Applied Water Science (2024) 14:213
https://doi.org/10.1007/s13201-024-02279-z

ORIGINAL ARTICLE

System dynamic model of water, energy and food nexus for policy implementation

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Received: 20 March 2024 / Accepted: 28 August 2024

Abstract

In this study, a spatiotemporal disaggregated simulation model was developed based on water–food–energy (WFE) nexus approach to assess water and food supply security considering ecosystem provisioning services. The main components of the developed model in this study (SD-WFE model) are population, water, agriculture, and energy modules. The model, which was developed using system dynamics (SD) approach, was utilized to simulate effectiveness of sectoral municipal, industrial, and agricultural water and energy consumption management and environmental protection policies in improving ecosystem provisioning services during a 20-year period. Through sensitivity analysis utilizing the Monte Carlo model, the study addresses the formulation of sustainable water resource policies across four main categories: water demand management, water supply management, food resource management, and energy resource demand management. Additionally, it explores the integration of policies within an optimal framework. The simulation of proposed solutions revealed that a combination of water demand management and food resource management yielded the most promising outcome. Specifically, the recommended solution entails enhancing water irrigation efficiency by 18% through the expansion of pressurized irrigation network coverage, adjusting cropping patterns by 14%, reducing agricultural product losses by 8% via improved food supply management, minimizing food demand by 9% due to reduced food consumption losses, and achieving an annual 10% increase in crop performance. These selected policies form the foundation for sustainable water resource management strategies.

Keywords Sustainable resource policy · System dynamics · Water resource security · Energy-food-water interdependence

Introduction

Annually, the global population increases by approximately 80 million individuals, contributing to a 1% annual rise in worldwide water consumption (Plessis 2023). Without appropriate policies in place, it is projected that by 2035, people worldwide will only have access to 60% of their required water (Boretti and Rosa 2019; Yousefi et al. 2024). Additionally, the agricultural sector must boost its production by 60% to meet the escalating population's needs by 2050 (Maghzian et al. 2024). Energy consumption is also anticipated to surge by around 50% by 2040 (Serraj et al. 2019). The "energy-water nexus" concept, emphasizing the interdependence of water and energy resources, has been delineated by the World Bank. Similarly, experts at the World Economic Forum have advocated for the water-food-energy nexus approach, which underscores the interconnectedness of these vital resources (Failed 2023; Zahedi et al. 2024a).

The objectives of this nexus approach encompass enhancing the security of water, food, and energy resources, facilitating cross-sectoral communication and decision-making while considering their interlinkages, and promoting the transition toward sustainability (Khan et al. 2017). Water security pertains to access to water resources, groundwater preservation, and water quality maintenance, while energy security involves ensuring coherence between energy supply and demand, access to energy products, and adequate energy supply to meet demand (Zahedi et al. 2024b). Food security encompasses access to food, food procurement capability, and food stability over time. In essence, the fundamental

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principle of water, food, and energy security revolves around balancing resource supply and demand (Tayefeh et al. 2023).

As demand escalates, competition over resources intensifies, leading to increased scarcity, resource dependence, competing consumers, and strategic mismanagement, underscoring the inseparable connection between water, food, and energy resources (Zahedi et al. 2024c). Previous research has predominantly focused on identifying linkages between water and food or water and energy, with limited studies on the water-food-energy nexus (Chellaney 2013). While studies on the water-food nexus are well-established, investigations into the water-energy nexus are comparatively sparse (Zhao et al. 2023). Studies have explored various aspects of the water-food-energy nexus, including optimizing agricultural water consumption, assessing relationships between food exports and virtual water, and evaluating the impact of the consumption of food patterns on the resources of water (Oliveira et al. 2022). Similarly, research on the water-energy nexus have examined topics such as water treatment infrastructure development, increasing the efficiency of energy in the systems of supplying water and assessing consumption of energy in the stages of water supply (Zhang et al. 2018).

Some studies have simultaneously addressed the water-food-energy nexus, employing qualitative and quantitative approaches. However, most studies have been conducted on a limited geographical scale. The dynamic system of sustainable water resource management based on the water-food-energy nexus, considering the increasing demand resulting from population growth and economic development, is crucial for addressing the water crisis in the world. Rapid population growth, inefficient agriculture, inadequate resource management, and developmental pursuits have exacerbated the water crisis, necessitating comprehensive planning, sectoral and intersectoral decision-making, and consensus on water resource policies. Therefore, this study aims to model a novel dynamic system of sustainable water, energy and food resources management to ensure resources security.

Materials and methods

In this research, the SD approach was used for nexus modeling. This approach is helpful for social-learning and is a suitable method for modeling WFE nexus because it makes the dynamics between different systems comprehensible using dynamic feedback loops and nonlinear ordinary differential equations. The SD model of the WFE nexus developed for the study area consists of inter-linked modules for modeling population, water, agriculture and energy subsystems and their interactions. The simulation model was constructed using VENSIM software and simulation period was from 2003 to 2023 with annual time steps. In the following sections, the modules of the SD-WFE model, which represent various subsystems are briefly described. The governing equations in each subsystem were developed based on basic equations of SD approach and causal loop diagrams of each subsystem using the law of conversation of mass.

Study area

Khuzestan Province encompasses parts of three major river basins: Karun-Dez, Karkheh, and Jarahi-Zohreh. The province has 17% of the Karkheh river basin, equivalent to 683.8 square kilometers (Liu et al. 2023). Khuzestan Province covers 43% of the Dez river basin, equivalent to 871.28 square kilometers (Failed 2024). It also includes 61% of the Karun river basin, equivalent to 832.24 square kilometers (Yi et al. 2022). The structure of Khuzestan as an economic view has unique situations (Hejazi et al. 2022). Industrial and mining sector, which includes oil, accounts for about 78% of the province's gross production, making it the main economic activity in the province (Hu et al. 2022). Khuzestan Province boasts a substantial contribution to Iran's energy sector, with around 80% of the nation's crude oil and 17% of its gas originating from this region (Lin and Zhu 2021). This prominence positions Khuzestan as a key investment destination for oil-related ventures (Jiang et al. 2023). Additionally, the province possesses a notable water infrastructure, with the construction of nine major dams either completed or underway across various locales (Mehan and Abdul 2022). These dams serve multifaceted purposes, supporting the development of agriculture, fisheries, energy generation, and potable water supply sectors within the region (Yang et al. 2024). Another advantage of the province is the presence of vast vegetation and soil resources, good climate conditions, and the possibility of three-season agricultural cultivation and harvesting in a large part of the province (Ho and Goethals 2019). This plays a crucial role in the development and progress of the area and the entire region (Li et al. 2021).

Dynamic system modeling

In this study, the system dynamics approach was used to model and simulate VENSIM DSS 6.4E software. This approach is helpful for social-learning and is a suitable method for modeling WFE nexus because it makes the dynamics between different systems comprehensible using dynamic feedback loops and nonlinear ordinary differential equations. Based on the Energy-Food-Water (WFE) Nexus and system dynamics (SD) Approaches, the problem of sustainable water resources management was designed in three subsystems of water resources, food resources and energy resources. In accordance with the conceptual framework and the system dynamics methodology, dynamic assumptions of the problem of water resource management integrity were designed. The present study is based on the systems dynamics approach to modeling and simulating sustainable water resources management using Vensim DSS 6.4E software. The systems dynamics methodology includes the following steps:

Step 1: Identification of the problem and its definition,

Step 2: Dynamic hypotheses identification,

Step 3: Causal loop diagram and flowchart,

Step 4: Model simulation and validation,

Step 5: Definition of different scenarios, selection, and implementation of appropriate solutions (Sterman, 2000).

In accordance with the systems dynamics methodology, dynamic hypotheses of the water-food-energy nexus-based sustainable water resources management problem were designed. Figure 1 illustrates the dynamic hypotheses of the present research.

After formulating the dynamic hypotheses, the connections among variables within each subsystem and across different subsystems are depicted in causal loop diagrams, incorporating positive and negative feedback loops. As shown in Fig. 2, these diagrams were designed accordingly.

Subsequently, to construct the model, the flow of variable trends over time is considered. Based on these trends and using mathematical equations and regression functions that describe the relationships between variables, the model is formulated. The flow diagrams for individual subsystems, along with their modeling specifics, will be outlined in the following sections.

Water resources security subsystem

As depicted in Fig. 3, this subsystem is designed to align with the hydrological cycle. Surface water sources, including variables like accumulation and precipitation rates, water return from renewable sources, and water release from reservoirs, contribute to the annual increase in surface water resources. On the other hand, variables such as evaporation and transpiration, the inflow volume to reservoirs, surface water consumption due to total water demand, environmental water requirements, soil infiltration, and virtual water exports are considered as reducing rates for available surface water resources (Pérez-Lucas et al. 2019). Another variable is the accumulation of groundwater resources, which increases with

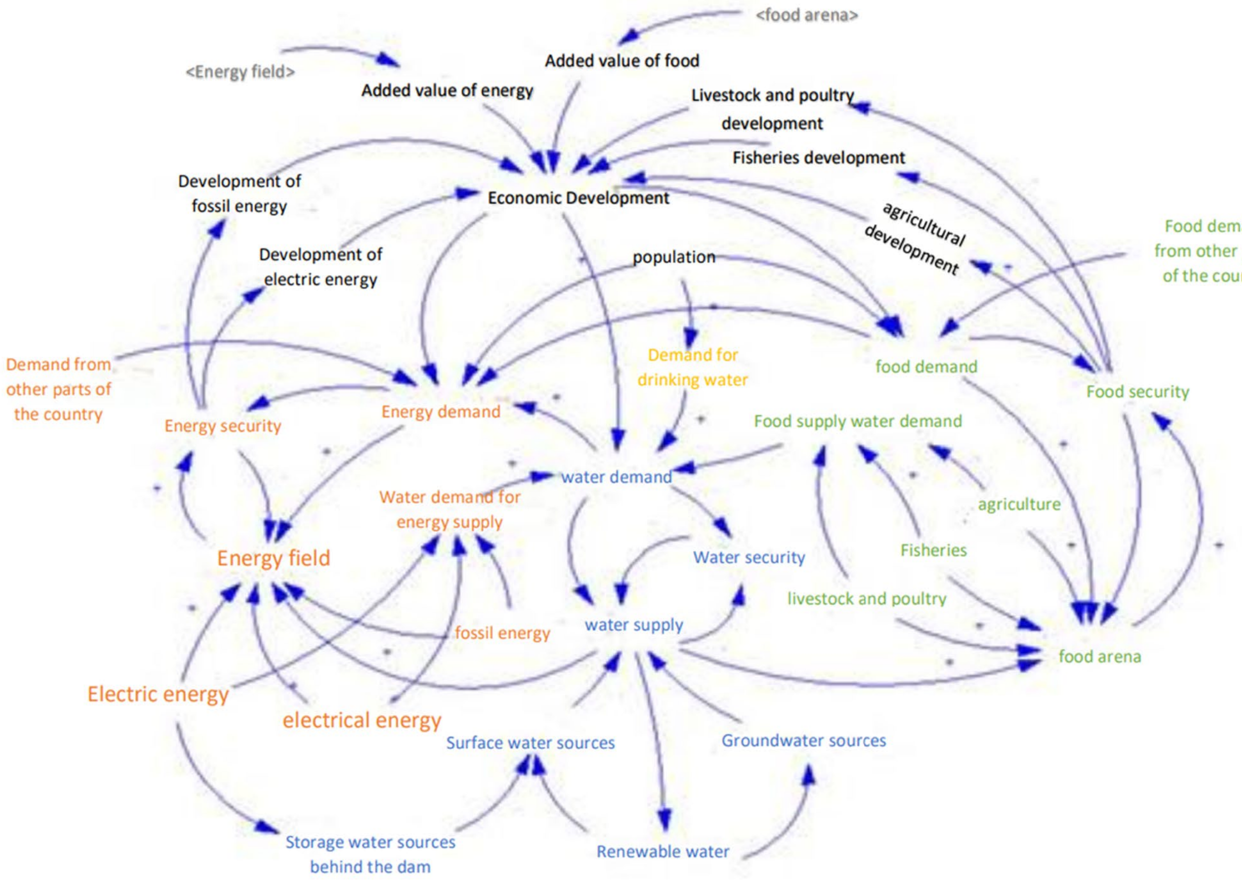

Fig. 1 Dynamic Hypotheses of the Water-Food-Energy Nexus-Based Sustainable Water Resources Management Model

the infiltration rate in the soil and the return of wastewater and agricultural return flows, while decreases with the rate of the consumption of groundwater due to groundwater demand and the non-extractable ratio.

Total water demand is derived from the demand for drinking water, which is in accordance with the population size and water consumption per capita, as well as the demand for water in the energy sector and the demand for water in industries other than the energy sector. Additionally, it includes the demand for water in the agricultural sector. Water resources are supplied through two sources: surface water resources and groundwater resources. Water resources security considers the difference between water supply and demand (Naghdi et al. 2021). Precipitation data is extracted based on historical data from three watershed basins from 1988 to 2023 and, considering Khuzestan Province's share of precipitation in these basins, the average precipitation for each basin is calculated using the Thiessen polygon method (TP) according to Eq. (1), where P represents the average precipitation at the basin level, i denotes the basin division, Pi represents the precipitation amount at station i, and Ai represents the station area i (Lee et al. 2018).

$$\overline{P} = \frac{\sum A_i \times P_i}{\sum A_i}$$

As shown in Fig. 3, the flow diagram of water resources subsystem has been designed to be consistent with the hydrological cycle of water so that surface water resources (SWR), stock variable and rainfall (W_{RF}), rate variables water return from renewable sources (W_{RS}), and water release from dams (W_{RD}) lead to an increase in the annual rate of surface water resources. On the other hand, evapotranspiration (W_{EV}), dams input volume (W_{ID}), surface water consumption (W_{SC}) due to overall water demand, environmental need (W_{EN}) and influence soil (W_{IS}) have been considered to be the decreasing rates of available surface water resources. The values of the fixed variables of the model are presented in Table 1.

The groundwater table and storage fluctuations were calculated using a groundwater balance model developed in this study for each sub-basin. The concept of aquifer storage calculation is depicted in Fig. 4. The aquifer storage fluctuation contributed to water table variation.

Subsystem of food resources security

As shown in Fig. 5, food supply is provided from agricultural, aquaculture, and livestock sectors. The demand for food is proportional to the domestic demand for food, which is derived from the population size and per capita

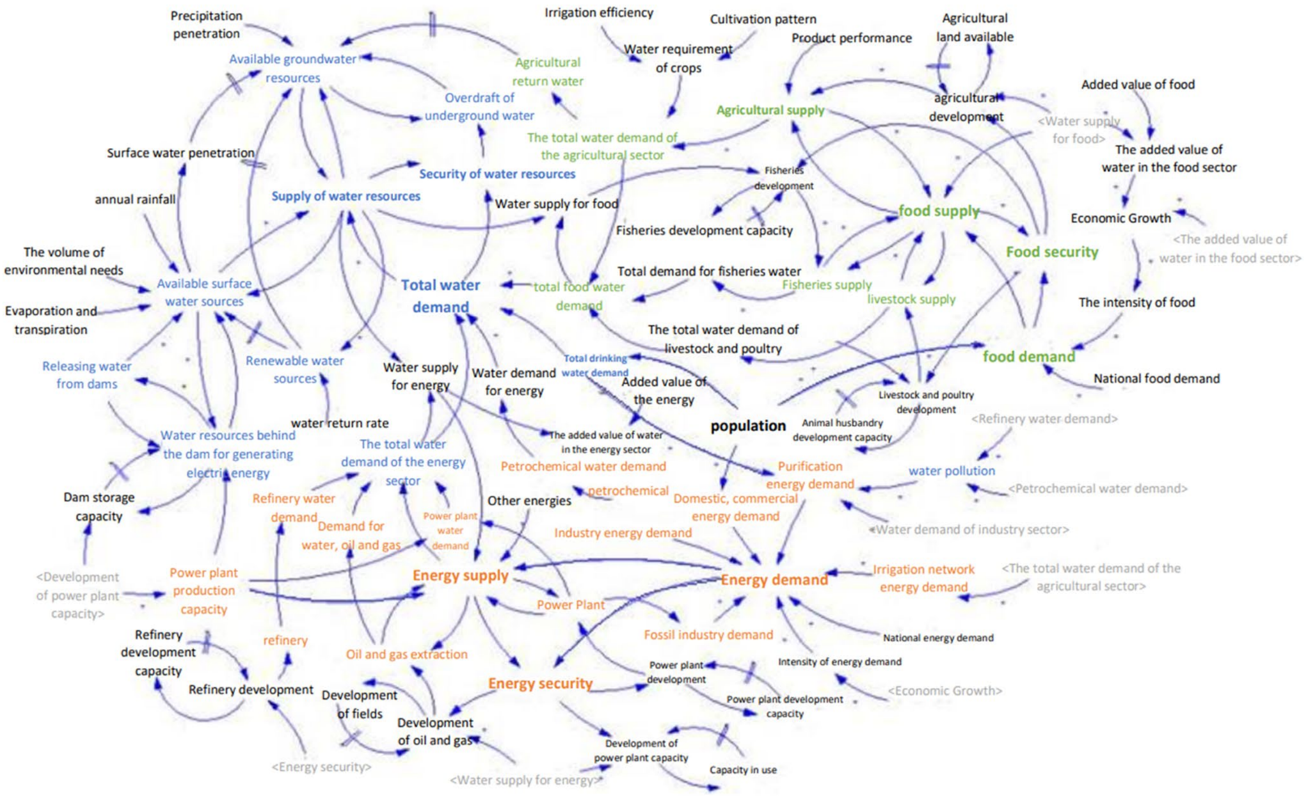

Fig. 2 Causal Loop Diagram of the Water-Food-Energy Nexus

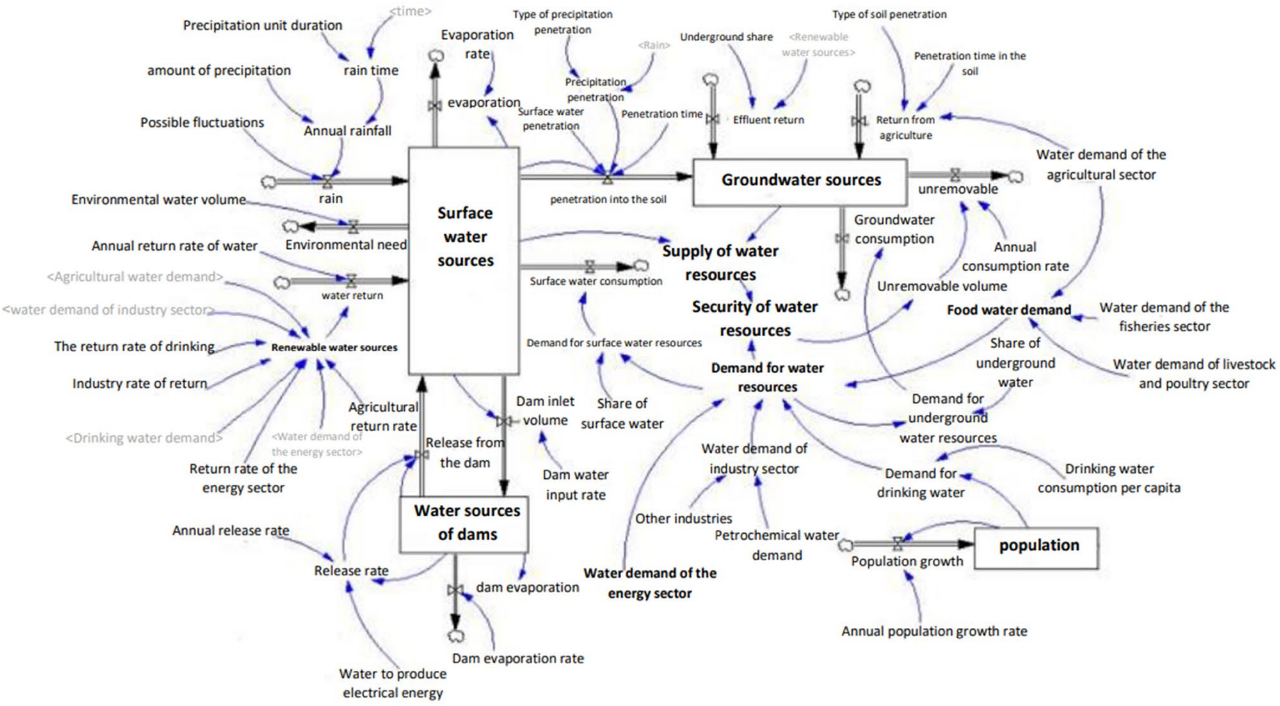

Fig. 3 Dynamic Flow of the Water Resources Security Subsystem in the Water-Food-Energy Nexus-based Sustainable Water Resources Management Model

Table 1 Some of the Fixed Variables of water resource subsystem

Variable	Value	Unit
Soil reversion rate	0.145	1/Year
Surface water share	0.86	1/Year
Environmental need	3,000,000,000	m^3/Year
Evaporation rate	0.25	1/Year
Groundwater share	0.14	1/Year
Per capita water consumption	171.87	m^3/person

food consumption, as well as the demand from other regions of the country for predominant agricultural products in the province (such as wheat, barley, sugar beet, date palm, corn, and tomatoes). The annual supply rate of the agricultural sector is determined by the cultivated area and crop yield (Ogunmoroti et al. 2022). Similarly, the annual supply rate of the aquaculture and livestock sectors is contingent on the potential of these sectors. Food resource security is regulated in line with the development capacity of agriculture, aquaculture, and livestock sectors if it deviates from equilibrium. Conversely, the total demand for food water is derived from the aggregate water demand of the agricultural, livestock, and aquaculture sectors (Lancker et al. 2019). The agricultural sector predominantly drives water demand, influenced by the level of food production, crop water needs, and water consumption intensity. The intensity of agricultural water consumption considers cropping patterns, irrigation efficiency, and sectoral water requirements (Mahmoudi et al. 2024). Economic growth, particularly rapid GDP growth, can significantly impact water resource demand. The value-added in the agricultural and energy sectors resulting from water, food, and energy resources plays a pivotal role in GDP and economic growth (Wriedt et al. 2009). The effect of value-added growth in the energy and food sectors on economic growth is addressed in Eqs. (2–4) of the model, where the logarithm of GDP signifies yearly economic growth, and the logarithms of value-added in the agricultural and energy sectors denote the annual growth rate of value-added in these parts (Playán and Mateos 2006; Wang and Zhang 2023).

$$\log GDP = b_0 + b_1 \times \log VA_{Agricalturet} + b_2 \times \log VA_{Energyt}$$

$$Economicgrowth = \frac{GDP_t - GDP_{t-1}}{GDP_{t-1}}$$

$$VA_{growth} = \frac{VA_t - VA_{t-1}}{VA_{t-1}}$$

The influence of the agricultural sector and B2 on the growth of the energy sector's value-added to economic growth has been assessed. Furthermore, the economic growth impact on water resource demand has been analyzed

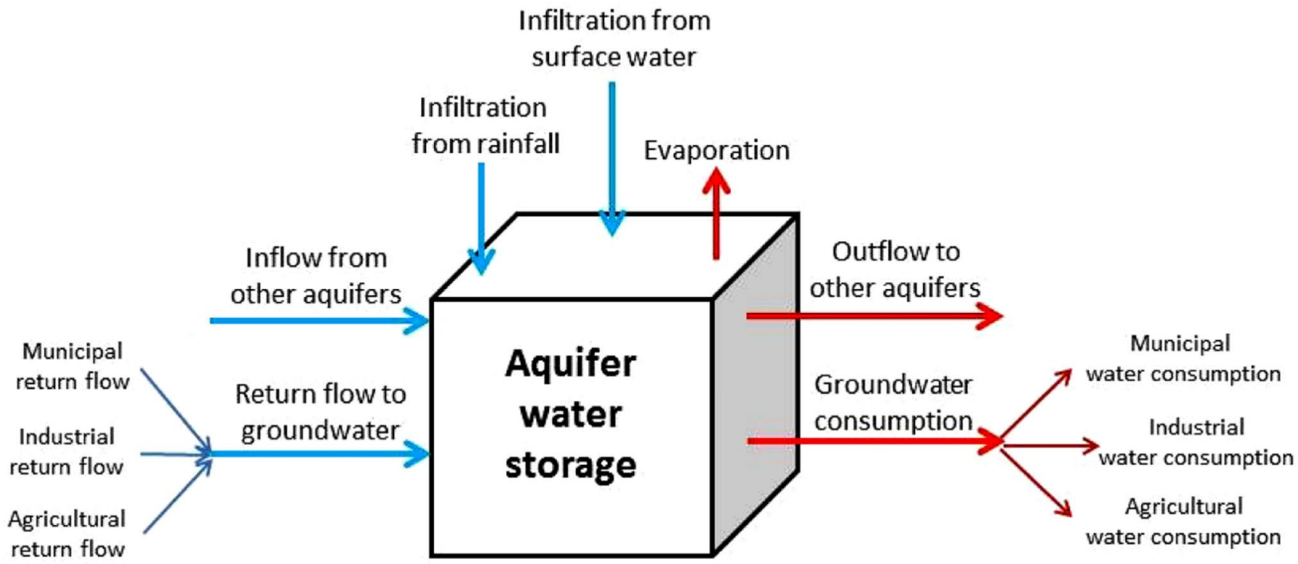

Fig. 4 Schematic of groundwater subsystem for each aquifer

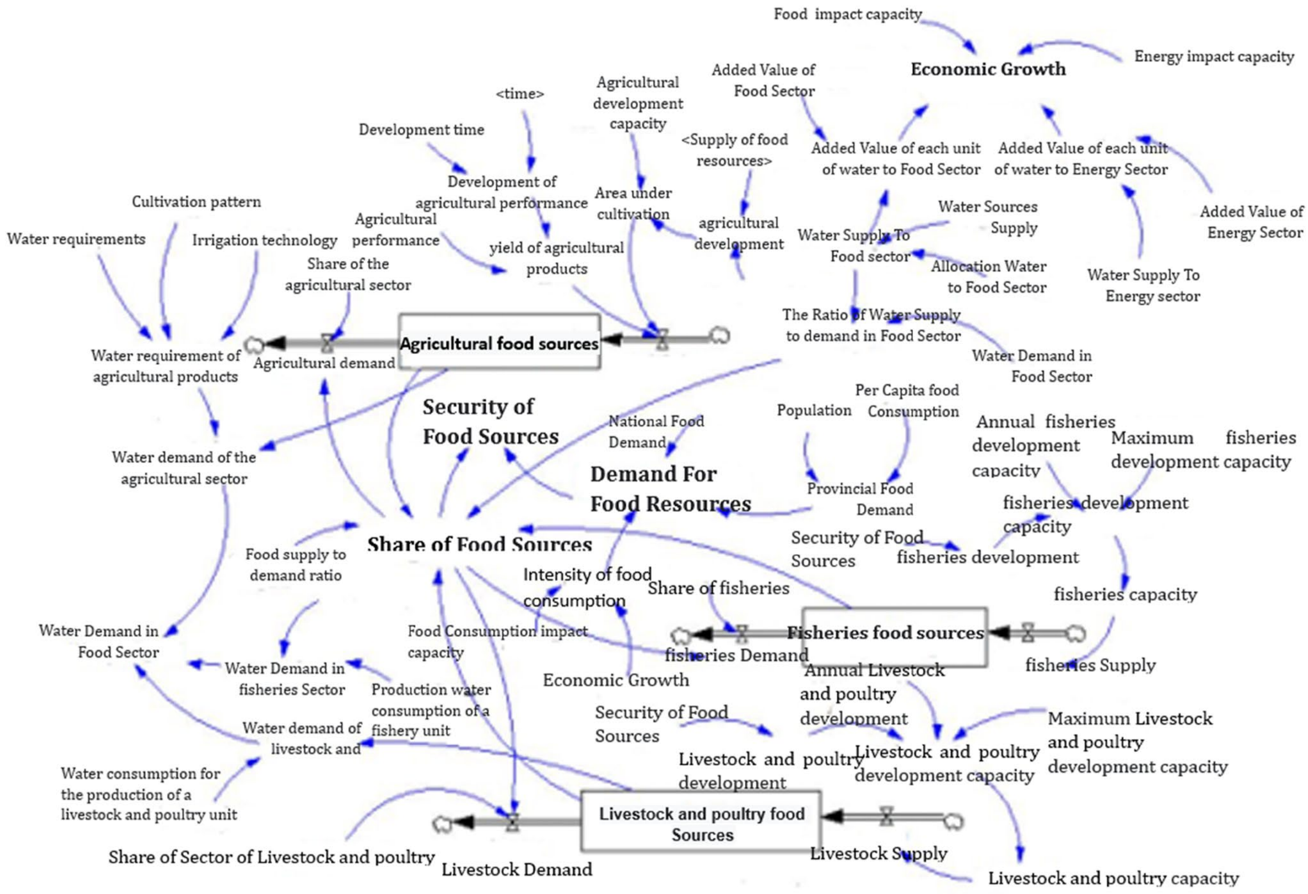

Fig. 5 Flow chart of the food resource security subsystem design of sustainable management of water resources based on energy-water-food nexus

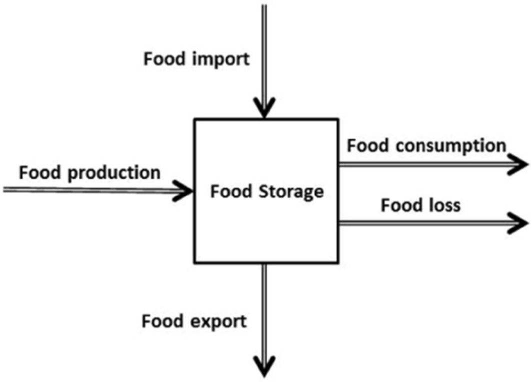

Fig. 6 Schematic of food production and consumption subsystem

Table 2 Some of the Fixed Variables of food resources subsystem

Variable	Value	Unit
Water requirements	146.25	m^3/ton
water consumption of livestock	15	m^3/kg
Allocation of water to food sector	0.9	Dmnl
Per capita food consumption	0.0418	ton/perspn

through coefficients of regression B1 and B2 based on time series data from the energy and food sectors. The focus has been on the period from 2018 to 2023. The calculating concept of food storage of each crop in all of 16 sub-basins is presented in Fig. 6.

Food demand for water stems from the water demand of all three sectors of agriculture, livestock and poultry, fisheries and the amount of water consumed per unit. The agricultural sector is the major demand for water, and the water demand in this sector is due to the amount of food production in agriculture sector, the water demand for crops, and the intensity of water consumption in the agriculture sector. The intensity of agricultural water consumption has been considered to be due to the pattern of cultivation and irrigation efficiency. The values of the fixed variables of the model are presented in Table 2.

Energy resource security subsystem

As seen in Fig. 7, energy is supplied from fossil energy sources, renewable sources of energy, power plant sources, and other resources of energy. The demand for energy is proportional to the domestic energy demand, which is influenced by population, energy consumption per capita, and energy consumption intensity resulting from economic development, as well as the demand from other regions of the country. The highest significant relation between security of energy resource and security of water resource is the level of water consumption in oil production and extraction, as well as water pollution (Ahmad and Zhang 2020). As it can be seen in Fig. 5, the energy supply comes from fossil energy sources, hydroelectric power energy sources, power plants and other energy sources. Energy demand is commensurate with the amount of domestic energy demand that comes from population and per capita energy consumption (Ed_{ur}), national energy demand (ED_{na}), energy sector demand (Ed_{en}), industrial energy demand (ED_{ind}), water refinery energy demand (ED_{ref}), irrigation network energy demand (Ed_{ir}) and the intensity of energy consumption affected by economic development.

Schematic of energy subsystem including various energy carriers (electricity, gasoline, and mazut) in the study area is depicted in Fig. 8. The following are some variables and mathematical relationships governing this subsystem, as described in Table 3, as well as some constant values of the model outlined in Table 4.

Results and discussion

An initial dynamic model simulation was conducted over a 20-year time horizon. The base year in the model is 2018 and time series data from 2018 to 2023 were used to evaluate the behavioral validity of the model. Time series data were collected based on the performance results of the Ministry of Agriculture, the Ministry of Energy, the country's dams, the value-added based on reports from the Statistical Center of Iran, and the Budget and Planning Organization of the country. The National Iranian Oil Refining and Distribution Company and the National Iranian South Oil Company were also considered. Model validation included the tests of goodness of fit, dimension compatibility, limit condition test, parametric validation test, parameter sensitivity test, frontier adequacy test, behavior reproduction test, and integral error test. Also, in terms of behavior, the pattern of variables of the model was approved by the experts. Table 5 shows. The results of the behavioral test according to the least square mean square error ratio index of some variables (Gupta et al. 2009).

After the successful completion of validation tests, a preliminary simulation was conducted for a 20-year horizon. Figure 9 presents the changes in each of the key variables' flow chart, which is essential for determining the overall processing status and importance.

As observed, during the 20-year simulation period (2023–2043), water resource security and food security will experience a declining trend, and food security will be at risk from the tenth year of simulation. Following the initial simulation, sensitivity analysis using 200 Monte Carlo iterations and a standard distribution of probability function was performed. Based on the results of the sensitivity analysis,

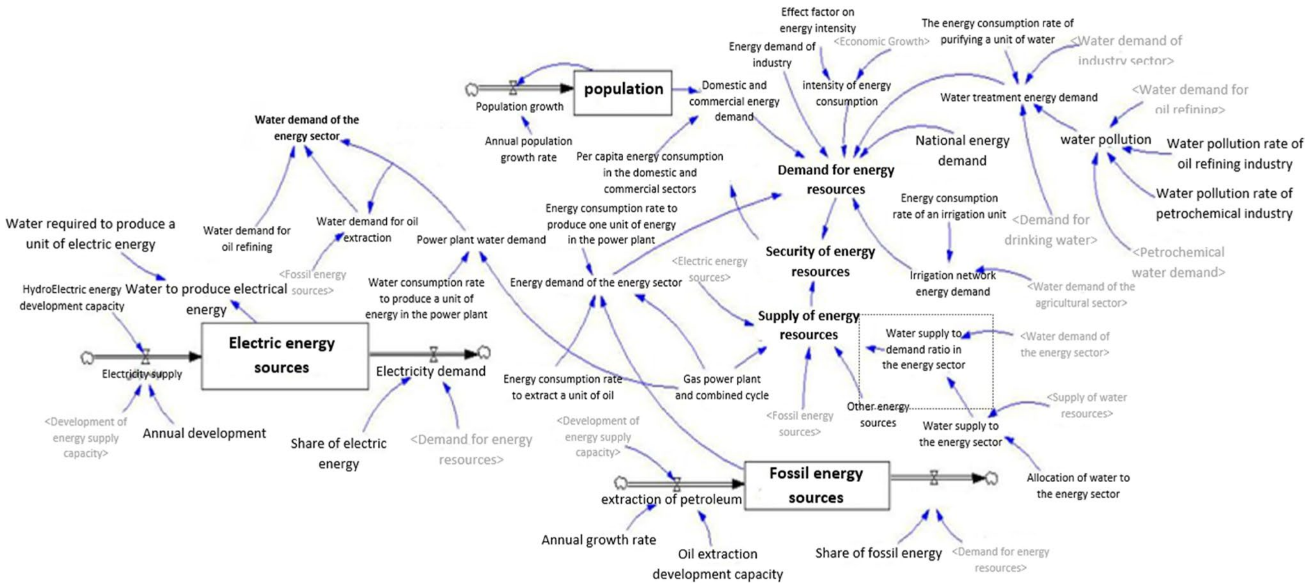

Fig. 7 Flow diagram of energy resources security subsystem model of sustainable management of water resources based on water-food-energy correlation

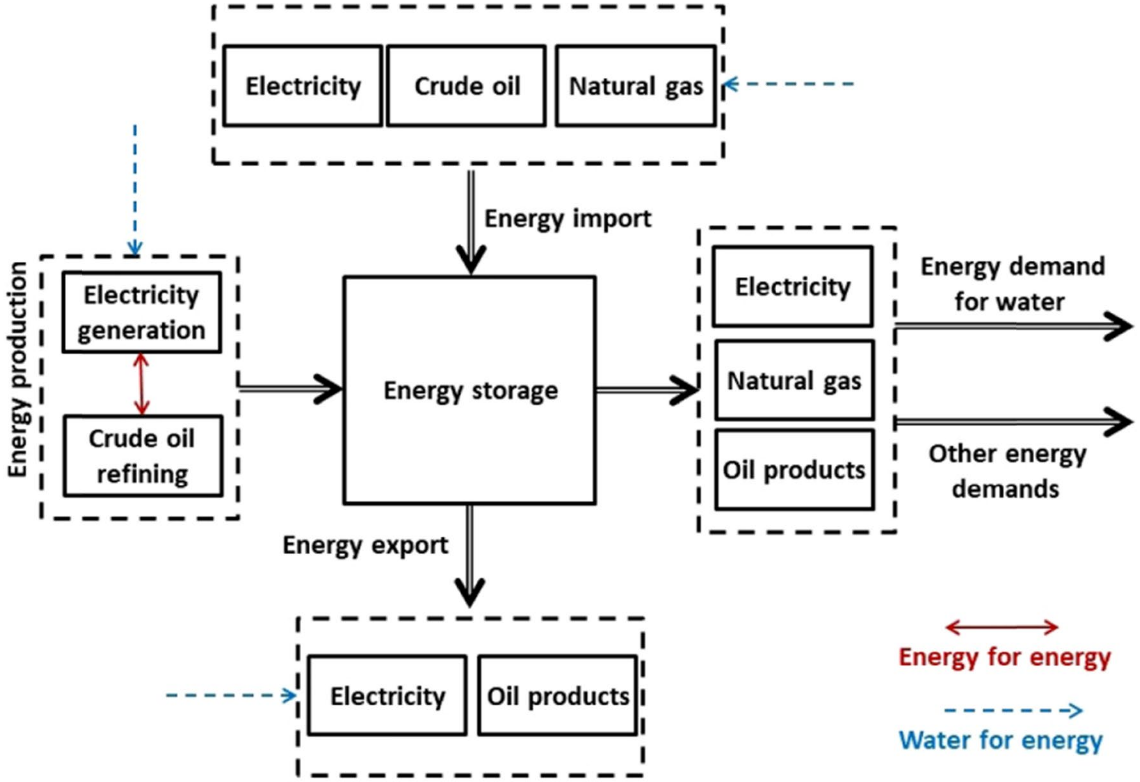

Fig. 8 Schematic of energy production and consumption subsystem for each energy carrier

the variables that created the most significant range of variations, known as leverage points, were identified. Figure 10 illustrates these results.

Based on the sensitivity analysis outcomes and consultations with experts, crisis management strategies for water resources were devised, classified into four

Table 3 Some mathematical relationships governing the dynamo model and sustainable management of water resources based on the correlation of water-food-energy (Mashaly and Fernald 2020; Li et al. 2022; Guo et al. 2023)

Water Resource Security Subsystem

Water Resource Security = Water Supply - Water DemandWater Supply = Surface Water Resources + Groundwater Resources Water Demand = Industrial Water Demand + Energy Sector Water Demand + Drinking Water Demand + Agricultural Water DemandSurface Water Resources = INTEG(Precipitation) + Dam Releases + Water Return - Dam Inflow Volume - Environmental Needs - Evaporation - Infiltration into Soil - Surface Water ConsumptionRenewable Water Resources = Industrial Water Demand × Industrial Return Rate + Energy Sector Water Demand × Energy Sector Return Rate + Agricultural Water Demand × Agricultural Return Rate + Drinking Water Demand × Drinking Water Return RateRelease Rate = IF THEN ELSE(Dams Water Resources ≤ Water for Hydropower Generation, Dams Water Resources - Water for Hydropower Generation) / Dams Water Resources, 0 × (Annual Hydropower Generation Release Coefficient = Hydropower Generation Resources × Water Required for One Unit of Hydropower GenerationPrecipitation = Annual Precipitation × Probable Fluctuations

Groundwater Resources = Wastewater Return + INTEG(Return from Agriculture) + Infiltration into Soil - Non-Extractable - Groundwater ConsumptionReturn from Agriculture = SMOOTH(Agricultural Water Demand × Soil Infiltration Rate, Soil Infiltration Time)

Population = INTEG(Population Growth) (4.764e+006)Energy Sector Water Demand = Power Plant Water Demand + Oil Extraction Water Demand + Oil Refining Water DemandFood Sector Water Demand = Aquaculture Water Demand + Livestock and Poultry Water Demand + Agricultural Water DemandAgricultural Water Demand = Agricultural Food Resources × Crop Water Requirement

Resource Security Subsystem

Food Resource Security = Food Supply - Food Demand

Food resources demand = National food demand + Provincial food demand × Food consumption intensity

Food resources supply = IF THEN ELSE (Water demand ratio in the food sector >= 1, Aquaculture food resources + Agricultural food resources + Livestock and poultry food resources, (Water demand ratio in the food sector × Supply-demand ratio + 1) × Aquaculture food resources + Agricultural food resources + Livestock and poultry food resources)

Agricultural food resources = INTEG (Agricultural supply - Agricultural demand, 1.6e+007)Agricultural supply = Cultivated area × Crop yieldAgricultural water demand = Agricultural food resources × Water requirement of agricultural productsWater requirement of agricultural products = Water requirement × Irrigation technology × Cultivation pattern

Food consumption intensity = 1 + Economic growth × Intensity impact coefficient

Water demand in the food sector = Water demand in the aquaculture sector + Water demand in the livestock and poultry sector + Water demand in the agricultural sector

Water demand in the livestock and poultry sector = Livestock and poultry food resources × Water consumption per unit of livestock and poultry production

Water demand in the aquaculture sector = Aquaculture food resources × Water consumption per unit of aquaculture production

Livestock and poultry food resources = INTEG (Livestock supply - Livestock demand, 21370)Livestock demand = Food resources supply × Livestock and poultry sector share

Aquaculture food resources = INTEG (Aquaculture supply - Aquaculture demand, 43138)

Economic growth = Value added per unit of water in the energy sector × Energy impact coefficient + Value added per unit of water in the food sector × Food impact coefficient

Resource Security Subsystem Equations

Energy Resource Security = Energy Resource Supply - Energy Resource Demand

Energy Resource Supply = IF THEN ELSE (Water Supply-Demand Ratio in the Energy Sector >= 1, Other Energy Resources + Hydroelectric Resources + Fossil Fuel Resources + Gas and Combined Cycle Power Plants, ((Water Supply-Demand Ratio in the Energy Sector) + 1) * Other Energy Resources + Hydroelectric Resources + Fossil Fuel Resources + Gas and Combined Cycle Power Plants)

Energy Resource Demand = Energy Demand in the Energy Sector + Water Treatment Energy Demand + Residential and Commercial Energy Demand + Irrigation Network Energy Demand + Industrial Energy Demand + National Energy Demand

Energy Consumption Intensity * Hydroelectric Resources = INTEG (Hydroelectric Supply - Hydroelectric Demand, 5923)

Water for Hydroelectric Power Generation = Hydroelectric Resources * Water Required to Generate One Unit of Hydroelectric Energy

Water Demand for Oil Extraction = Fossil Fuel Resources * Water Consumption Rate for Extracting One Unit of Oil

Water Demand in the Energy Sector = Water Demand for Oil Extraction + Power Plant Water Demand + Water Demand for Oil Refining

Power Plant Water Demand = Gas and Combined Cycle Power Plants * Water Consumption Rate for Generating One Unit of Energy in Power Plants

Energy Demand in the Energy Sector = Gas and Combined Cycle Power Plants * Energy Consumption Rate for Generating One Unit of Energy in Power Plants + Fossil Fuel Resources * Energy Consumption Rate for Extracting One Unit of Oil

Fossil Fuel Resources = INTEG (Oil Extraction - Fossil Fuel Demand, 9e+008)

Water Supply-Demand Ratio in the Energy Sector = Water Demand in the Energy Sector / Water Supply to the Energy Sector

Table 3 (continued)

Resource Security Subsystem Equations
Irrigation Network Energy Demand = Agricultural Water Demand * Energy Consumption Rate for Irrigating One Unit of Water
Energy Consumption Intensity = 1 + Economic Growth * Intensity Impact Coefficient
Water Treatment Energy Demand = Drinking Water Demand + Water Pollution + Industrial Water Demand * Energy Consumption Rate for Treating One Unit of Water

Table 4 Some parameters and fixed values of the dynamic model of sustainable management of water resources based on water-food-energy correlation (Sun et al. 2021; Wang et al. 2023; Sušnik 2018)

Variable name value unit	Amount	Unit	Variable name value unit	Amount	Unit
Food Consumption Per Capita	0.0418	Ton/Person	National Energy Demand	6e+008	Barrel
National Food Demand	1e+007	Ton	Energy Intensity Impact Coefficient	0.05	1/Percent
Population	4.764e+006	Person	Industrial Energy Demand	2e+007	Barrel
Environmental Requirement	3e+009	M 3/Year	Residential and Commercial Energy Intensity Per Capita	26	Barrel/Person
Petroleum Refining Water Demand	2.7e+007	M 3	Annual Population Growth Rate	0.01	1/Year
Drinking Water Return Rate	0.7	1/Year	Consumption Rate of Energy for Treating One Unit of Water	7e-008	Barrel/(M 3)
Industrial Water Return Rate	0.8	1/Year	Industrial Water Pollution Rate	0.8	
Evaporation Rate	0.3	1/Year	Subsurface Share	0.17	
Reservoir Water Resources	1.8e+010	M 3	Gas and Combined Cycle Power Plants	1298	Barrel
Water Consumption Rate for Generating One Unit of Energy in Power Plants	5	M 3/ Barrel	Energy Consumption Rate for Generating One Unit of Energy in Power Plants	100	
Infiltration Rate	0.145	1/Year	Development Capacity for Oil Extraction	7.5e+008	Barrel/Year
Drinking Water Consumption Per Capita	171.87	M3/Person	Energy Consumption Rate for Extracting One Unit of Oil	1e-010	
Hydroelectric Resources	5923	Barrel	Water Consumption for Producing One Unit of Aquaculture	10,000	M 3/Ton

Table 5 Behavioral validity test (least square mean square error ratio) of some model variables

Agricultural Products	2018	2019	2020	2021	2022	2023	RMSPE
Actual Value	13.2	13.5	13.9	14.5	14.5	15.2	0.043
Simulated Value	13	14	14.7	15.2	15.6	15.9	
Population (Millions)							
Actual Value	4.53	4.57	4.62	4.67	4.71	4.72	0.004
Simulated Value	4.53	4.57	4.65	4.68	4.72	4.76	
Agricultural Water Demand							
Actual Value (Billion m^3)	11.96	12.5	12.9	13.3	14.2	14.5	0.021
Simulated Value	11.84	12.72	13.41	13.83	14.16	14.45	
Crude Oil Production							
Actual Value (Million barrels)	800	825	830	850	880	960	0.022
Simulated Value	800	827	857	880	905	930	

categories. These policies integrate perspectives from experts and align with existing literature and planning in relevant units. Subsequently, each policy was implemented in the model, and the outcomes were evaluated for target variables, including security of energy, security of food and security of water. The subsequent section presents a comprehensive delineation of these policies.

Water supply management policy

This category of solutions is focused on managing supply of water and aims to enhance water resources which are available. By decreasing the capacity of hydropower development, which was considered based on the trend of executive dam development, from 3.2% to 8.1% annually, the water

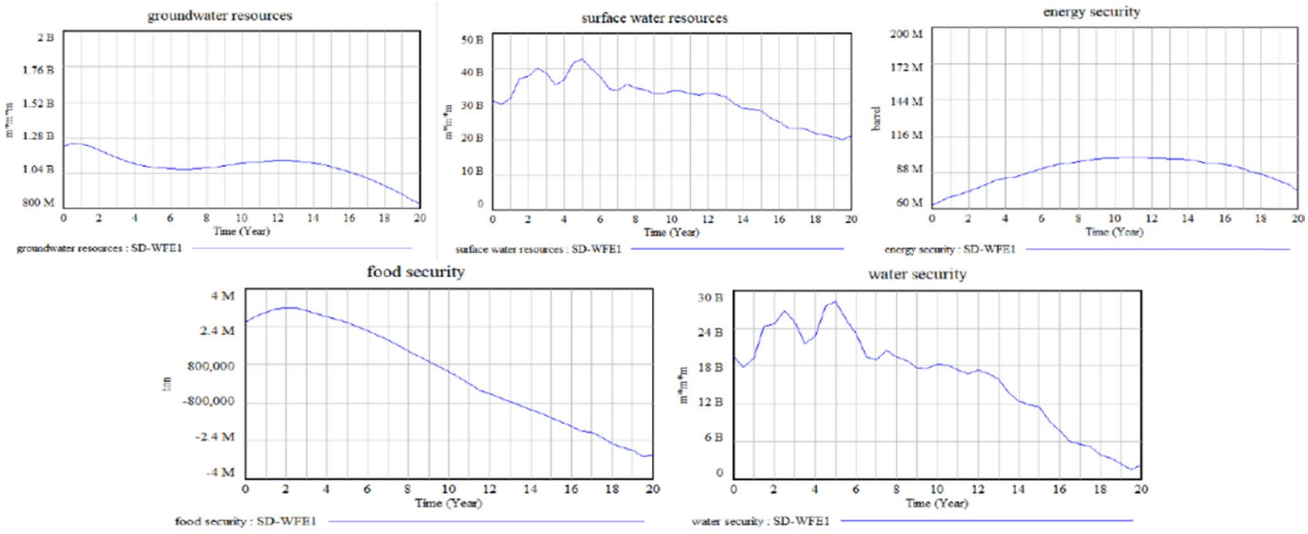

Fig. 9 The behavior of variables of surface and underground water resources, security of water resources, security of food resources and security of energy resources in the simulation horizon

stored behind regional dams volume is reduced, resulting in an increase in available water resources. Considering that capacity development trends are developed in order to meet the demand for electricity in the province and also electricity exports from the province, this change has been implemented in a way that ensures the power plant capacity meets the increasing demand in the Khuzestan ecosystem. Additionally, by changing the renewable water rate in industry, energy and drinking water sectors, considering implementable and feasible changes, the water supply situation is improved. Consistent with the reports of water resources studies in Khuzestan province, the urban water return rate is approximately 80%. Therefore, by developing the sewage system and water treatment, a 10% increase in the achievable water return rate is possible. Regarding the changes in water return rates from the energy and industrial sectors, a range of approximately 5% to 10% increase is considered feasible through the development of industrial wastewater networks.

Demand management policy

This solutions type focuses on managing water demand and is primarily designed to address the largest water consumer, the agricultural sector. These solutions aim to increase

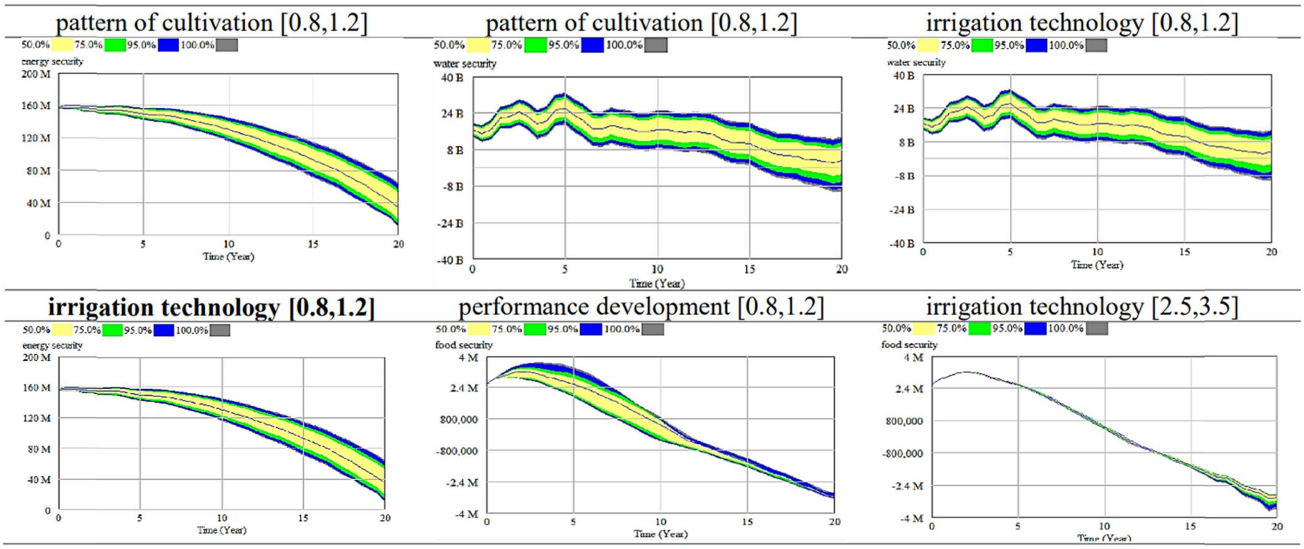

Fig. 10 Results of Monte Carlo sensitivity analysis of some exogenous variables of the model

Table 6 Irrigation information for dominant agricultural and garden crops and the efficiency of surface irrigation methods and pressurized irrigation methods

Product	Surface irrigation method	Irrigation efficiency	Pressurized irrigation method	Drip irrigation efficiency
Wheat	Furrow	40	Sprinkler	65
Barley Furrow	Furrow	40	Sprinkler	65
Tomato	Drip tape	45	Drip	85
Corn	Drip tape	43	Drip	85
Sugar	Beet drip tape	47	Drip	85
Sugarcane	Drip tape	36	Low-Pressure	60
Date palm	Leakage	48	Drip	85

irrigation efficiency through the development of irrigation and drainage system technologies and the improvement of agricultural cropping patterns. Surface irrigation and pressurized irrigation methods are dominant for agricultural and horticultural crops, as indicated in the report of the Agricultural Jihad Organization of Khuzestan Province. As shown in Table 6, the difference in irrigation efficiency is calculated considering the cultivated area of agricultural and horticultural crops, which is approximately 32%. Currently, 30% of the irrigated lands are covered by pressurized irrigation systems (sprinkler, drip, and low-pressure systems). Therefore, if other lands are also brought under pressurized irrigation coverage, at least 16% of the total agricultural water demand can be reduced. On the other hand, by taking into account the changes in cropping patterns for certain crops like corn, tomatoes and rice, considering conditions of the region and national food security, the required water for the agricultural sector can be reduced by up to 10% (Studies of the Agricultural Jihad Organization, Khuzestan Province, 2012).

Policy for demand and supply management of food resources

According to the reports of the FAO and the Ministry of Agriculture in Iran, the average food loss is 12% at the production stage and before harvesting, 25% during handling, storage, processing, and distribution, and 10% at the consumption stage. By identifying and managing these losses at various stages, we can increase the supply of food resources. Based on this policy, the management of production losses is considered to be 12% for major agricultural and horticultural products in the region, such as wheat and barley. By achieving half of the loss management, we aim to reduce production losses from 12% to a minimum of 6%. Furthermore, through promoting a culture of efficient resource consumption and achieving half of the loss management, we aim to reduce food demand by 5%. Additionally, by improving the annual performance of production by 5% through seed improvement, fertilizers, and modern agricultural methods, we can find sustainable solutions for resource security. The minimum thresholds for the implementation of this policy have been chosen to ensure food security.

Policy for energy resources demand management

In the studied region, fossil energy resource extraction, along with oil refining and petrochemical industries, exhibit the most demand for water consumption in the energy sector. Additionally, water pollution poses a significant future challenge in these sectors. Development endeavors in the Khuzestan region primarily prioritize maximizing the utilization of oil and gas resources and fostering dependent industries. Despite the high added value of these industries and their pivotal part in the country's development and growth of economic, the detrimental impacts of these sectors often go unnoticed. This policy endeavors to attain resource sustainability by mitigating pollution rates in industries, thereby reducing energy consumption in water treatment and power plants, as well as in oil refining and petrochemical industries. Notably, based on the Hydrocarbon Balance Sheet for 2023, the energy loss in thermal power plants approximates 805 thousand barrels of crude oil per day, constituting approximately 40% of the country's primary energy supply and being squandered before reaching consumption destinations. Based on energy management studies, which estimate the potential for energy savings and waste prevention in the oil refining industry, optimization levels have been considered for each sector in the energy management policy. Table 7 summarizes the proposed policies and the implemented changes in the model.

Figure 11 compares the implemented policies on the model variables. As observed, each policy focuses on the development and improvement of water, food, and energy resources from one or two perspectives, but the simultaneous improvement of all three resources has not been achieved.

Table 7 Summary of proposed policies and applied changes on the model

Policy	Implemented change	Magnitude of change
Water resources management	Decrease capacity of hydroelectric power plant to reduce stored water volume behind dams	20% decrease
	Increase urban water return rate	10% increase
	Increase energy sector water return rate	5% increase
	Increase industrial sector water return rate	5% increase
Demand-side water resources management	Improve crop patterns	10% improvement
	Develop irrigation efficiency using pressurized irrigation technologies	16% increase
Food resources management	Reduce food demand through food loss management	6% decrease
	Reduce per capita food demand through consumption pattern modification	5% increase
	Improve production performance through seed and fertilizer modification and innovative agricultural methods	5% yearly improvement
Energy resources management	Reduce energy waste in combined cycle and gas power plants	5% yearly decrease
	Reduce energy consumption in oil refining industry through energy management	10% decrease
	Reduce energy consumption in petrochemical industries by optimizing wastewater production	10% decrease
	Reduce energy consumption in petrochemical industries by optimizing wastewater production	15% decrease
	Reduce energy consumption in Refinery plants by optimizing wastewater production	15% decrease

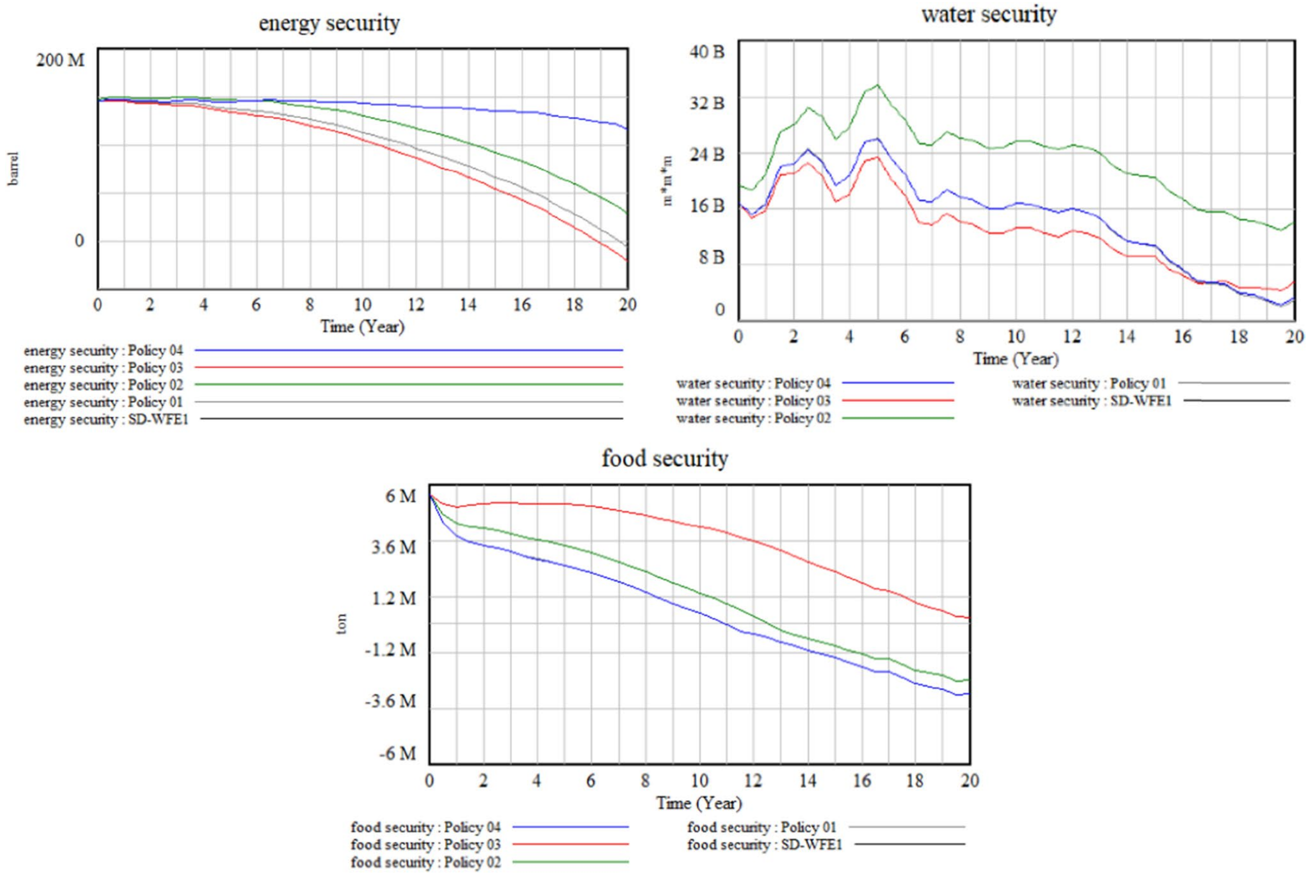

Fig. 11 Comparison chart of applied policies on model variables in the twenty-year simulation horizon

Conclusion

There is a need to develop region-specific tools that are tailored to available resources, consumption patterns, existing infrastructure, climate conditions, and regional challenges. The studied area (Khuzestan province), which plays a significant role in the country's water, energy, and food resources, requires strategic modeling and optimization of water resource management decisions in the water, agricultural, and energy sectors to respond to the increasing demand resulting from economic growth and population growth. In this research, a model for sustainable water resource management was developed, and the system's behavior was simulated in a twenty-year horizon. Based on sensitivity analysis results, expert opinions, and decision-makers' input, the following strategies were identified as desirable and implementable in the long term:

- Development of irrigation and drainage networks for agricultural lands to increase irrigation efficiency by 18%.
- Modification of cropping patterns by 14% considering regional climate conditions, national food security, and crops with lower water requirements.
- Management to reduce pre-harvest, harvest, and post-harvest food losses by 8%.
- Modification of food consumption patterns for managing consumption losses and reducing food demand by 9%.
- Annual development of agricultural product performance by 10%, utilizing seed improvements, fertilizer use, and innovative cultivation methods.

For future research, the inclusion variables of virtual water, the development of a variable for modifying cropping patterns based on standardized plant water requirements and climate conditions, the consideration of wastewater reuse with gray water footprint, specifications related to land use and migration, and the impact of renewable and alternative energy sources on resource security and water quality are suggested.

Funding The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.

Data availability Datasets analyzed during the current study are available and can be given following a reasonable request from the corresponding author.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Ethics approval and consent to participate The authors herewith do confirm that this manuscript has not been published elsewhere and is not also under consideration by the other journals. The authors approve the presented manuscript and do agree with the submission under your management as the editor in chief of Applied Water Science. The current study was carried out under the University of Tehran, Department of Energy Systems Engineering, Tehran, Iran.

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