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Dynamic Modeling of Iran's Integrated Water Market

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ABSTRACT

The civilizational role of arid-region countries experiencing water stress—such as Egypt and Iran—and particularly the provinces situated along Iran's desert fringes (Semnan, Yazd, Qom, Kerman, Isfahan, and Khorasan), has been historically distinctive in the management of water resources, qanat construction, and water distribution. Therefore, this study aims to model the creation of an integrated water market through a system dynamics approach. Utilizing system tools and variables, as well as referencing water markets in other countries, the study identifies key variables and model boundaries. It further defines processes of supply, demand, optimal allocation and distribution, and the interrelationships among them. The connections between elements are illustrated using diagrams, causal loop diagrams, and feedback loops (supply and demand). A portion of the tested assumptions, along with both mathematical and mental models, were designed and implemented in the Vensim software. Establishing an integrated water market as a complex natural and social system is deemed an unavoidable necessity under current water scarcity conditions. Consequently, the developed dynamic model, incorporating relevant elements and variables, was locally validated and optimized as a comprehensive model. The application and repeated simulation of the model within its defined boundaries yielded outcomes such as improved water supply and reduced wastage of water resources. The study identifies dynamic integration in the water market as one of the primary solutions to the issue and emphasizes the urgency of its implementation adapted to the local conditions of each country.

Keywords: *Water market, modeling, price discovery, water rights, dynamic allocation, market governance, development index.*

1. Introduction

Water scarcity has become one of the most pressing global challenges, particularly in arid and semi-arid regions such as Iran. The growing imbalance between water supply and demand, aggravated by population growth, urban expansion, climate variability, and inefficient consumption patterns, has led to an urgent need for innovative governance and market-based mechanisms to manage water resources sustainably. Among the strategies considered globally, integrated water markets have emerged as an effective approach to enhance water allocation efficiency, ensure environmental sustainability, and support economic resilience under conditions of increasing scarcity and uncertainty (Karimpour et al., 2021; Lima et al., 2021; Mohamed et al., 2021).

In Iran, the traditional reliance on centralized water governance structures and command-and-control mechanisms has proved insufficient to address contemporary water challenges. The absence of economic valuation for water, fragmented management of surface and groundwater, and lack of participatory approaches have contributed to over-extraction, resource degradation, and stakeholder conflicts (Khodaei Marandi Fard, 2020; Mehrabi et al., 2022; Soltani & Zibaei, 2020). These concerns have motivated scholars and policymakers to explore decentralized, market-oriented models of water management that enable dynamic allocation based on supply-demand conditions, opportunity costs, and socio-environmental trade-offs (Keramatzadeh et al., 2011; Kiani, 2008).

Water markets, as voluntary platforms for trading water rights or allocations, can enhance resource-use efficiency by transferring water from lower- to higher-value uses, incentivizing conservation, and enabling adaptation to climatic and hydrological variability (Kiani & Bagheri, 2013; Shahnoushi, 2014). However, their successful implementation depends on clearly defined water rights, transparent pricing, robust legal frameworks, and real-time monitoring infrastructures. In Iran's context, such markets are still in their infancy, with limited institutional development and case-specific applications mostly in agricultural basins such as Khorasan Razavi and Bojnourd (Keramatzadeh et al., 2011; Shahnoushi, 2014).

A critical component of effective water market design is the integration of hydrological, economic, and social dimensions through system dynamics modeling. This approach allows for the simulation of complex feedback loops between supply, demand, pricing, regulation, and behavioral change over time, thus providing a decision-support framework for policy testing and scenario analysis (Behloulund, 2006; Mogholi et al., 2016). Tools like Vensim have been utilized to construct simulation models that consider groundwater extraction, consumption quotas, delay mechanisms, and policy leverage points, enabling stakeholders to visualize the long-term consequences of different water allocation strategies under uncertainty (Ghandi & Roozbahani, 2019; Mogholi et al., 2016).

The Iranian experience with informal and localized water exchanges—such as the Majan water market—demonstrates that water trading can emerge organically under conditions of scarcity and when supported by traditional norms and local agreements (Kiani, 2008). Yet, the economic implications of these local markets—particularly in terms of price formation, welfare impacts, and sustainability—require rigorous evaluation and regulatory oversight (Kiani & Bagheri, 2013; Tehami Pour, 2017). Moreover, agricultural dominance in water use—with inefficient irrigation systems and low value-added returns—demands a shift toward demand-side management practices and pricing mechanisms that reflect water's true economic and environmental value (Sadat Fazeli, 2022; Soltani & Zibaei, 2020).

Several studies have underscored the importance of coupling water demand management with pricing policies, behavioral interventions, and educational programs to induce conservation across user groups. For instance, raising awareness among students and communities about optimal consumption has shown positive outcomes in modifying usage behavior and promoting civic responsibility in water stewardship (Khodaei Marandi Fard, 2020; Parsakia, 2024). Similarly, the development of crisis management frameworks based on water demand scenarios—especially in major cities like Tehran—has highlighted the role of real-time decision-support tools in enhancing urban resilience (Ghandi & Roozbahani, 2019; Mogholi et al., 2016).

In the international context, empirical evidence from benchmark cities and regions shows that integrated water resource planning combined with flexible allocation mechanisms can significantly reduce water losses, improve hydraulic performance, and increase economic efficiency (Ray Biswas et al., 2023; Roshani & Filion, 2014). For example, system-wide simulations have demonstrated how varying consumption patterns and seasonal fluctuations affect the reliability of water distribution systems, offering insights for infrastructure rehabilitation and investment planning (Mohamed et al., 2021; Roshani & Filion, 2014).

The adoption of public-private partnerships (PPPs) in water service provision is another dimension relevant to Iran's transition toward a more adaptive water economy. These arrangements can leverage private sector efficiency, technical capacity, and investment capital, provided that transparent contracts and performance benchmarks are established to safeguard public interests and ensure accountability (Lima et al., 2021). However, local socio-political dynamics, governance maturity, and public trust play a crucial role in shaping the outcomes of such reforms.

From a systems-thinking perspective, water markets are not merely economic instruments but part of a broader socio-ecological system. Their design must consider long-term sustainability, equity among users, ecological thresholds, and dynamic feedback between policy actions and system responses. This holistic view is critical in contexts like Iran, where inter-basin transfers, transboundary water sharing, and climatic vulnerabilities create additional layers of complexity (Mehrabi et al., 2022; Sadat Fazeli, 2022).

This study builds upon these theoretical and empirical foundations to develop a conceptual and simulation-based model of an integrated water market in Iran, using a systems dynamics approach.

2. Methods and Materials

This study was designed to follow a four-phase modeling process aimed at identifying and analyzing coordinates, data, and variables by utilizing the research literature, existing studies, and practical models, while also presenting the concept of the system and water markets in other countries.

Although in its initial stage this research is considered a scientific, literature-based, and library-oriented study, the model design process draws upon both deductive and exploratory reasoning. Given the novelty of the topic and the presence of both actual and potential challenges, the model incorporates adjustments in causal loops and state variables. As a result, in some instances, better outcomes were achieved based on input variable modifications.

System Mapping: The main and key variables, along with interconnection variables, were identified and defined. Causal loop diagrams (CLDs) were developed to explain and illustrate these variables. Process analysis, input variable revision, and diagrammatic representation of interrelations were also performed.

Behavioral Analysis of Dynamic Cycles: This step involved identifying feedback generated from modeling and influential variables (based on their degree of dependency or independence), detecting potential conflicts within the resulting graphs, and evaluating the influence of leverage points—such as resources and price factors—on the model.

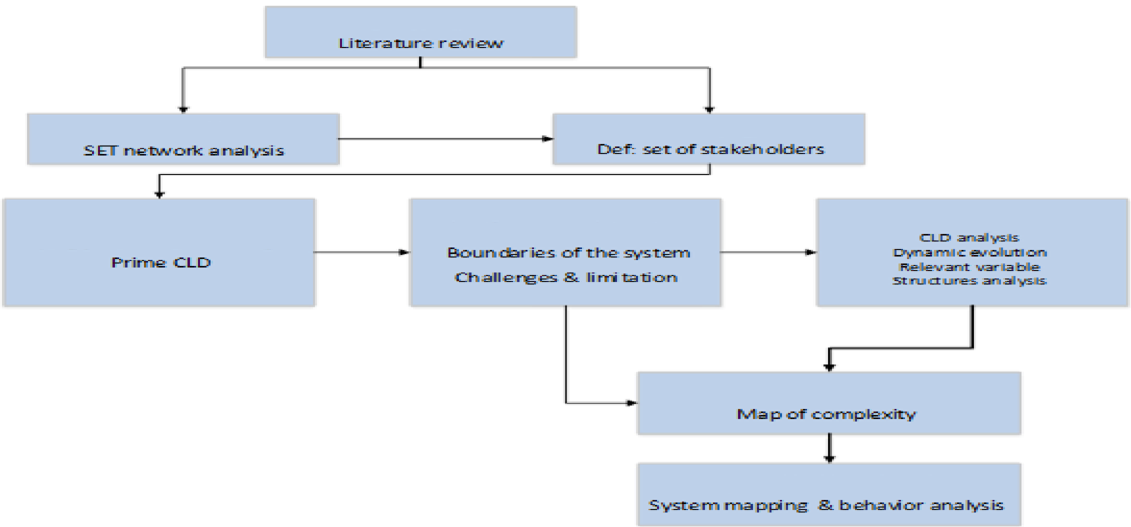
System Simulation: The model was tested repeatedly with variations in the magnitude and type of variables. CLDs were simplified, and stock-and-flow structures were analyzed. Various supportive, comparative, and evolutionary models were evaluated through multiple quantitative, data-driven scenarios.

Throughout the study, several unidirectional statistical models were employed—models that start from independent variables and lead to dependent variables. Despite the inclusion of mediating and moderating variables, the model did not contain recursive structures. Instead, variables and their interrelationships were merely identified and defined.

Given the complexity and dynamic nature of the research topic, innovative modeling techniques were adopted. These methods emphasized the inclusion of a greater number of variables within a closed system boundary, which significantly contributed to the effectiveness of result analysis.

Figure 1

Research Literature



Dynamic Hypothesis Formulation: To model the behavior of system dynamics variables, a dynamic hypothesis was formulated. This hypothesis was based on internal factors of the model and focused on defining the scope and boundaries of the model while distinguishing between endogenous and exogenous variables. It aimed to clarify the behavioral characteristics of the problem.

Since this type of research is relatively new in Iran, the model's scope was intentionally limited. Expanding the model unnecessarily by including irrelevant variables would increase its complexity and potentially reduce the validity of its results.

Influential Factors and System Variables in This Model:

Level Variables:

Water resources level, population, agricultural water consumption, and industrial water consumption.

Rate Variables:

Water supply, water demand, demand growth rate in agriculture and industry, and the rate of demand reduction.

Constant Variables:

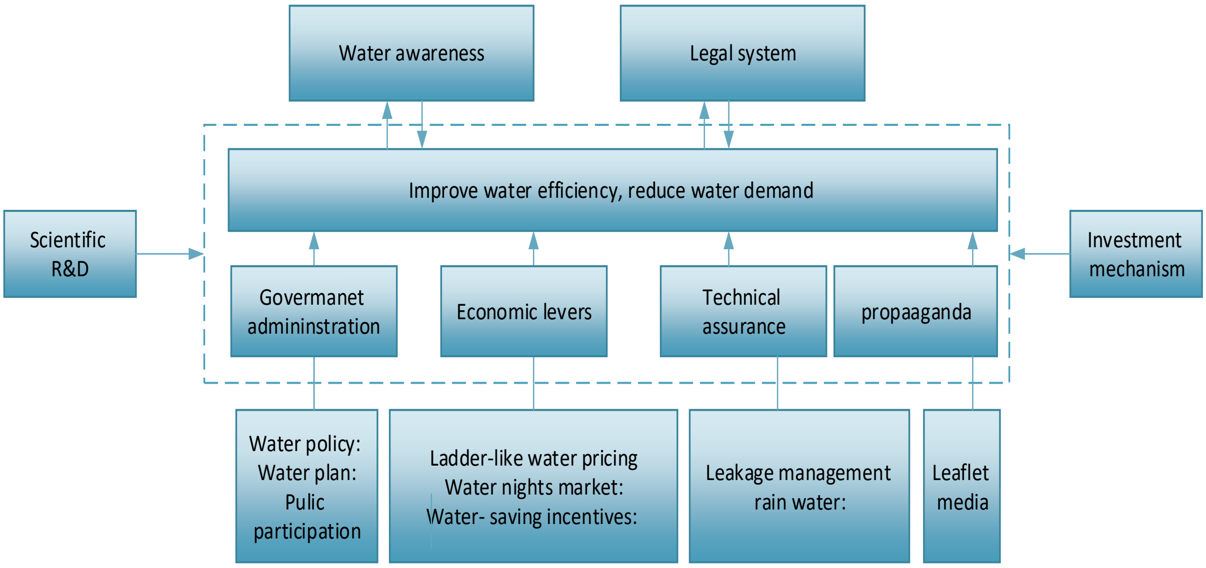
Average agricultural and industrial water consumption, volumetric price of demanded water, and volume of allocated water.

Legal and Governmental Factors:

Water laws, distribution and allocation regulations, ownership regulations, water policy-making, and investment strategies.

Figure 2

Water Demand Level Model and Water Productivity Enhancement



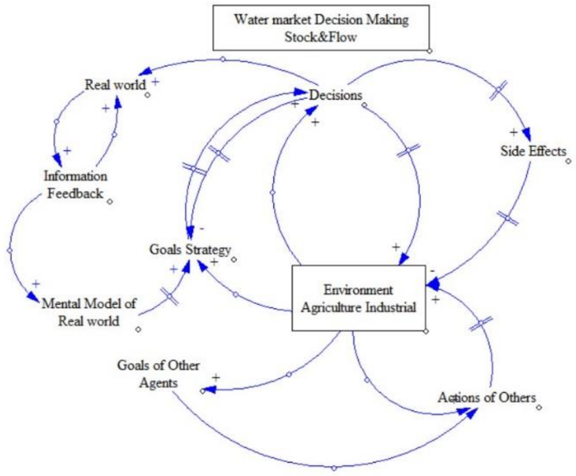
3. Findings and Results

In this article, to explain the subject and to promote general acceptance of establishing a water market, the system dynamics model was used with minimal mathematical formulas and complex calculations. Instead, diagrams, graphs, and tables were utilized.

Analysts in the decision-making process of an integrated water market, beyond strategic planning and primary and secondary objectives in agriculture, industry, and sanitation, consider the societal consequences of decisions crucial and evaluate public reactions to each decision based on awareness of future benefits. Hence, causal loops are tied to the timing and context of decisions; the stronger this link, the more complex the model becomes, altering its boundaries and influencing the level of delays, feedback, and outcomes. Positive and negative loops in the water market vary depending on attractiveness, water demand levels, and supply availability.

Figure 3

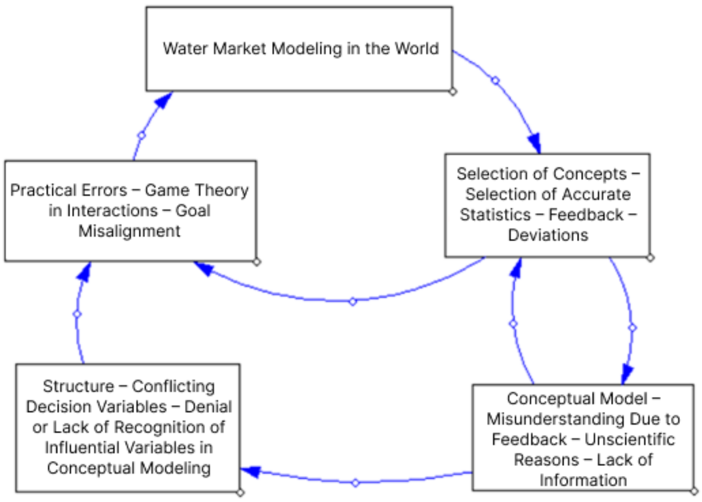
Decision Simulation Model in the Integrated Water Market



Due to the complexity of the integrated water market, delays in processes increase, which in turn impacts the system’s learning capability.

Figure 4

A Tested Example of Integrated Water Market Modeling



In this section, a description of the causal loops—comprising various sub-models—is presented, along with communication loops and their parameters. First, a sub-model for groundwater markets and localized or regional demand loops is defined.

The primary model consists of a main model and two sub-models. The main model explains the equilibrium between water demand and supply and introduces the parameters and variables of each. Countries with similar variables in terms of scale and consumption (agriculture, industry) demonstrate differing consumption behaviors and parameter analyses, highlighting the socio-economic complexity of Iran’s agriculture and industry sectors.

Although the current demand and consumption rate (DSR) has a minimal impact on water prices (for both agriculture and industry), regression analysis (Table 1) shows that DSR values below 1 indicate market saturation. Accordingly, with decreasing demand, volumetric water prices also decline. If the DSR exceeds 1, it signals rising demand and supply constraints, leading to price increases.

Table 1

Variables and Constraints

Row	Information / Variables / Constraints
1	Current status of consumers (active in cycle, controllability)
2	Forecasted demand volume and minimum/maximum needs during the period
3	Identification of disconnected or non-operational units
4	Interregional exchange limitations
5	Evaluation of needs for major and key units
6	Cross-border exchanges per period
7	Assessment of supply from other sources (rainfall, floodwater, seasonal rivers)
8	Determination of emergency reserves
9	Technical constraints of supply units per market logic (e.g., minimum/maximum production, ramp-up/down time, illegal usage boundaries, max/min daily consumption limits, production/consumption frequency limits, regional inventory assessments, defining permissible boundaries)

Table 2

Historical Water Use and Value Added

Row	Province	Agricultural Use (%)	Value Added (%)	Province	Agricultural Use (%)	Value Added (%)
1	Khorasan Razavi	3.7	19.6	Isfahan	1.6	67.4
2	South Khorasan	2.1	33.1	Qom	1.0	93.0
3	Kerman	3.7	7.0	Tehran	3.0	35.6
4	Yazd	4.1	4.2	Semnan	2.1	24.1

Based on historical data (2013–2019) on industrial and agricultural water use in the listed provinces, linear regression reveals a partial relationship between price, consumption rate, and demand. Although the trend may gradually shift, the model applies the Least Absolute Deviation (LAD) method instead of OLS to minimize error and yield more accurate results.

Table 3

Logical Computation Model

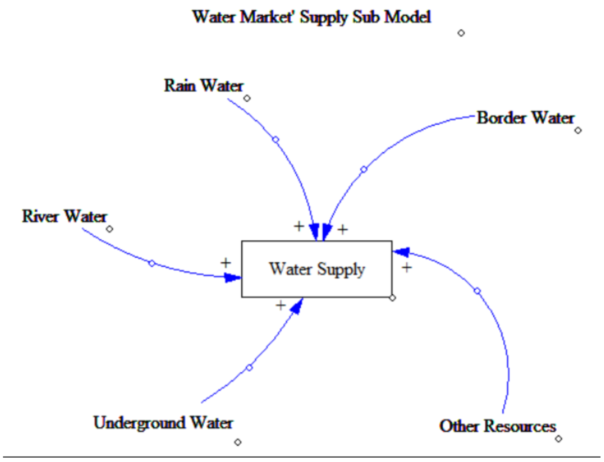
Slope	Intercept	Regression Method
149	-119	Least Absolute Deviation
285	-286	Ordinary Least Squares

The water market is fundamentally influenced by supply and demand. Price increases or decreases alter consumption rates, making DSR one of the key levers for managing consumption. It became evident that demand and supply are not independent variables; multiple factors influence them.

Water supply is divided into several components: groundwater, surface water, desalination plants, and renewable water sources.

Figure 5

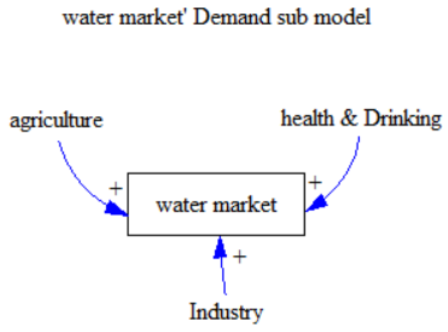
Water Supply Market Sub-model



The supply loops of groundwater and surface water, as the main sources of water in the country, serve both economic and social objectives. Including other sources such as renewables could significantly contribute to integrated water market formation.

Figure 6

Demand Market Sub-model

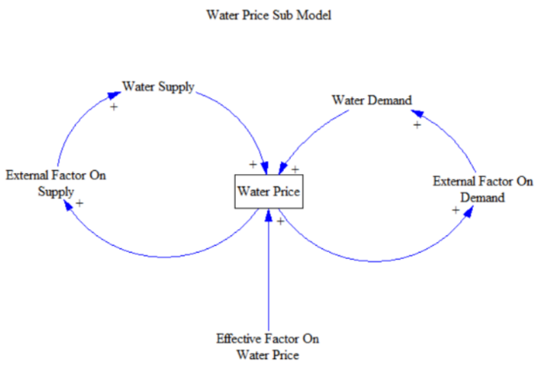


This section defines the integrated water market model across supply, demand, pricing, demand rate, consumption, and price mechanisms.

1. The main model, similar to energy and capital markets, is affected by demand, supply, and price. Influencing factors are discussed accordingly.
2. The water supply sub-model shows that much of the national demand is met by groundwater, posing social and environmental challenges.
3. The water pricing model is highly responsive to supply-demand dynamics and associated factors.

Figure 7

Water Pricing Model



Formulas:

Available Water = INTEG (Supply - Consumption, 1000)

Supply = Seasonal Input * (1 - Drought Index)

Consumption = MIN(Quota, Available Water)

Water Price = IF THEN ELSE(Water Shortage > Shortage Threshold, High-priced, Base Price)

Water Demand = Base Demand * (1 - Price Sensitivity * Water Price)

Water Shortage = MAX(Water Demand - Supply, 0)

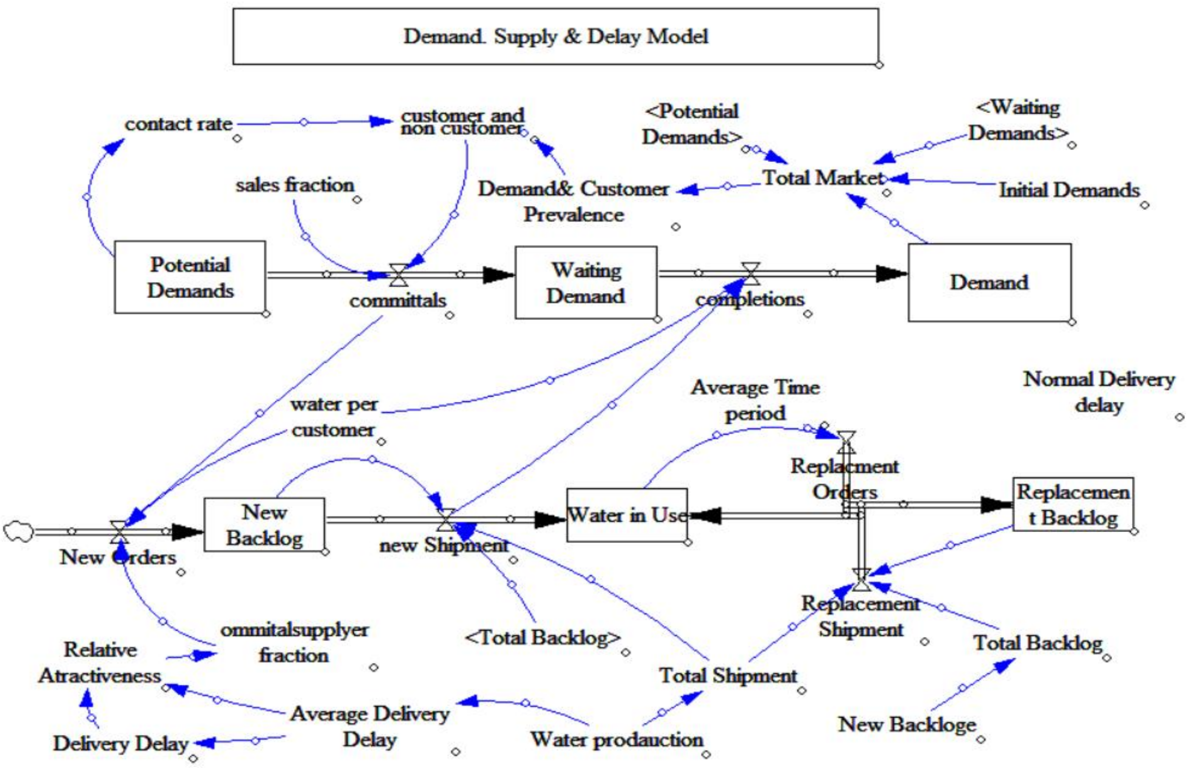
Crisis Index = Water Shortage / Water Demand

Use Quota = IF THEN ELSE(Crisis Index > 0.3, 1, 0)

Quota = IF THEN ELSE(Use Quota = 1, Max Quota, Water Demand)

Figure 8

Demand-Supply and Delay Model



A key formula in the modeling technique addresses the nominal and real values of level variables and potential substitutes. Understanding the problem in terms of price, water rate across time spans, and the supply-demand ratio is critical. Performance is optimized when backward processes and inflow/outflow streams are balanced.

Billings = Production Value

Awaiting Billing / Billing Processing Time = Production Value

Or

Awaiting Billing = Production Value * Billing Processing Time

Accounts Receivable = Billings * Average Payable Delay

Losses = Accounts Receivable * Fractional Loss Rate

Billings = Cash Receipts + Losses

Accounts Receivable = Billing / (1 / Average Payable Delay + Fractional Loss Rate)

Fractional Loss Rate = Reciprocal of Time Constant

This model significantly aids in rate calculations and considers supply-demand balance as a dynamic and flexible concept.

Given the assigned coefficients for each sub-model in supply, price, and demand, the model structure and control units were measured and evaluated. Model iterations reduced deviations, producing acceptable and occasionally distinct results.

Simulation with available quantitative data—mostly reflecting a steady decline in water resources—was conducted. Assuming stability in key variables, the model confirms the downward trend in water availability and projects a gradual increase in demand with a sharp price surge over the next five years. If a water market is formed, supply trends would gradually improve, and volumetric water efficiency (cubic meters) would increase due to improved distribution systems.

1. Due to the nonlinear nature of financial markets, causality is not always proportionate, which is a fundamental feature of markets.
2. System actors in water supply and demand are highly interconnected through economics, food security, and environmental systems.
3. Because of the tight interdependence of system actors (especially on the demand side), any decision can impact livelihoods, society, and nature. Thus, changes in nature (climate, population, prices) generate new situations, triggering feedback loops that influence the market dynamically.
4. The water market is inherently dependent on history and resources. According to the second law of thermodynamics, quality matters as much as quantity. For instance, a broken egg cannot be restored unless actively restructured. Variables like price, accumulation, and long-term delays highlight temporal constants tied to seasons, rainfall, and reserves.
5. The dynamic and complex nature of the water market evolves over time. As individuals learn from experience, this can shape development strategies or, rarely, serve as barriers.
6. The financial model in the water market can be revised according to key demand variables, price fluctuations, seasonal cycles, and temperature changes. However, the market's creation and its role in balancing supply and demand remain unchangeable.
7. Once established, the water market becomes self-organizing due to necessity. If initiated correctly, feedback structures strengthen, temporal and spatial patterns emerge, and path dependency forms—completing the cycles.
8. In integrated water market modeling, causes and effects are often temporally and spatially distant. Researchers tend to seek causes near effects, but this misalignment leads to unmet expectations.
9. Instability caused by delays in the water market sometimes reduced the capacity to control variables and identify causes and effects. However, with continued market operation, these challenges diminish, leading to greater stability and improved future decision-making.

4. Discussion and Conclusion

The present study aimed to develop and simulate a dynamic systems-based model of an integrated water market in Iran by incorporating key variables such as water supply, demand, pricing, legal frameworks, and behavioral responses. The results derived from the simulation models—using historical data and logic-based computational structures—clearly revealed several critical insights into the functioning, constraints, and potentials of water markets under conditions of water scarcity and socio-ecological complexity.

One of the most prominent findings from the simulation was the delay effect in water supply and demand adjustments, which directly impacts price fluctuations and feedback cycles. The demand-supply ratio (DSR), as a central determinant of market dynamics, demonstrated that when DSR values fell below one, the market entered a state of saturation, leading to reductions in volumetric water pricing. Conversely, when the DSR exceeded one, the simulation indicated increased demand pressures and constrained supply, thereby triggering steep price hikes. This confirms the theoretical assertion that water, as an economic good, responds to scarcity signals through price mechanisms—a point emphasized in earlier empirical studies on local water markets in Iran (Keramatzadeh et al., 2011; Kiani & Bagheri, 2013).

Furthermore, the dynamic loops integrated into the system—particularly those representing positive feedbacks (increased demand leading to higher prices and further extraction pressure) and negative feedbacks (conservation incentives triggered by high prices)—allowed for a nuanced understanding of policy leverage points. These findings align with previous modeling efforts suggesting that dynamic simulation is a valuable method for managing natural resources with high uncertainty and feedback complexity (Behloulund, 2006; Mogholi et al., 2016). The study also confirmed that supply elasticity, especially from renewable or surface water sources, was limited, thus reinforcing the structural dependence on groundwater, a concern long documented in the literature (Mehrabi et al., 2022; Shahnoushi, 2014).

The model's segmentation into sub-models of supply, demand, pricing, and delay dynamics contributed to a better understanding of the differentiated behaviors of various stakeholders, especially in agriculture and industry. Notably, the historical consumption data from provinces like Khorasan, Kerman, and Isfahan showed significant disparities between water use and value-added outcomes, pointing to inefficiencies in agricultural allocation—a finding consistent with the conclusions drawn by Soltani and Zibaei (2020) regarding the mismatch between consumption and productivity in Iranian agriculture (Soltani & Zibaei, 2020). This reinforces the need for market-based reallocation mechanisms that can redirect water toward higher-value uses.

Another key result emerged from the regression analyses. Using both Least Absolute Deviation (LAD) and Ordinary Least Squares (OLS) methods, the study found that consumption trends and pricing structures could be reliably predicted under static variable conditions, but unexpected shocks—such as extreme droughts or policy shifts—could disrupt these relationships. This unpredictability underlines the necessity of including adaptive elements in water governance models and is echoed in the crisis management literature that emphasizes scenario-based planning (Ghandi & Roozbahani, 2019; Ray Biswas et al., 2023).

The modeling approach also highlighted the critical role of legal and institutional parameters. As shown in the variable matrix (Table 1), constraints such as inter-regional exchange limits, technical supply restrictions, and ownership regulations were among the most influential factors affecting water availability and market responsiveness. These results are in line with Kiani and Bagheri (2013), who argued that unclear or fragmented water rights pose major obstacles to market formation in Iran (Kiani & Bagheri, 2013). Additionally, findings suggest that technical factors such as billing delays, quota enforcement, and metering infrastructure have direct implications for pricing stability and loss reduction, supporting earlier observations by Mohamed et al. (2021) about the sensitivity of hydraulic systems to operational variability (Mohamed et al., 2021).

Incorporating social dimensions into the model further validated the importance of demand-side management through public awareness and educational interventions. For example, simulations indicated that when awareness campaigns were introduced in the modeling environment—especially those targeting household and agricultural users—water demand decreased measurably. This result aligns with Khodaei Marandi Fard (2020), who found that optimal water use education significantly improved behavioral outcomes among school students (Khodaei Marandi Fard, 2020). These outcomes also resonate with Parsakia (2024), who emphasized the integration of sustainability values in resource-intensive industries as a dual pathway for profit and conservation (Parsakia, 2024).

Additionally, the scenario testing component of the study—run through multiple simulations—suggested that integrated water markets can lead to price stabilization over the medium term, provided there is real-time data on supply conditions, and dynamic pricing policies are implemented. However, the model also warned of volatility in the early stages of market formation, primarily due to learning curves, institutional inertia, and infrastructure limitations. These insights validate findings from international studies on public-private partnerships and water governance reforms, where implementation phases are often marked by adjustment frictions and stakeholder resistance (Lima et al., 2021; Roshani & Filion, 2014).

Moreover, the study's analytical modeling offered new evidence on the interdependencies among physical availability, economic value, and behavioral adaptation. The modeling formulae (e.g., for billing cycles, loss rates, and crisis indices) demonstrated that water markets, while driven by economics, are also profoundly shaped by hydrological uncertainty and social responsiveness. As emphasized in earlier works by Tehami Pour (2017), pricing schemes that ignore these feedbacks can produce distorted incentives and undermine long-term sustainability (Tehami Pour, 2017).

Overall, the results show that water markets are not merely transactional platforms but embedded systems influenced by legal norms, behavioral inertia, hydrological limitations, and governance architectures. The model's predictive strength and internal validity support its use as a planning tool for adaptive water policy in Iran's arid regions.

While the model captures multiple layers of system behavior and offers valuable insights, several limitations must be acknowledged. First, the reliance on historical data between 2013 and 2019 may not fully reflect future variability, especially under climate change scenarios. Second, although the model attempted to balance complexity and usability, certain institutional and socio-political variables—such as informal water trading, conflict resolution mechanisms, or local governance quality—were not explicitly included. Third, the simulation environment, while sophisticated, assumes rational behavior and consistent policy implementation, which may not hold true in real-world settings. Finally, the use of LAD over OLS improves accuracy for outliers but may reduce generalizability when policy shocks are sudden and non-linear.

Future studies should expand the temporal and spatial range of the model by incorporating climate forecasting, remote sensing data, and inter-basin hydrological interactions. There is also a need to explore behavioral economics elements such as user trust, risk aversion, and fairness perceptions in water trading. Further research might focus on comparative modeling across regions with different ecological, agricultural, and industrial profiles to test the robustness and adaptability of market-based frameworks. Additionally, exploring hybrid governance models that blend public oversight with private participation can offer nuanced perspectives for scalable implementation.

To effectively implement an integrated water market in Iran, practitioners should prioritize legal clarity in water rights allocation, invest in metering and monitoring infrastructure, and develop dynamic pricing tools responsive to real-time supply-demand changes. Policymakers must engage local stakeholders through participatory planning and educational campaigns to build trust and improve compliance. Lastly, leveraging digital technologies and decision-support systems can enhance transparency, reduce transaction costs, and align market mechanisms with environmental sustainability objectives.

Authors' Contributions

Authors contributed equally to this article.

Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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Declaration of Interest

The authors report no conflict of interest.

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Ethics Considerations

In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were considered.

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