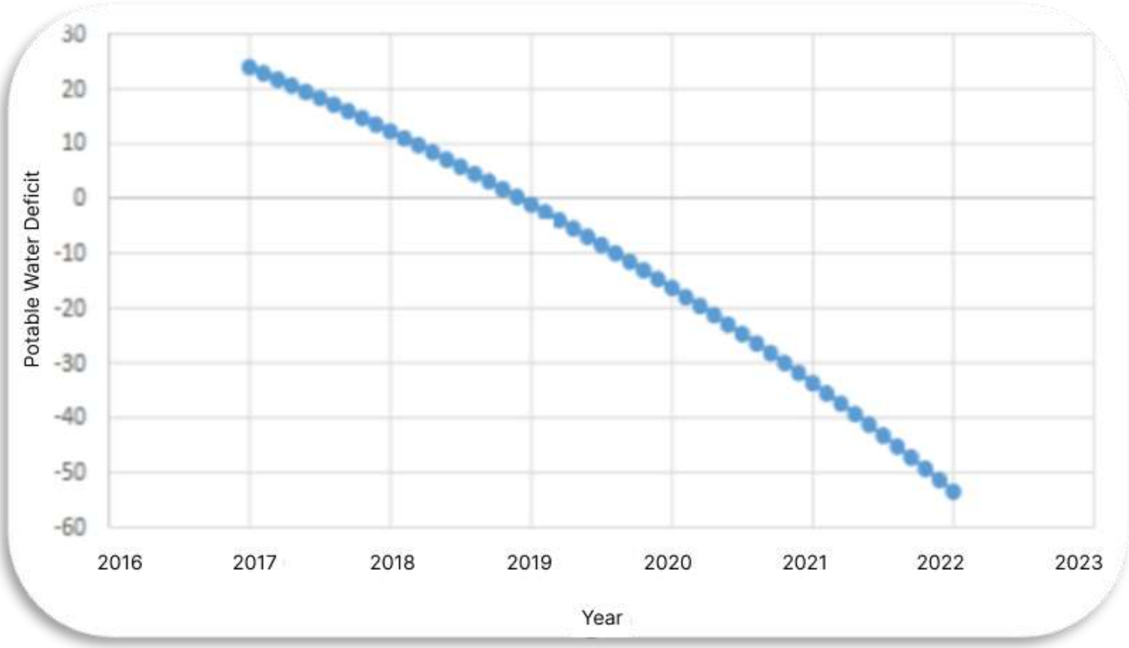

Figure 6. Potable Water Deficit – Scenario 1

Policy 2: Policies in Response to Increasing Industrial Water Consumption Demand: The policy focus in this scenario addresses increasing water demand in the industrial sector. Given the continuous addition of new production units, the industrial sector requires more water. Consequently, policies must be formulated and implemented to meet this demand. One effective policy is to grant operational permits only to industrial activities with significantly lower water consumption. As the industrial water demand growth rate increases, total demand rises accordingly, as shown in Figure 7. With the rising demand for industrial water, the gap between supply and demand narrows. Based on Figure 7, the Khuzestan Plain will face a shortage of water in the industrial sector. The demand trajectory for industrial water use in Khuzestan from 2016 to 2023 is consistently upward. Accordingly, expert-recommended strategies and variables for water demand management in this sector must be prioritized.

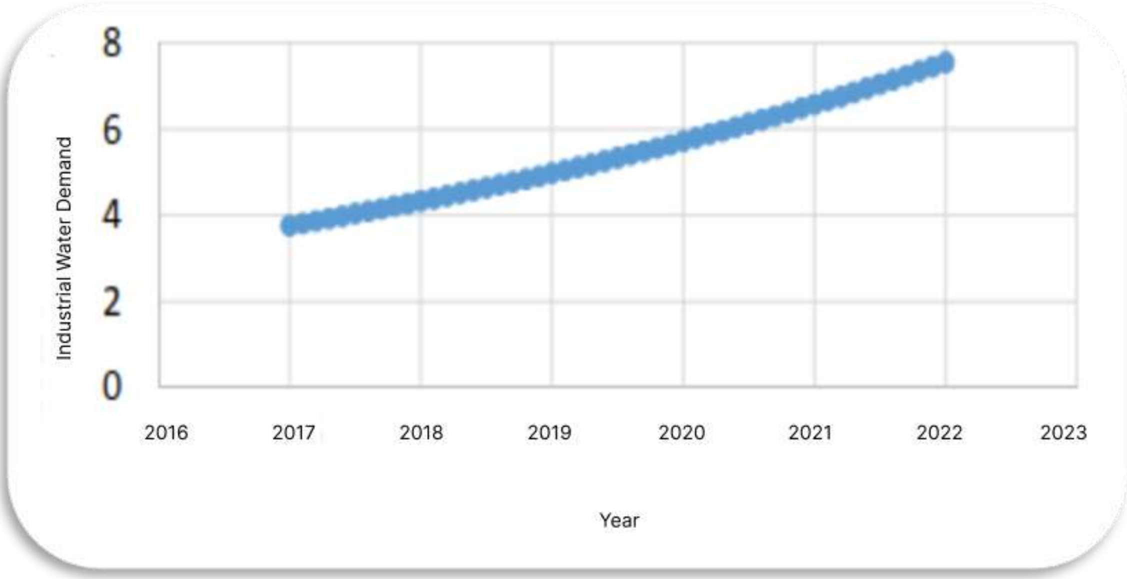

Figure 7. Industrial Water Demand – Scenario 2

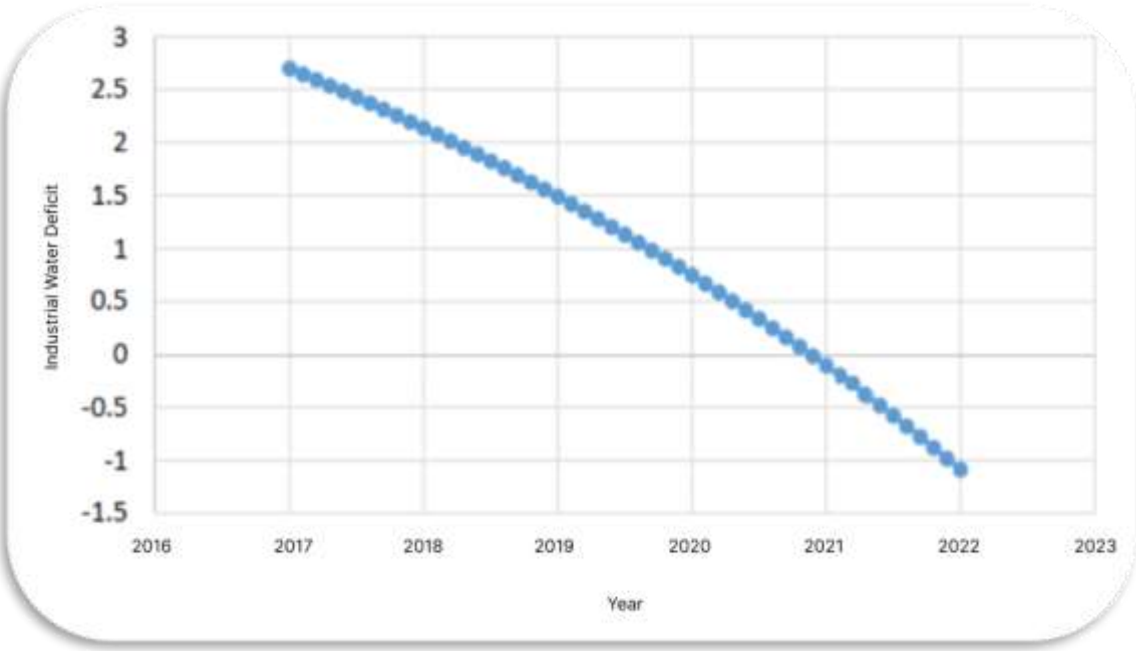

Figure 8. Industrial Water Deficit

Policy 3: Policies in Response to Increasing Agricultural Water Consumption Demand: Among the various water-consuming sectors in Iran, agriculture holds the largest share. Thus, effective demand management in this sector based on suitable strategies is essential. Strategic policies must be implemented, including enhancing farmer participation in agricultural water management, expanding effective training programs to build resilience and adaptability, and providing government support to organizations and cooperatives aimed at transforming agricultural and irrigation practices. Reforming the water pricing system based on the economic value of water in agriculture is one of the most efficient demand management tools available to planners and policymakers, helping to optimize consumption patterns. In fact, proper water pricing across all sectors is one of the best approaches for preserving water resources by promoting optimal usage. With the increasing rate of agricultural water demand, long-term projections indicate future water shortages in this sector. As shown in **Figure 9**, if agricultural water demand continues on its current trajectory, the Khuzestan Plain will face water shortages in agriculture.

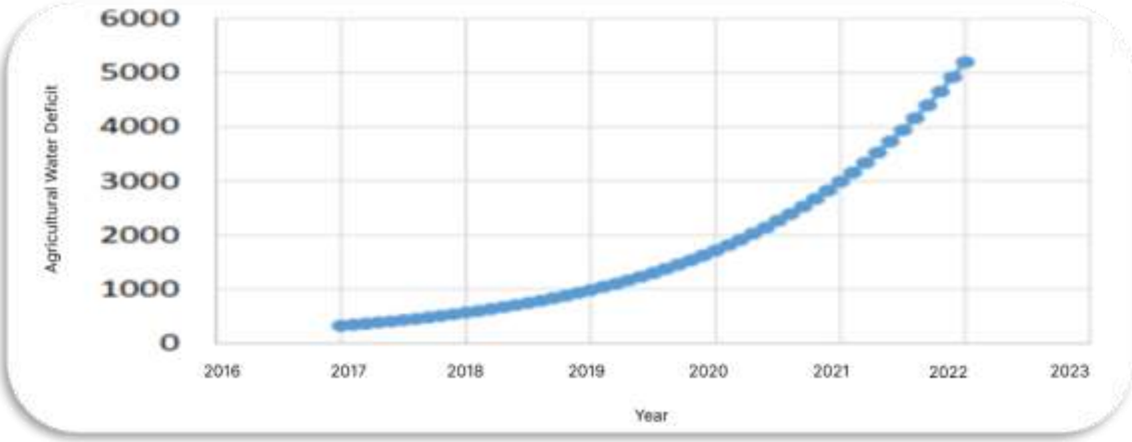

Figure 9. Agricultural Water Demand – Scenario 3

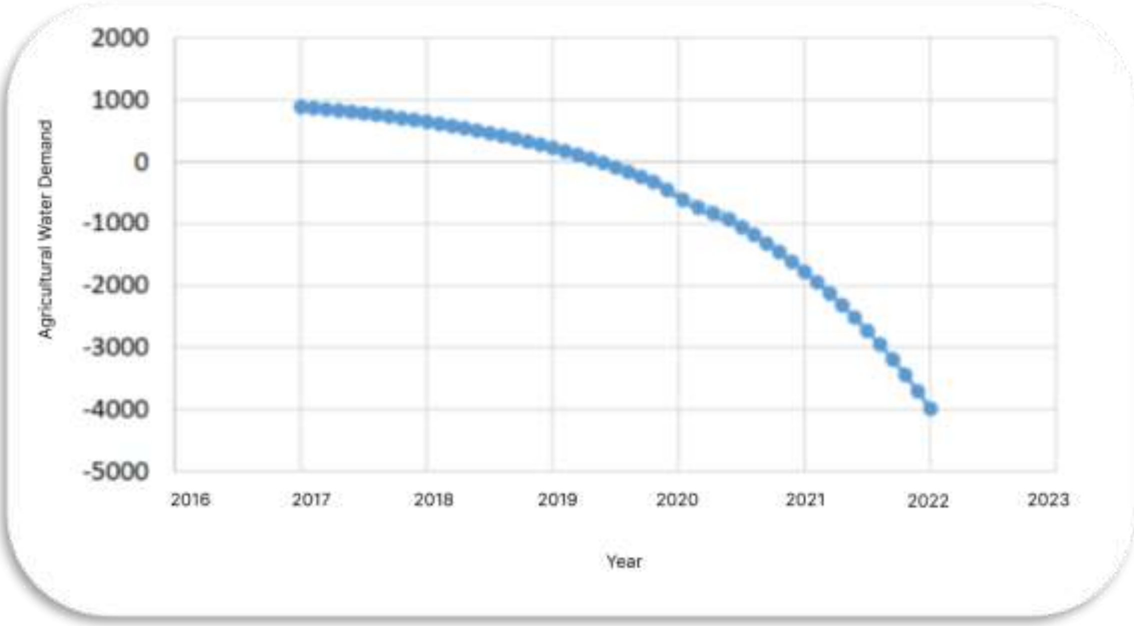

Figure 10. Agricultural Water Deficit

4. Discussion and Conclusion

The results of the system dynamics simulation underscore the urgency and complexity of water resource management in the Khuzestan Plain. The model's first scenario, which simulated a 20% increase in domestic water demand, revealed a progressively narrowing gap between potable water supply and demand, ultimately culminating in a deficit. This trend is particularly concerning given that Khuzestan already consumes water at rates significantly higher than national and international averages, driven largely by rapid population growth and inefficient usage practices [2, 9]. As the simulation results showed, if current consumption patterns persist without strategic intervention, even the complete volume of extracted water will be insufficient to meet demand, resulting in negative supply-demand differentials. These findings are in line with the conclusions of Khodaei Marandi Fard (2020), who emphasized the role of public awareness and education in altering unsustainable water use behaviors, especially in urban settings [12].

In the second scenario, addressing industrial water demand, the model projected a steady rise in consumption between 2016 and 2023, narrowing the supply-demand gap and indicating imminent water scarcity in the industrial sector. The pressure exerted by industrial growth on Khuzestan's water resources reflects both increased production activity and poor infrastructure planning [13]. These outcomes mirror the findings of Khoshnevis et al. (2023), who noted that many water and wastewater infrastructure projects lack risk-informed designs, thereby compounding the system's vulnerability under increasing stress [14]. The simulation suggests that permitting new industrial activities without considering their water footprint may exacerbate regional water shortages. Moreover, the absence of diversified water sourcing, such as the integration of treated wastewater or industrial water recycling, places unsustainable pressure on potable and surface water supplies [15].

The third scenario, involving agricultural water demand, revealed the most alarming trend. The agricultural sector—already the largest consumer of water in Iran—continued to show exponential demand increases, leading to projected severe shortages. As highlighted in the simulation, if agricultural consumption continues at this pace, Khuzestan will face a structural water crisis in this sector. This finding is corroborated by Sadat Fazeli (2022), who illustrated how water-intensive crops and poor irrigation practices significantly lower resilience in drought-prone provinces [8]. Additionally, Soleimani (2019) demonstrated that inefficient surface water drainage systems further exacerbate resource wastage [4]. The simulation validates these concerns by showing how delayed policy responses can result in irreversible deficits. It also supports the argument by Mirzaei et al. (2020) that poor alignment between agricultural expansion and water availability is one of the root causes of Iran's water crisis [11].

Importantly, the simulation provides empirical backing for demand-side management strategies proposed in the literature. For instance, Khoda Shenas and Tajbakhsh (2021) argue for integrating flood control and urban runoff systems as part of a broader water conservation strategy in urban and peri-urban settings [7]. The model's feedback loops demonstrate how infrastructural improvements, combined with behavioral interventions, can reduce demand pressure. Rajaeian et al. (2018) further assert that educational initiatives, such as flipped classroom models for teaching sustainable water use, can have a long-term impact on community-level consumption patterns [6]. This aligns with the model's projection that even minor changes in user behavior—when amplified across a large population—can significantly delay or even prevent water supply crises.

Furthermore, the results affirm the importance of implementing economic instruments such as proper water pricing. Mirzaei et al. (2020) and Nabavi (2024) emphasize that the lack of value-based water pricing mechanisms leads to overexploitation and undervaluation of resources, particularly in agriculture [5, 11]. The simulation clearly illustrates that aligning price structures with actual consumption can serve as a powerful tool to regulate demand. Moreover, as demonstrated by Parsakia (2024), data-driven resource management in high-demand sectors can enable real-time policy adaptation, allowing institutions to preemptively respond to emerging resource gaps [18]. The feedback-oriented design of the system dynamics model reflects these realities, providing policymakers with a replicable tool to assess the outcomes of various intervention scenarios.

Lastly, the simulation reiterates the value of inter-sectoral coordination and long-term planning. The three scenarios examined in this study make evident that isolated interventions in one sector (e.g., domestic water conservation) cannot sustainably resolve broader systemic inefficiencies without parallel reforms in agriculture and industry. This supports the findings of Barzegari Benadkoki et al. (2021), who stressed that global success stories in sustainable water management often hinge on synchronized, multi-stakeholder policy frameworks [10]. The use of system dynamics in this study validates its applicability as a strategic decision-making tool for managing complex, resource-scarce environments like Khuzestan.

This study, while comprehensive in its modeling approach, is subject to several limitations. First, the simulation relies on aggregated data and assumed growth rates across sectors, which may not capture localized variations in water use behaviors or infrastructural constraints. Additionally, the model does not fully account for the impact of climate change variables—such as temperature increases, changes in precipitation patterns, or extreme weather events—which could significantly alter water supply and demand projections. There is also a limitation in stakeholder engagement; while expert insights were utilized, the perspectives of local communities, policymakers, and industry leaders were not directly incorporated into the modeling process. Moreover, although the system dynamics model offers a holistic view, its outcomes are sensitive to initial assumptions and parameter estimations, which may limit generalizability if applied to different regions or under different governance structures.

Future research should consider the integration of climate models and real-time hydrological data to enhance the precision and applicability of system dynamics simulations. Expanding the model to include additional variables such as groundwater recharge rates, evapotranspiration, and land-use changes would provide a more nuanced understanding of the environmental feedback mechanisms affecting water resources. Further studies could also employ participatory modeling approaches, engaging stakeholders from agricultural unions, industrial associations, and civil society to co-develop scenarios and validate outcomes. Comparative case studies between water-stressed provinces within Iran or across similar ecological contexts in the Middle East could also yield valuable insights into policy transferability and regional cooperation. Lastly, longitudinal studies that assess the impact of implemented policy reforms over time would help validate the predictive capacity of system dynamics tools in resource management.

From a practical standpoint, water resource management in Khuzestan and similar regions should be approached through integrated, cross-sectoral strategies. Decision-makers are advised to institutionalize system dynamics modeling within local and national planning agencies to support data-driven policymaking. Public education campaigns should be expanded and embedded in school curricula, targeting behavioral change from an early age. Economic instruments such as water pricing, usage-based tariffs, and subsidies for efficient irrigation technologies must be optimized to reflect the true value of water. Policymakers should also invest in infrastructure for wastewater treatment and reuse, thereby reducing dependence on finite freshwater sources. Finally, developing a centralized water monitoring system—linking municipal, industrial, and agricultural consumption data—can enhance transparency, accountability, and adaptive management across the water governance spectrum.

Authors' Contributions

Authors equally contributed to this article.

Acknowledgments

Authors thank all participants who participate in this study.

Declaration of Interest

The authors report no conflict of interest.

Funding

According to the authors, this article has no financial support.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

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