



## OPEN Water agriculture nexus a system dynamics approach for the next three decades

Mohammad Jamali<sup>1✉</sup>, Hamed Yazdian<sup>2</sup>, Ghazaleh Bahman<sup>2</sup> & Saeid Eslamian<sup>1</sup>

Agriculture, being a major consumer of water resources, is crucial for ensuring global food security. Current patterns of water use and agricultural practices, if continued, are projected to cause severe water shortages, particularly in agriculture, by 2054. This water scarcity has already reduced crop cultivation, threatening future food and water security. This study introduces a dynamic system-based model to simulate water resources, focusing on agricultural water consumption and groundwater reclamation from 2025 to 2054. The model evaluates cultivated areas using three indicators: physical productivity, economic productivity, and water consumption. Under projected conditions, significant water shortages and declining underground water levels are anticipated. The most effective scenario involves halting cultivation of water-intensive crops, reducing groundwater withdrawal by 25%, and transferring 250 million cubic meters of water annually. This approach increases surface and underground water levels by 29.5% and 36.5%, respectively, and offsets 65.1% of the water shortage. These results emphasize the urgent need for sustainable water management to address future water scarcity and ensure agricultural and food security. The proposed model serves as a valuable tool for policymakers to design and implement strategies in water-scarce regions.

**Keywords** Water and agriculture nexus, System dynamic, Physical productivity, Economic productivity, Scenario analysis, Zayandehrud basin

In recent times, the global population has seen a significant increase, accompanied by the rapid growth of industries and a strong desire for development<sup>1</sup>. Unfortunately, this surge in activity, coupled with mismanagement and the overall rise in water consumption, has led many regions of the world to face a severe water crisis<sup>2,3</sup>. If a suitable solution is not found in the near future, this crisis will only worsen. Looking ahead, water is expected to become the most critical and strategic resource, particularly in arid and semi-arid regions across the globe<sup>4</sup>. As evidenced by historical data, policymakers in these areas have attempted to address water scarcity issues through various means such as building dams, replenishing groundwater, cloud seeding, desalination, wastewater reuse, and the implementation of large-scale water transfer projects<sup>5,6</sup>. However, it is essential to acknowledge that unsustainable and misguided decisions aimed at meeting the growing demands for water can actually contribute to or worsen the water scarcity crisis<sup>7,8</sup>. While supply-based water management strategies may yield promising results in the short term, they often lead to unintended and destructive consequences in the long run<sup>9,10</sup>. Food security is one area which is vastly suffering at unprecedented scales threatening the prosperity in the Middle East and North African region<sup>11</sup>. Water, agriculture and food are mutually dependent and the water crisis in many regions has caused the security of agriculture and food to be endangered. The nexus of water and agriculture and the use of common and practical solutions is the solution to overcome this crisis<sup>8</sup>.

The Zayandehrud basin holds great importance in development planning due to its advantageous and unique location, as well as its significant agricultural, industrial, and environmental value. It is regarded as one of the most strategic regions in Iran<sup>12</sup>. Over the past few decades, various factors have led to a substantial increase in water tension within this region. To address these issues, several solutions, including the implementation of various water transfer projects, have been employed<sup>13,14</sup>. While several solutions, including water transfer projects, have been implemented, there is a lack of comprehensive analysis on their long-term effectiveness and sustainability. Previous studies have often focused on isolated aspects of water management without integrating the broader impacts on agriculture and overall resource sustainability<sup>15,16</sup>. It is recommended to examine the long-term effects of each decision and avoid a one-sided approach to the issue. By using a dynamic system and combining the model that includes it, it is possible to find a suitable solution to address the water crisis

<sup>1</sup>Department of Water Science and Engineering, College of Agriculture, Isfahan University of Technology, Isfahan 84156-83111, Iran. <sup>2</sup>Department of Civil Engineering, University of Isfahan, Isfahan, Iran. ✉email: mohammad.jamali@ag.iut.ac.ir

in the region by fully examining the long-term results<sup>17</sup>. Extensive research has been done around the world, including Iran, focusing on solutions and strategies for managing the water crisis and the water-food-energy nexus using the concept of a dynamic system. Some notable studies include those conducted by<sup>18–27</sup>. Researchers such as<sup>15,16,28–30</sup> have contributed to the modeling of water resources and utilization in the Zayandehrud basin and Isfahan province. They have employed various models based on dynamic systems and proposed diverse scenarios to tackle water-related challenges in this region. The outcomes of their studies have been compared and evaluated accordingly.

Global research highlights significant regional variations in water-agriculture dynamics due to differences in climatic, economic, and social conditions. Studies in water-scarce regions emphasize the critical need for efficient irrigation systems and crop selection to reduce water consumption. Conversely, research in water-abundant areas focuses on improving water quality and addressing runoff-related issues. In the Zayandehrud basin, previous studies have also examined scenarios such as water transfer, similar to our approach and these studies concluded that water transfer alone, without considering system dynamics and complementary scenarios, ultimately leads to increased water demand. Additionally, while some studies have considered crop pattern changes, the criteria for crop replacement or elimination were often limited to water consumption alone.

To address these gaps, this study introduces an integrated dynamic system model that aims to assess the sustainability of water and agricultural resources in the Zayandehrud basin. Unlike previous research, which may have concentrated on individual components or short-term outcomes, our model takes a holistic approach by incorporating both physical and economic productivity indicators to evaluate water use and agricultural sustainability<sup>17</sup>. This model specifically addresses the limitations of previous studies by focusing on the amount of water consumed by each agricultural product and modeling the cultivation area of different crops. This unique approach allows for the identification and classification of the most favorable products based on water consumption levels and productivity indicators, providing a more nuanced understanding of agricultural sustainability. By exploring various management scenarios and altering cultivation patterns, the model simulates potential future scenarios to assess their impact on water availability for agriculture. Additionally, the inclusion of a water transfer scenario enhances the analysis, offering a comprehensive evaluation of potential solutions. The study aims to fill the gaps left by prior research and propose the most effective scenario for improving agricultural conditions in the region based on a thorough analysis of long-term results. This study, while providing valuable insights into sustainable water management and agricultural practices, acknowledges several limitations. One significant challenge is the limited availability of accurate and up-to-date data for certain variables, which may influence the precision of the model's outputs. Additionally, the modeling process involves several assumptions and simplifications, such as considering climate change impacts primarily through precipitation changes, which may not fully capture the complexity of all interacting factors. Furthermore, external factors, including future socioeconomic and policy developments, introduce uncertainties that could affect the applicability of the results under evolving conditions. These limitations highlight the need for continuous refinement of the model and integration of more comprehensive datasets to improve the robustness and generalizability of the findings. The findings of this study will be useful for policymakers, water resource managers, and agricultural stakeholders by providing practical insights into sustainable water management strategies and agricultural practices, especially in water-scarce regions. In general, given the critical water and subsidence situation in this region, this research and its solutions can have an impact on other sectors and the lives of the people in the region.

## Methods

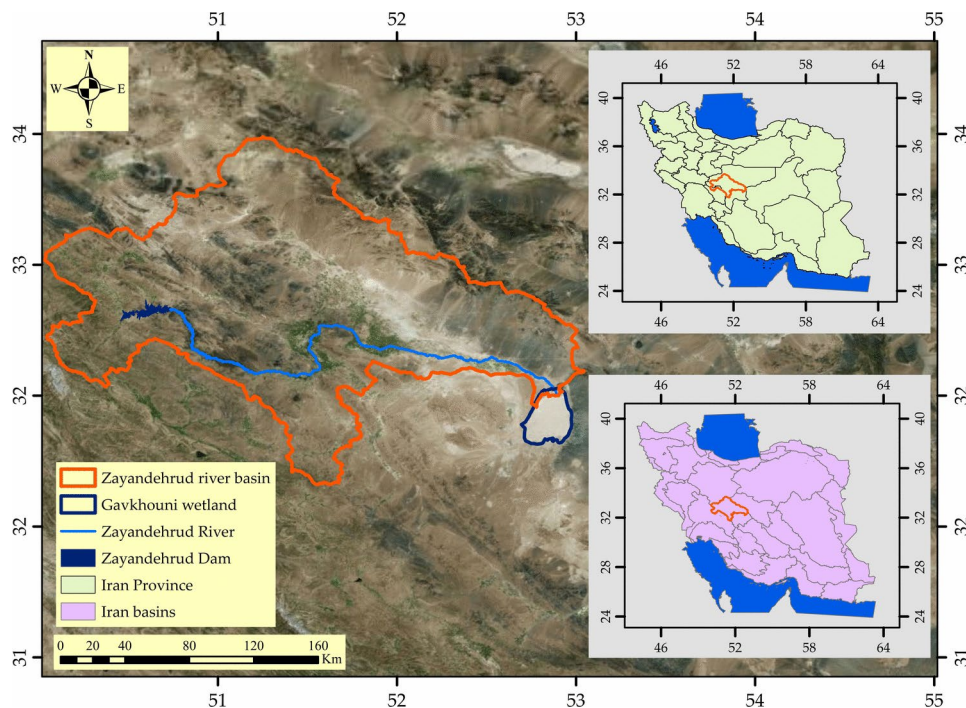
### Study area

The Zayandehrud River Basin, shown in Fig. 1, covers an area of approximately 41,524 km<sup>2</sup>. It is located in central Iran, stretching between longitudes 50° 24' to 53° 24' and latitudes 31° 11' to 33° 42'. Within this region lies the Zayandehrud River, one of the largest rivers in central Iran, serving as a vital resource for domestic, industrial, and agricultural purposes. Originating from the Zagros Mountain range, this river flows through diverse landscapes until it reaches the GavKhouni wetland. Along its course, the Zayandehrud River undergoes various forms of exploitation. Stretching approximately 350 km in length, it boasts an average natural discharge of 850 million cubic meters. The basin, with an elevation ranging from 1450 m in the east to 3974 m in the west, experiences average rainfall between 50 and 1500 mm, and temperatures fluctuate between 3 and 30 degrees Celsius. Moreover, the basin witnesses an annual evaporation and transpiration rate of around 1500 mm. As of 1996, the population of the basin was approximately 3,104,000, with an average annual population growth rate of 2.14%. Notably, a total of 260,000 hectares of land are under irrigation, with an irrigation efficiency range of 35–39%<sup>28,31</sup>.

The Zayandehrud Basin encompasses part of Isfahan Province, a key industrial and agricultural region in Iran. This basin itself is a sub-basin of the Gavkhouni basin. Agriculture is the primary user of water in the region and relies on both surface (30%) and groundwater (70%) sources for its supply. However, the occurrence of severe droughts, coupled with the rising population and water demand across all sectors, has led to numerous water-related challenges, particularly in agriculture. These problems have become increasingly significant in recent years. Amidst the water crisis in agriculture, there has been a growing strain on underground water resources for irrigation purposes. Consequently, these resources are also facing a crisis. Unless a suitable solution is implemented, the region will encounter a myriad of issues in the coming years, predominantly concerning underground water reserves<sup>32,33</sup>.

### Model development

The initial and foremost step in system dynamics modeling involves the identification of the system's structure. This encompasses the establishment of both positive and negative causal relationships between components, as well as the identification of feedback loops<sup>17</sup>. Generally, the qualitative analysis phase of a system dynamics study



**Fig. 1.** The Zayandehrud River Basin.

comprises two key steps. Firstly, there is the development of a conceptual model or a causal loop diagram (CLD) to illustrate the problem. Secondly, a stock and flow diagram (SFD) are created based on the CLD to further depict the issue at hand. Specific to the Zayandehrud basin, the model comprises three interconnected sub-systems that aim to conceptualize the system structure of the entire basin. These sub-systems include the areas of hydrology, water, and wastewater; agriculture; and social-economic aspects. The simulation period spanned from 2002 to 2012 with annual time increments.

The hydrological system encompasses various elements such as water, sewage, and their intricate interplay with regional hydrological processes. It includes surface and underground water dynamics, crucial hydrological factors like precipitation, the natural flow between basins, sewage, return water, as well as the overall management of water resources and its applications. A representation of this subsystem can be observed in Fig. 2, which exhibits a CLD. Within this diagram, SW represents surface water, while GW pertains to groundwater.

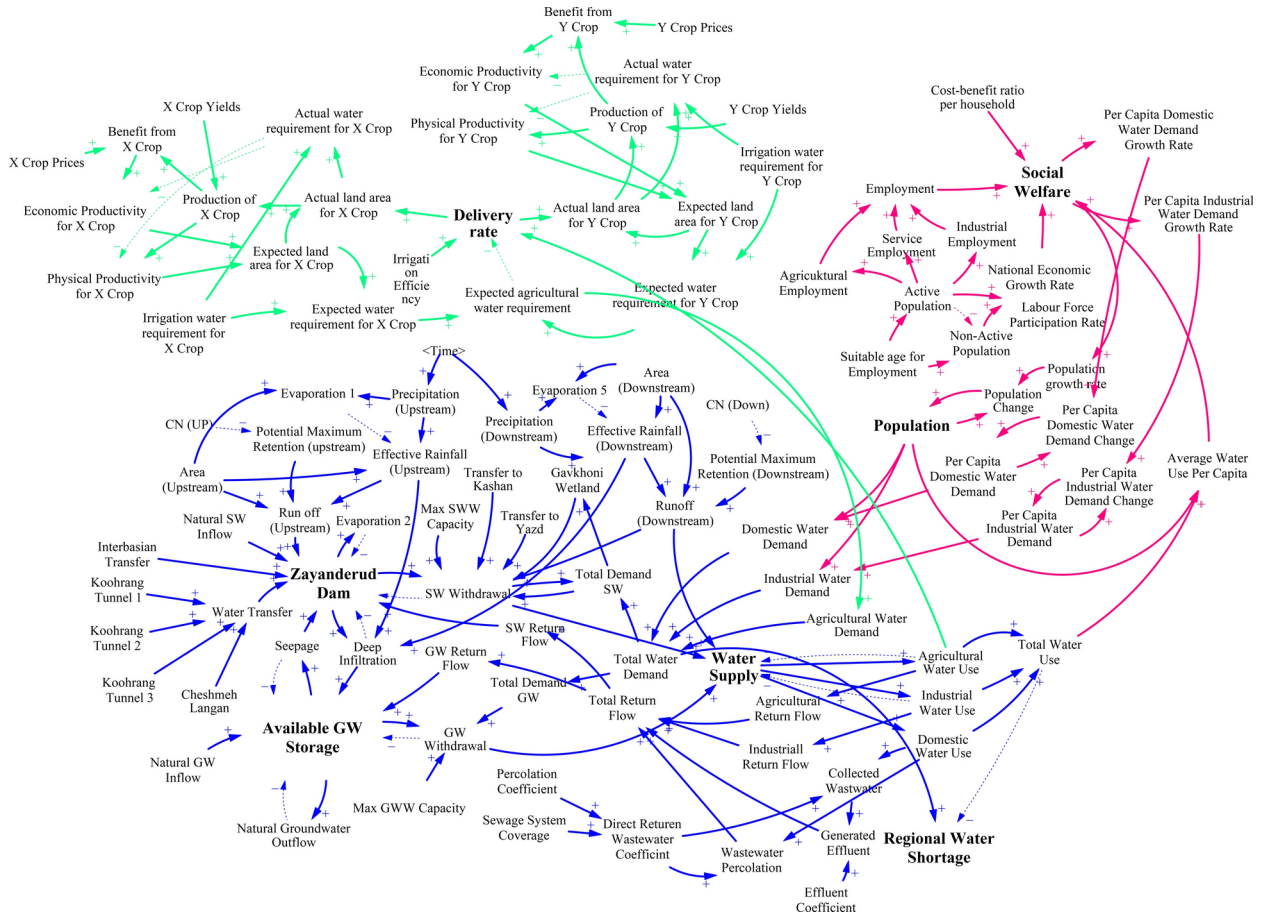
In the agricultural subsystem, the model considers eleven dominant crops: wheat, barley, rice, vegetables, summer crops, oilseeds, sugar beet, forage crops, dried fruits, garden crops, and legumes. This subsystem takes into account various variables such as cultivated area, water requirement, yield, net price, production, profit, and physical and economic productivity of different products. Figure 2 show the CLD of the agricultural system. However, due to brevity, only the modeling of two hypothetical products, X and Y, is shown. To view the complete model of the agricultural subsystem, please refer to the stock and flow diagram (SFD) in the attached file (Fig. 1). In this research, the expected annual land area of agricultural products is calculated using two indicators: physical productivity (PP) and economic productivity (EP). Equations 1 and 2 define physical and economic productivity respectively.

$$PP = \frac{\text{Production}}{\text{Actual water requirement}} \quad (1)$$

$$EP = \frac{\text{Sale}}{\text{Actual water requirement}} \quad (2)$$

The physical productivity (PP) of each individual product is determined by calculating the ratio between the production of the product and the actual water usage for its cultivation. Additionally, the economic productivity (EP) of each product is assessed by calculating the ratio between its sales revenue and the actual water requirements. The determination of the actual land area dedicated to each crop is based on the annual water allocation for that crop and its projected land requirements. By considering both physical productivity and economic productivity, various products can be categorized, enabling the identification of valuable crops in terms of water consumption, product performance, and economic aspects simultaneously. This process aids in establishing suitable management strategies within the agricultural sector and facilitates a shift away from cultivating low-value crops with high water usage.

In the socioeconomic system, the primary catalyst for urban water demand, industrial growth, population surge, and migration from nearby towns is the social welfare factor of the region. This study defines the residents'



**Fig. 2.** CLD of the water, agricultural, and socio-economic sub-systems (Understanding the interconnections within the hydrology subsystem are illustrated using a blue arrow, while the agricultural subsystem employs a green arrow to represent its relationships, and the socio-economic subsystem is depicted with a red arrow).

social welfare index as a function influenced by various internal and external factors. The Social Welfare Index is computed as a weighted sum of normalized variables, including per capita water consumption, employment rate, cost–benefit ratio per household, and national economic growth rate. The weights assigned to each variable were determined through a calibration process based on real historical data. This approach enhances the model’s reliability and ensures that the index dynamically captures socio-economic variations over time (More details in the attachment). The city’s socio-economic progress has led to greater development in comparison to neighboring regions, resulting in increased job opportunities, migration towards the city, escalated population in the region, and heightened water consumption across different consumer sectors.

The complete depiction of the model, comprising hydrological, agricultural, and socio-economic subsystems, is presented in the attached file (Fig. 1). A SFD has been constructed to illustrate the warehouse’s structural layout and system dynamics<sup>15,34</sup>.

The dynamic equations for the subsystems were derived based on the system dynamics methodology and causal loop diagrams (CLDs). These equations were formulated by analyzing historical data, consulting local experts, and leveraging existing standard models (e.g., common hydrological and agricultural models). For instance, in the hydrology subsystem, equations such as mass balance for surface and groundwater flows were derived using data on precipitation, evaporation, and inter-basin water transfers. In the agricultural subsystem, equations for physical and economic productivity were defined as shown in Eqs. 1 and 2. All equations were parameterized and simulated using the VENSIM software.

The model parameters were calibrated using historical data from the Zayandehrud basin (2002–2012), including meteorological statistics, agricultural reports, and local census data. To enhance the model’s accuracy, sensitivity analysis was conducted to evaluate the impact of parameter variations on model outputs.

The developed dynamic equations are grounded in general principles of system dynamics (e.g., conservation of mass and productivity concepts). Therefore, the model is potentially applicable to other regions with similar characteristics. However, successful implementation in other areas requires localization of the model, which involves incorporating region-specific data and conditions during the parameterization and validation stages. For example, adapting the model to another arid or semi-arid region would require tailoring inputs such as precipitation levels, crop types, and water usage patterns to match the new context.

## Model calibration and validation

In order to evaluate various strategies and policies for water resources management, it is important to assess the dynamic performance and accuracy of the model. The model's implementation will take place over a time span of 30 years, starting from 2025 and ending in 2054, with yearly time intervals. To calibrate the model, historical observation data from a period of 10 years, specifically from 2002 to 2011, were taken into consideration. Initially, extreme conditions were applied to test the structural behavior of the model, as outlined by Barlas in a previous study. The behavior replication test aims to determine if the model can accurately reproduce patterns observed in the real system. This test focuses on comparing the outputs generated by the model to the historical data within the given time frame. To conduct this test, both observed (real) data and simulated data from the model were used. Also, to accurately evaluate the behavior of the model, statistical indicators including coefficient of determination ( $R^2$ ), root mean square error (RMSE) and coefficient of variation (U0) were used<sup>18</sup>.

Extreme conditions tests are conducted to evaluate how different parameters impact the behavior of a model<sup>35</sup>. In order to evaluate the performance of the model in extreme conditions and to validate the model, three specific scenarios were applied: no withdrawal of groundwater, economic stagnation, and an increase in the volume of surface water resources. The no withdrawal of groundwater condition assumed that there would be zero extraction of water from underground sources. Under the economic recession condition, the model examined the impact on the social welfare by reducing variables related to water consumption in the agricultural sector and the job opportunity index. Social welfare represents the overall satisfaction and well-being of individuals within a society, encompassing both economic and social aspects. For this study, it's calculated as a dimensionless composite index. Furthermore, by assuming a 100 million cubic meters increase in the volume of surface water resources due to water transfers into the basin, it was anticipated that both the per capita water consumption and the region's added value would rise. Overall, these extreme condition tests play a crucial role in evaluating the model's behavior and its capability to produce reliable results even in challenging scenarios.

## Policy scenarios

By carefully choosing the most appropriate scenarios, it is possible to ensure favorable results for the future development of the region and maintaining water and food security. The first category encompasses individual executive and management policies, which are designed to address the future situation of the region. These policies take into consideration factors such as population growth, increasing water consumption across all sectors (particularly in agriculture), and the status of underground water resources. In this category, specific scenarios have been formulated, including plans for water transfer, reduction of extraction from underground water sources, and the recommendation to abstain from cultivating water-intensive crops. These scenarios aim to improve the overall condition of the region. The second category consists of hybrid policies, which combine the most effective management scenarios from the previous section. One notable strategy employed in these scenarios is the enhancement of water utilization efficiency in agriculture. After evaluating multiple options, the optimal scenarios have been selected for implementation to ensure positive outcomes in the future. Detailed explanations and descriptions of the specific scenarios and policies utilized can be found in Table 1.

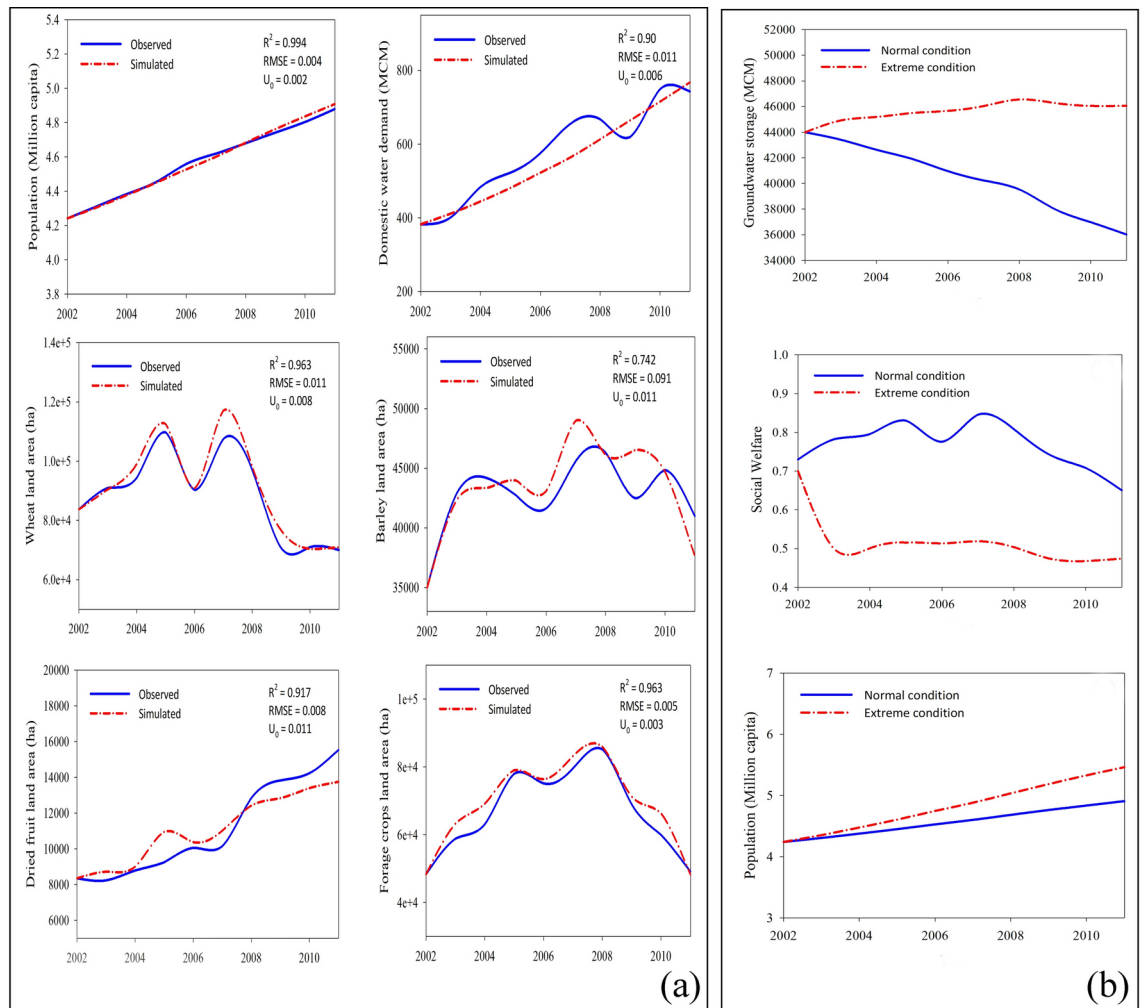
## Results and discussion

### Model calibration and validation results

Figure 3a shows the comparison between observed and simulated values for some different variables to evaluate the model calibration. By analyzing the graphs, it can be concluded that there is a logical correlation between the trend of the observed data and the predicted variables for the model. Additionally, the results of statistical indicators such as the coefficient of determination ( $R^2$ ), root mean square error (RMSE), and discrepancy coefficient (U0) are presented in the figure. These results also indicate a good fit between the model and the observed data.

Grouping	Scenario name	Description	Scenario name	Description
Primitive	BAU	Business as usual	-	-
Operational	TW	250 MCM of water transfer to the basin	NCSFR	No cultivation of sugar beet, forage crops, and rice
	RGW	25% reduction in groundwater extraction	RLSFR 50_ALD	Reducing the land area of sugar beet, forage crops, and rice by 50% and adding to the land area of dry fruits (pistachios, walnuts and almonds)
	RLSFR 50	Reducing the land area of sugar beet, forage crops, and rice by 50%	RLSFR 75_ALD	Reducing the land area of sugar beet, forage crops, and rice by 75% and adding to the land area of dry fruits (pistachios, walnuts and almonds)
	RLSFR 75	Reducing the land area of sugar beet, forage crops, and rice by 75%		
Combinatorial	NCSFR_TW	Non-cultivation of sugar beet, forage crops, rice, water transfer, and a 20% increase in agricultural efficiency	NCSFR_TW_RGW	Non-cultivation of sugar beet, forage crops, rice, 250 MCM water transfer, and 25% reduction of groundwater withdrawal, and a 20% increase in agricultural efficiency
	RLSFR 75_TW	Reducing the land area of sugar beet, forage crops, and rice by 75%, water transfer, and a 20% increase in agricultural efficiency		

**Table 1.** Policy scenarios. This table presents a set of policy scenarios designed to address water scarcity in the Zayandehrud basin. Scenarios are grouped into three categories: Primitive (BAU), Operational, and Combinatorial. The policies consider factors such as population growth, water consumption, and the status of underground water resources. These scenarios include specific plans such as water transfer projects, changing and modifying cropping patterns in agriculture, reducing groundwater extraction, and improving water use efficiency in agriculture.



**Fig. 3.** The comparison between model simulated data and observational data (a) and The behavior of selected parameters of the model in the test of extreme conditions (b).

The results of the extreme condition tests are presented in Fig. 3b. According to this figure, it was observed that by implementing a scenario of no groundwater extraction, the volume of groundwater resources increased significantly. Additionally, by applying an economic recession scenario, the model examined the impact on regional welfare through reductions in agricultural water consumption and the job opportunity index. It was assumed that the cessation of agricultural cultivation, the elimination of water consumption in agricultural and industrial sectors, and the reduction in job opportunities would decrease the welfare of the region's residents. Figure 3b visually demonstrates this downward trend. Finally, by implementing a scenario of increasing surface water resources and transferring 100 million cubic meters of water to the basin, both per capita water consumption and the region's value added increased, resulting in a population increase compared to the baseline condition.

The model yielded satisfactory results in both behavior repetition tests and under extreme conditions, establishing its readiness for future applications and flexibility in implementing diverse policies.

### Implementing various policy scenarios

In the Business-as-usual scenario (BAU), there will be a significant increase in water shortage, particularly within the agricultural sector, due to the rising water demand from 2025 to 2054. This scarcity of water has resulted in a decline in crop cultivation. Evidently, the groundwater levels have experienced a sharp decrease as a consequence of the higher water demand for agriculture. Furthermore, the storage capacity of Zayandehrud Dam has been observed to follow a declining trend. Over time, there has been a notable decrease in the variable representing social welfare. Figures 4 and 5 present a comparison between different scenarios and the BAU scenario throughout the simulation period. The transferring water (TW) scenario assumes a transfer of approximately 250 million cubic meters of water annually to Zayandehrud Dam. Based on Fig. 4, it can be concluded that in this scenario, the water shortage experienced a relatively small decrease compared to the BAU scenario. The volume of water within the dam has increased, and the decline in groundwater has been less severe, showcasing improvement. This particular scenario allows for a larger amount of water available for crop

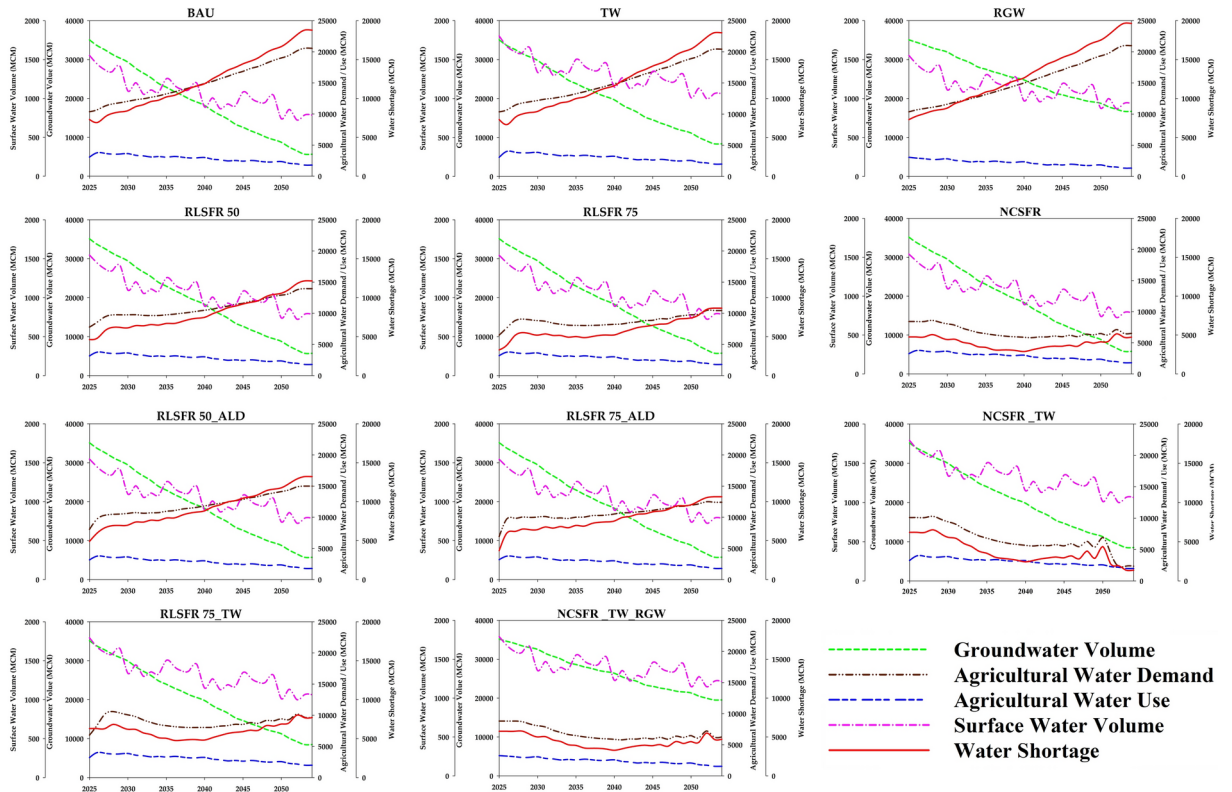


Fig. 4. Behavior of selected hydrological and water subsystem variables under simulated policy scenarios.

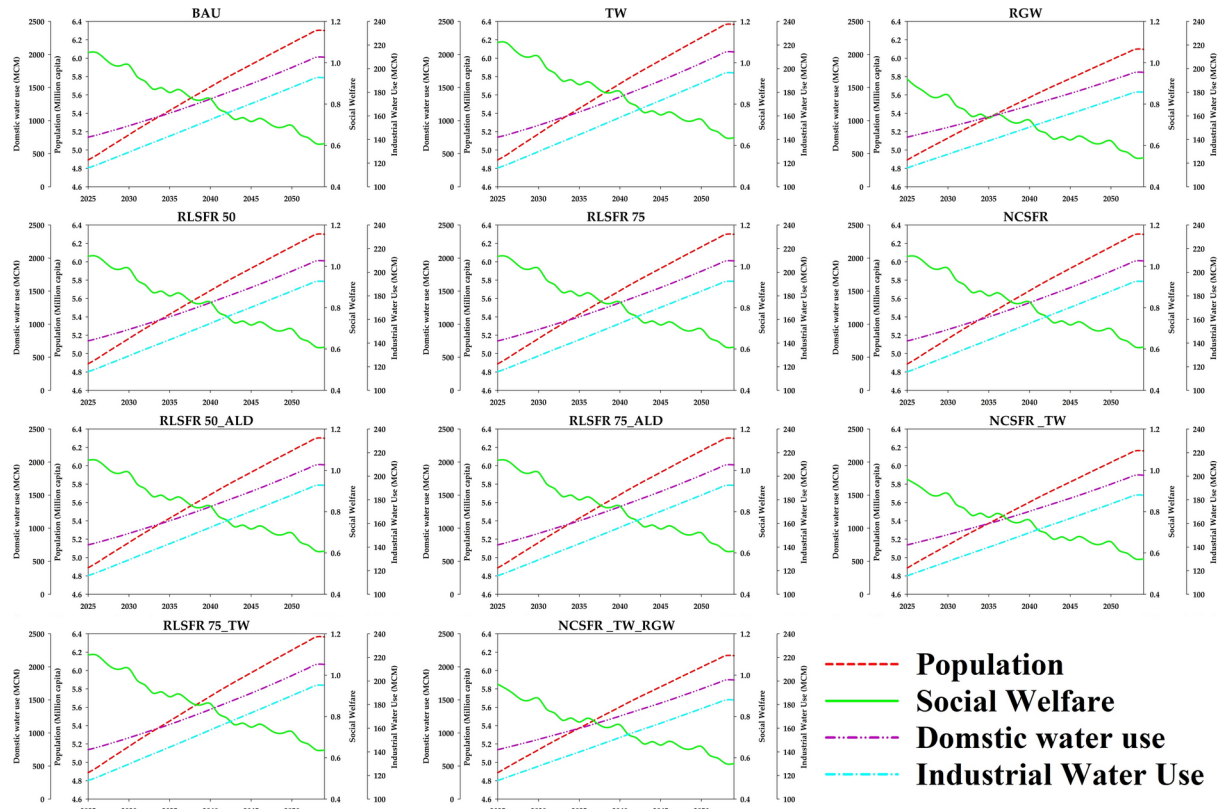


Fig. 5. Behavior of selected socioeconomic subsystem variables under simulated policy scenarios.

cultivation, resulting in increased agricultural activities. Figure 5 shows that the decrease in social welfare has been less severe under this scenario.

As a result of the significant and catastrophic decline in groundwater levels, a situation has been identified in this particular domain. It is projected that groundwater extraction will decrease by 25% compared to the Business as Usual (BAU) scenario. In the Reduced Groundwater Withdrawal (RGW) scenario, it has been observed that groundwater is in a far more favorable state compared to the other two scenarios. The reduction in groundwater levels transpires at a gentler slope and occurs in 2054, instead of reaching the previously estimated volume of 5653 million cubic meters, it actually triples to an impressive 16,700 million cubic meters. In this particular scenario, water scarcity in the region reaches its peak and sees a significant increase in comparison to previous scenarios. The social and economic well-being of the region has been steadily declining, and the population in the area is projected to be lower than the BAU and TW (Total Withdrawal) scenarios. Therefore, even though the RGW scenario offers some improvements in groundwater conditions, it is also linked to exacerbating water scarcity issues and causing a reduction in the overall social welfare of the region. Consequently, relying solely on this scenario is not deemed suitable.

Three different types of plants, namely sugar beet, forage crops, and rice, are known to consume large amounts of water. In light of this fact, and in response to the pressing issue of water scarcity in the agricultural sector of the region, five different scenarios have been devised to address the excessive water consumption associated with these crops. The first scenario, termed RLSFR 50, envisages a 50% reduction in the land area dedicated to cultivating sugar beet, forage crops, and rice. Under this scenario, there is no significant change observed in the overall availability of ground and surface water compared to the Business-As-Usual (BAU) scenario. However, the water shortage situation does improve considerably, with a reduction of approximately 34% on average. The region's population and welfare experience only marginal changes. Additionally, the land area dedicated to other crops increases in comparison to the previous scenarios. Moving on to the RLSFR 75 scenario, this envisions a more substantial reduction of 75% in the land area devoted to sugar beet, forage crops, and rice. In this scenario, there is a parallel result to the previous scenario concerning the availability of ground and surface water. However, there is a more significant improvement in the water shortage situation, with a reduction of about 52% compared to the previous scenarios. Similar to the BAU and RLSFR 50 scenarios, there are negligible changes in the population and social welfare of the region. However, the area of land devoted to other crops is increasing, including major crops such as wheat and barley. In the NCSFR scenario, it is assumed that sugar beet, forage crops, and rice will no longer be cultivated. While this scenario does not lead to significant changes in the availability of ground and surface water sources, the water shortage in the region does experience a substantial reduction of 69%. This scenario also contributes to a decrease in the overall water demand for agricultural purposes. Similarly, to the previous scenarios, the population and social welfare factors remain relatively stable. However, the area devoted to cultivating other crops sees further increases compared to the previous scenarios where the three water-intensive crops were not cultivated. However, the total water withdrawal remains nearly the same because the saved water from high-consumption crops is reallocated to other agricultural activities. This reallocation results in an expansion of cultivated areas for alternative crops rather than an actual reduction in water extraction. Consequently, despite the improvement in water-use efficiency and a reduction in water shortages, the absolute levels of groundwater and surface water resources do not increase.

In the following situation, the cultivated area of sugar beet crops, forage crops, and rice has been diminished by 50%. Instead, it is proposed to use the cultivated area for growing dry fruits (pistachios, walnuts and almonds), which require less water and show promising physical and economic productivity based on two indicators (RLSFR 50\_ALD scenario). However, this scenario does not come recommended for practical implementation as it has only resulted in a modest 25% improvement in water scarcity compared to the RLSFR 50 scenario. Moving on to the RLSFR 75\_ALD scenario, where there is a 75% reduction in the cultivation area of water-intensive products, an additional amount of dry fruits cultivation area has been introduced. Despite this, the water scarcity in the region has only slightly improved by an average of 36%, which is even worse than the RLSFR 75 scenario. Consequently, this particular scenario has performed poorly and is not considered favorable.

As a result, we can identify two NCSFR and RLSFR 75 scenarios as the top choices in this category. Additionally, three other scenarios have been formulated by combining the best scenarios with water transfer, improved irrigation efficiency, and a reduction of 25% in groundwater extraction. In the NCSFR\_TW scenario, it is assumed that sugar beet, forage crops, and rice will not be cultivated in the region. Moreover, it involves an annual water transfer of 250 million cubic meters and a 20% increase in agricultural irrigation efficiency compared to the previous state. The outcome of this scenario reveals that the condition of underground water and surface water surpasses that of the BAU, RLSFR 50, RLSFR 75, NCSFR, RLSFR 50\_ALD, RLSFR 75\_ALD scenarios. Furthermore, the region's water shortage has been alleviated by 70%, which represents the most significant improvement in terms of water scarcity within this scenario. Notably, the population and social welfare of the region have reached their highest level in comparison to the preceding scenarios. In this particular situation, the cultivated area for most crops has reached its peak, thanks to a 20% increase in efficiency. This increase has allowed farmers to enhance their crop production even with the same amount of water allocated for cultivation. However, it is important to note that despite these improvements, the underground water situation remains critical. Now, focusing on the RLSFR 75\_TW scenario, the cultivated area for three specific crops—sugar beet, forage crops, and rice—has remarkably declined by 75%. Additionally, there is an assumption that water transfer to the designated region and irrigation efficiency will experience a 20% increase. In terms of water supply, both underground and surface water conditions in this scenario mirror those of the NCSFR\_TW scenario. Although there is a shortage of water in this scenario, approximately 52% of that scarcity has been compensated for. The population and welfare of the region are currently at their peak, similar to the NCSFR\_TW scenario. Furthermore, other crops in the region have a higher cultivated area in this scenario compared to the BAU, TW, RGW, RLSFR 50, RLSFR 75, RLSFR 50\_ALD, and RLSFR 75\_ALD scenarios.

The NCSFR\_TW\_RGW scenario constitutes the final scenario executed in the model. Within this particular scenario, the cultivation of three crops namely sugar beet, forage crops, and alfalfa is omitted. Annually, an estimated 250 million cubic meters of water is transferred for various purposes. A reduction of 25% in the extraction of water from underground sources is implemented alongside a 20% enhancement in irrigation efficiency. Notably, the scenario demonstrates peak levels of both surface and underground water. By the year 2054, the ultimate quantity of underground water reaches a substantial 20,000 million cubic meters. The water deficit observed in this scenario is closely akin to that of the NCSFR and NCSFR\_TW scenarios, with roughly 66% of the deficit being compensated. Furthermore, in terms of implemented scenarios, the cultivation area for other crops ranks second in this particular scenario.

### Comparing percentage changes in variables

Table 2 provides a summarized overview of how different scenarios affect the key variables in the model. The land area dedicated to wheat is presented as the primary crop, representing other crops except for sugar beet, forage crops, and rice, which require additional water. Based on the table, the NCSFR\_TW\_RGW scenario demonstrates the best performance in terms of surface and groundwater, exhibiting improvements of 29.5% and 36.5% respectively. This performance surpasses that of other scenarios. The NCSFR\_TW, NCSFR, and NCSFR\_TW\_RGW scenarios outperform others in addressing water shortage in the region, with reductions of 69.5%, 68.9%, and 65.1% respectively. However, it is worth noting that the NCSFR scenario ranks second in surface water restoration and third in underground water restoration, with increases of 23.1% and 7.3% respectively. Similarly, the NCSFR\_TW scenario ranks sixth in both surface and underground water restoration, with increases of 0.18% and 0.8% respectively. Therefore, the NCSFR\_TW\_RGW scenario is deemed the most favorable option. Lastly, the NCSFR\_TW, NCSFR\_TW\_RGW, and NCSFR scenarios exhibit the highest increase in the area of wheat cultivation.

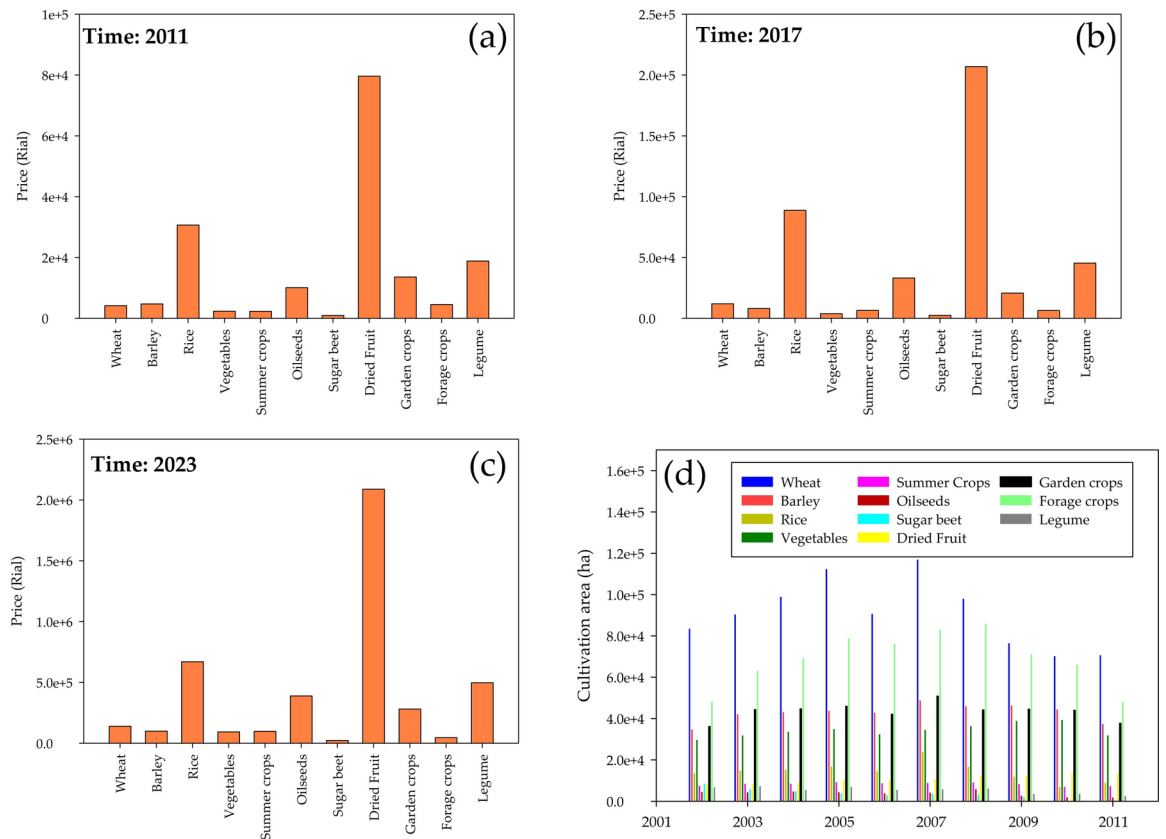
### Economic impacts of scenarios

The majority of farmers in the Zayandehrud basin rely solely on agriculture for their livelihood. When evaluating the proposed scenarios, it is crucial to not only consider the reduction of water scarcity and the improvement of key indicators like groundwater and surface water levels, but also the economic implications of each scenario. Figure 6 presents an analysis of price fluctuations for agricultural products during 2011, 2017, and 2023, and it also shows the changes in the cultivated area of these products over the 10-year study period.

Figure 6A–C reveals that dried fruits, specifically pistachios, walnuts, and almonds, commanded the highest market prices. Rice, legumes, orchard fruits, and oilseeds followed in terms of pricing. Sugar beet exhibited the lowest price among the examined commodities. Figure 6D shows that wheat is the most widely cultivated crop in the region, dominating the agricultural landscape. Forage crops, barley, and gardens are the next most common crops. Dried fruits, on the other hand, account for a relatively small portion of the overall annual cultivated land. Analysis of the RLSFR 75\_ALD and RLSFR 50\_ALD scenarios revealed that substituting dried fruits for sugar beet, forage crops, and rice led to increased economic returns for farmers. These two scenarios were identified as the most economically favorable options. Moreover, they demonstrated an improvement in water scarcity conditions relative to the business-as-usual scenario. The NCSFR\_TW\_RGW scenario, recognized for its water resource improvements, involves eliminating sugar beet, forage crops, and rice cultivation and reducing groundwater extraction by 25%. While this may seem to negatively impact farmers' incomes, the scenario's water transfer and 20% efficiency increase mitigate the effects of reduced groundwater use. Moreover, reallocating water from the eliminated crops to high-value, low-water crops like pistachios and almonds can enhance farmers' economic returns.

Scenario	TW	RGW	RLSFR 50	RLSFR 75	NCSFR	RLSFR 50_ALD	RLSFR 75_ALD	NCSFR_TW	RLSFR 75_TW	NCSFR_TW_RGW
Surfacewater volume	22.9	6.5	0.091	0.141	0.18	0.09	0.14	23.1	23	29.5
Rank	4	5	9	7	6	10	8	2	3	1
Groundwater volume	6.5	29.2	0.4	0.6	0.8	0.37	0.58	7.3	7	36.5
Rank	5	2	9	7	6	10	8	3	4	1
Water Shortage	-1.8	5.4	-34.4	-51.6	-68.9	-25.2	-36.1	-69.2	-52	-65.1
Rank	9	10	7	5	2	8	6	1	4	3
Social Welfare	4	-12.5	-0.073	-0.11	-0.14	-0.072	-0.1	3.94	3.97	-8.4
Rank	1	10	5	7	8	4	6	3	2	9
Population	0.56	-1.8	-0.027	-0.04	-0.05	-0.027	-0.04	0.5	0.51	-1.3
Rank	1	8	4	5	6	4	5	3	2	7
Wheat Land area	6.9	-20.8	34.5	63.8	115.3	22.1	35.8	189.5	107.2	120.6
Rank	9	10	7	5	3	8	6	1	4	2

**Table 2.** Comparison of percentage changes in different variables between simulated policy scenarios and the business-as-usual (BAU) scenario. (Positive values indicate an increase, and negative values represent a decrease). In this table, the results of the key model variables for each defined scenario are compared pairwise with the business-as-usual (BAU) scenario, and the results are presented as a percentage increase or decrease in the variable.



**Fig. 6.** Comparison of price fluctuations for agricultural products (A–C) and cultivation area changes for agricultural products during period (D).

## Conclusions

This study presents a dynamic model that effectively represents the water resources and water requirements of the drinking, agricultural, and industrial sectors in the Zayandehrud basin and Isfahan province. The model focuses primarily on the agricultural sector and its water supply. The land allocated for agriculture is determined by considering physical productivity, economic productivity, and the availability of water resources. These factors are simultaneously taken into account in determining the land area. This aspect of the study serves to define various scenarios and assess the impact of changing cultivation patterns on the model. To examine the future state of variables in the region, the existing model was implemented from 2025 to 2054 under the current conditions and the BAU (Business as Usual) scenario. The findings revealed an alarming situation if there is no change in the region. The surface water situation is deteriorating, and the underground water resources are experiencing a severe decline. By the end of 2054, the amount of underground water is projected to have decreased by approximately 80%. Consequently, a significant and catastrophic water shortage is predicted, resulting in numerous challenges in the supply of water for agriculture and crop cultivation.

This research aimed to address the issue of water scarcity in the region by assessing ten different scenarios. These scenarios focused on water transfer, changes in cultivation patterns, reducing groundwater extraction, and enhancing water consumption efficiency in agriculture. The findings revealed that the scenario involving water transfer of 250 million cubic meters per year and a 25% reduction in groundwater extraction alone did not offer a suitable solution for the region. These measures did not significantly alleviate the water shortage problem. Similarly, reducing sugar beet, forage crops, and rice by 50% and 75% did not have a substantial impact on improving surface and groundwater conditions. However, when sugar beet, forage crops, and rice were not cultivated, the water shortage in the region was compensated by an average of 68.9% during the 30-year simulation period. Nonetheless, the groundwater situation remained critical, rendering this scenario unsuitable. A more effective approach was found in the combined scenario of not cultivating sugar beet, forage crops, and rice, while simultaneously transferring 250 million cubic meters of water annually, reducing groundwater extraction by 25%, and increasing agricultural water consumption efficiency by 20%. This comprehensive scenario, termed NCSFR\_TW\_RGW, yielded the best results. Surface and groundwater resources were enhanced by 29.5% and 36.5%, respectively, compared to the base situation. Additionally, the land area dedicated to wheat, the dominant crop, expanded by approximately 120%.

Ultimately, it is crucial for the authorities responsible for managing water resources, agriculture, and the political leaders within the Zayandehrud River basin and Isfahan province to acknowledge that solely relying on water transfer is neither a viable nor an effective solution to address the water-related challenges in the area. It is earnestly appealed that they instead focus on altering the cultivation practices and driving the growth of

crops that necessitate lesser water usage. Furthermore, reducing the extraction of groundwater and improving irrigation efficiency in agriculture should also take center stage in their efforts, parallel to addressing the matter of water transfer.

To build upon the findings of this study, future research directions and recommendations are proposed to address key challenges and opportunities. Future research should investigate the detailed impacts of climate change, including temperature and evapotranspiration effects, on agricultural productivity and water resources. Additionally, it is crucial to explore the socio-economic implications of water management strategies, focusing on their effects on employment, household income, and regional food security. Applying the developed model to other water-scarce regions would also help assess its generalizability and adaptability to diverse climatic, social, and economic contexts. On the practical side, recommendations include promoting integrated water management strategies that combine water-efficient agricultural practices, improved irrigation systems, and policies encouraging crop diversification. Cross-sector collaboration among policymakers, water managers, and agricultural stakeholders should be encouraged to design and implement sustainable solutions. Furthermore, raising awareness among local farmers about the benefits of cultivating less water-intensive crops and adopting advanced irrigation technologies is essential.

By addressing these areas, this research can guide long-term planning and policy development, ensuring sustainable water management and agricultural productivity in the Zayandehrud basin and similar regions globally.

### Data availability

A portion of the data is included in the attached file. The remaining dataset, generated and/or analyzed during the current study, is available upon reasonable request to the corresponding author.

Received: 7 December 2024; Accepted: 14 February 2025

Published online: 18 February 2025

### References

1. UN. World Water Development Report 2022: Groundwater: Making the Invisible Visible. *The United Nations world water development report* (2022).
2. Sadoff, C., Grey, D. & Borgomeo, E. (Oxford University Press, 2020).
3. Munia, H. et al. Water stress in global transboundary river basins: significance of upstream water use on downstream stress. *Environ. Res. Lett.* **11**, 014002. <https://doi.org/10.1088/1748-9326/11/1/014002> (2016).
4. Mekonnen, M. M. & Hoekstra, A. Y. Four billion people facing severe water scarcity. *Sci. Adv.* **2**, e1500323. <https://doi.org/10.1126/sciadv.1500323> (2016).
5. Braga, B. et al. *Water and the future of humanity: revisiting water security*. (Calouste Gulbenkian Foundation, 2014).
6. Water, U. Groundwater: Making the invisible visible. *The United Nations world water development report* (2022).
7. Postel, S. L. Entering an era of water scarcity: The challenges ahead. *Ecol. Appl.* **10**, 941–948. [https://doi.org/10.1890/1051-0761\(2000\)010\[0941:EAEOWS\]2.0.CO;2](https://doi.org/10.1890/1051-0761(2000)010[0941:EAEOWS]2.0.CO;2) (2000).
8. Jamali, M. & Eslamian, S. in *Handbook of Climate Change Impacts on River Basin Management* 225–236 (CRC Press, 2024).
9. Gleick, P. H. Global freshwater resources: Soft-path solutions for the 21st century. *Science* **302**, 1524–1528. <https://doi.org/10.1126/science.1089967> (2003).
10. Pahl-Wostl, C. A conceptual framework for analysing adaptive capacity and multi-level learning processes in resource governance regimes. *Global Environ. Change* **19**, 354–365. <https://doi.org/10.1016/j.gloenvcha.2009.06.001> (2009).
11. Namany, S., Govindan, R. & Al-Ansari, T. Operationalising transboundary cooperation through game theory: An energy water food nexus approach for the Middle East and North Africa. *Futures* **152**, 103198. <https://doi.org/10.1016/j.futures.2023.103198> (2023).
12. Gohari, A., Savari, P., Eslamian, S., Etemadi, N. & Keilmann-Gondhalekar, D. Developing a system dynamic plus framework for water-land-society nexus modeling within urban socio-hydrologic systems. *Technol. Forecast. Soc. Change* **185**, 122092. <https://doi.org/10.1016/j.techfore.2022.122092> (2022).
13. Makvandi, A., Mohammadi, H., Kardovani, P., Faraj Zadeh Asl, M. & Javadi, S. Analysis and evaluation of water resources sustainability indicators in Zayandeh Rud basin and its balanced solution (case study: Najaf Abad aquifer in Zayandehrud Basin). *J. Clim. Res.* **1399**, 1–14 (2020).
14. Javadinejad, S. *Vulnerability of water resources to climate change and human impact: scenario analysis of the Zayandeh Rud river basin in Iran*, University of Birmingham, (2016).
15. Madani, K. & Mariño, M. A. System dynamics analysis for managing Iran's Zayandeh-Rud River Basin. *Water Resour. Manag.* **23**, 2163–2187. <https://doi.org/10.1007/s11269-008-9376-z> (2009).
16. Sharifinejad, A., Zahraie, B., Majed, V., Ravar, Z. & Hassani, Y. Economic analysis of water-food-energy nexus in Gavkhuni basin in Iran. *J. Hydro-environ. Res.* **31**, 14–25. <https://doi.org/10.1016/j.jher.2020.03.001> (2020).
17. Sterman, J. *System Dynamics: systems thinking and modeling for a complex world*. (2002).
18. Naderi, M. M., Mirchi, A., Bavani, A. R. M., Goharian, E. & Madani, K. System dynamics simulation of regional water supply and demand using a food-energy-water nexus approach: Application to Qazvin Plain, Iran. *J. Environ. Manag.* **280**, 111843. <https://doi.org/10.1016/j.jenvman.2020.111843> (2021).
19. Larkin, A., Hoolohan, C. & McLachlan, C. Embracing context and complexity to address environmental challenges in the water-energy-food nexus. *Futures* **123**, 102612. <https://doi.org/10.1016/j.futures.2020.102612> (2020).
20. Wicaksono, A. & Kang, D. Nationwide simulation of water, energy, and food nexus: Case study in South Korea and Indonesia. *J. Hydro-environ. Res.* **22**, 70–87. <https://doi.org/10.1016/j.jher.2018.10.003> (2019).
21. Jia, B. et al. System dynamics model for the coevolution of coupled water supply–power generation–environment systems: Upper Yangtze river Basin, China. *J. Hydrol.* **593**, 125892. <https://doi.org/10.1016/j.jhydrol.2020.125892> (2021).
22. Wen, C., Dong, W., Zhang, Q., He, N. & Li, T. A system dynamics model to simulate the water-energy-food nexus of resource-based regions: A case study in Daqing City, China. *Sci. Total Environ.* **806**, 150497. <https://doi.org/10.1016/j.scitotenv.2021.150497> (2022).
23. Keyhanpour, M. J., Musavi Jahromi, S. H. & Ebrahimi, H. System dynamics model of sustainable water resources management using the Nexus Water-Food-Energy approach. *Ain Shams Eng. J.* **12**, 1267–1281. <https://doi.org/10.1016/j.asej.2020.07.029> (2021).
24. Valencia Cotera, R. et al. An assessment of water management measures for climate change adaptation of agriculture in Seewinkel. *Sci. Total Environ.* **885**, 163906. <https://doi.org/10.1016/j.scitotenv.2023.163906> (2023).

25. Kotir, J. H., Smith, C., Brown, G., Marshall, N. & Johnstone, R. A system dynamics simulation model for sustainable water resources management and agricultural development in the Volta River Basin, Ghana. *Sci. Total Environ.* **573**, 444–457. <https://doi.org/10.1016/j.scitotenv.2016.08.081> (2016).
26. Sivagurunathan, V., Elsawah, S. & Khan, S. J. Scenarios for urban water management futures: A systematic review. *Water Res.* **211**, 118079. <https://doi.org/10.1016/j.watres.2022.118079> (2022).
27. Nika, C. E. et al. Assessing circularity of multi-sectoral systems under the Water-Energy-Food-Ecosystems (WEFE) nexus. *Water Res.* **221**, 118842. <https://doi.org/10.1016/j.watres.2022.118842> (2022).
28. Gohari, A. et al. Water transfer as a solution to water shortage: A fix that can Backfire. *J. Hydrol.* **491**, 23–39. <https://doi.org/10.1016/j.jhydrol.2013.03.021> (2013).
29. Ravar, Z., Zahraie, B., Sharifinejad, A., Gozini, H. & Jafari, S. System dynamics modeling for assessment of water–food–energy resources security and nexus in Gavkhuni basin in Iran. *Ecol. Indic.* **108**, 105682. <https://doi.org/10.1016/j.ecolind.2019.105682> (2020).
30. Gozini, H., Zahraie, B. & Ravar, Z. System dynamics modeling of water-energy nexus for resource-saving policy assessment. *Int. J. Environ. Res.* **15**, 349–367. <https://doi.org/10.1007/s41742-021-00321-5> (2021).
31. Madani, K. Watershed management and sustainability-A system dynamics approach (case study: Zayandeh-Rud River Basin, Iran), Thesis (Master). Lund University, Sweden, (2005).
32. Enteshari, S. & Safavi, H. R. Development of system dynamics for holistic conceptualization of water resources problems using grounded theory: A case study of the Zayandehrud River Basin. *Iran. J. Sci. Technol. Trans. Civil Eng.* **45**, 413–428. <https://doi.org/10.1007/s40996-020-00487-6> (2021).
33. Enteshari, S., Safavi, H. R. & van der Zaag, P. Simulating the interactions between the water and the socio-economic system in a stressed endorheic basin. *Hydrol. Sci. J.* **65**, 2159–2174. <https://doi.org/10.1080/02626667.2020.1802027> (2020).
34. Mirchi, A., Madani, K., Watkins, D. & Ahmad, S. Synthesis of system dynamics tools for holistic conceptualization of water resources problems. *Water Resour. Manag.* **26**, 2421–2442. <https://doi.org/10.1007/s11269-012-0024-2> (2012).
35. Bayer, S. *Interfaces* **34**, 324–326 (2004).

### Author contributions

All authors collaborated in the research presented in this publication by making the following contributions: research conceptualization, M.J. and G. B.; formal analysis, M. J., H. Y., G. B., and S. E.; data curation, M. J. and G. B.; result from analysis and validation, M. J. and S. E.; writing-original draft preparation, M. J.; review and editing, H. Y. and S. E.

### Funding

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. Also, there is no Funding.

### Declarations

### Competing interests

The authors declare no competing interests.

### Ethics approval

The authors confirm that this article is original research and has not been published or presented previously in any journal. This study does not include any animal experiments. All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for authors.

### Additional information

**Supplementary Information** The online version contains supplementary material available at <https://doi.org/10.1038/s41598-025-90728-3>.

**Correspondence** and requests for materials should be addressed to M.J.

**Reprints and permissions information** is available at [www.nature.com/reprints](http://www.nature.com/reprints).

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

**Open Access** This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© The Author(s) 2025