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Dynamic nexus between agricultural water consumption, economic growth and food security

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ABSTRACT

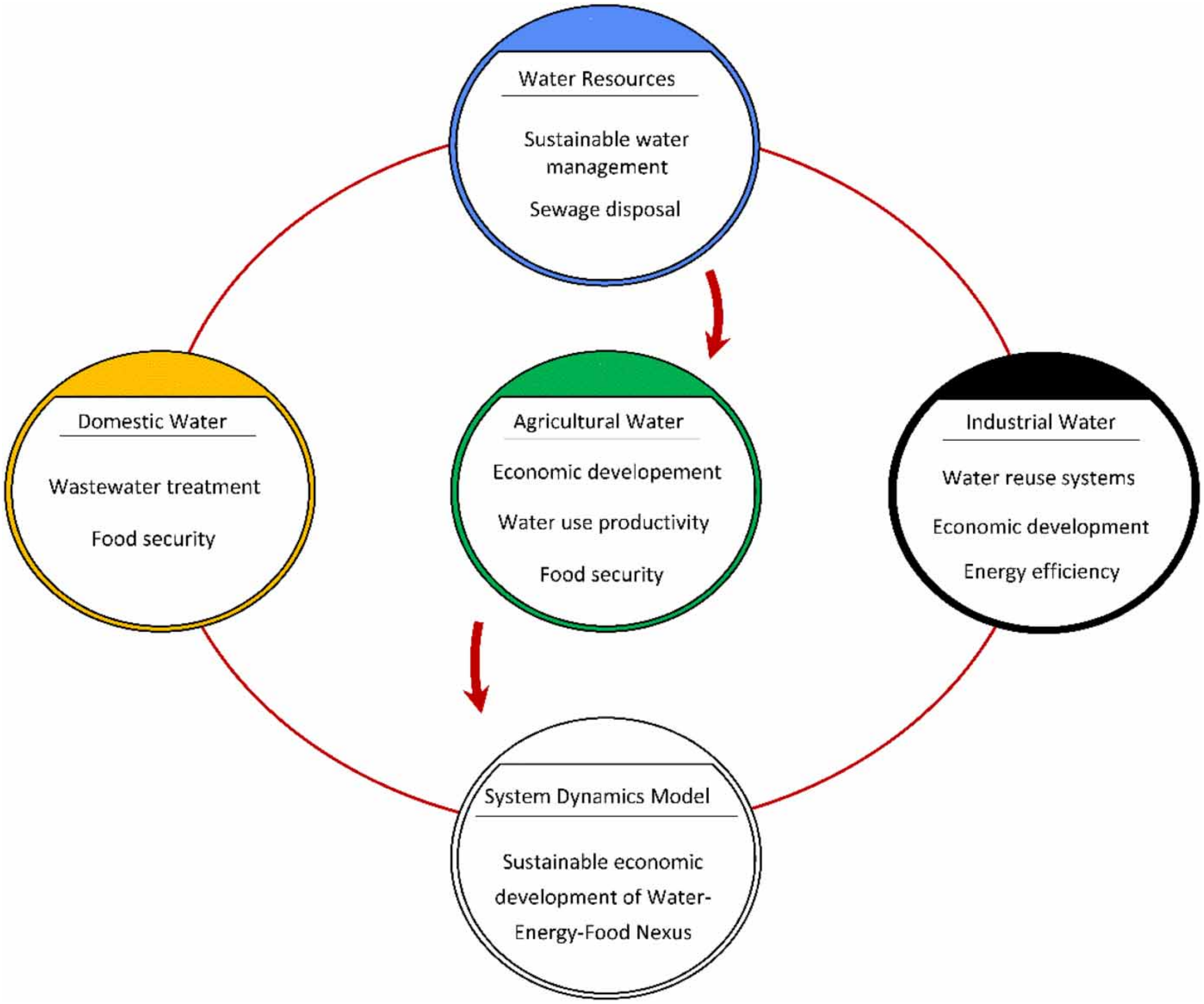
Water, energy and food (WEF) are important strategic resources for economic development in arid agriculture-based regions. Analyzing development indicators in the management of limited resources to achieve sustainability on a time scale is one of the basic goals of this research. Therefore, a system dynamics model was developed to analyze the WEF system resource flow relationship to achieve sustainable resource development. First, the subsystems of WEF resources were created and their dynamic relationship was formed in the form of a logical loop in a 10-year time frame. The evolution of 7 years (from 2015 to 2022) was taken into consideration to predict the 3-year period (from 2023 to 2025). The results showed that the reduction of water resources exploitation rate in China in interaction with agricultural productivity has automatically improved energy consumption and the nexus index. In China, a dynamic balance between WEF with a focus on water is recommended for planning.

Key words: nexus dynamics analysis, sustainable development, water resource, energy efficiency

HIGHLIGHTS

- A dynamic relationship is evaluated for the water, agriculture and economy nexus.
- The role of water and energy productivity in food security and industrial development has been analyzed.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Rapid population growth and expansion of cities and lifestyle changes have led to an unstable supply of water, energy and food (WEF) resources (Khayatnezhad *et al.* 2023). Researchers have concluded that the most important factor in changing the current approach to sustainable development is increasing productivity and reducing planning risk. In past studies, balance between the vital resources of WEF has been done with economic, social, ecosystem and environmental approaches (Murena *et al.* 2020). The challenges for planning are finding the relationship and logic between the parameters, which can be analytical, mathematical or simulation. Therefore, it is of great importance to accurately identify the effects of water–energy–food nexus (WEFN) coupling and mutual feedback on different types of water resource demand (Gao *et al.* 2023).

The territory of China is the second largest land area in the world. China is a populous country whose economic development is of great importance in accordance with urbanization and community growth. Serious problems in the supply and demand of resources may affect food security in the future. Population, especially in arid areas, has a high demand for water and energy resources, but the carrying capacity of the environment is limited, creating important challenges for sustainable development. Arable land resources in China are only about 10% of the drylands in the world, and a large amount of food is imported. Water resources are abundant, but its population is large, resulting in very low water consumption per capita, about 25% of the global average. Moreover, oil and other energy resources are also very scarce. Resource scarcity has affected economic development, and there is a mutually limiting relationship between WEF, which is related to sustainable development. System dynamics can demonstrate the flow relationships between different resources, and can be used to simulate the changes in system resources.

Water supply, energy balance and food security are interrelated and critical resources for environmental goals and human well-being (El Gafy *et al.* 2017). In recent years, the WEFN has been widely studied in different approaches. Water and food resources are the basis for the survival and development of oases in arid regions, while energy is the factor of production security and economic development (Banibayat *et al.* 2022). There are many interdependent and synergistic exchanges between water supply and food security, and both are important indicators and rulers for the sustainable development of the local natural and social economy. Energy and water systems are closely related, but energy and water resources policies are formulated separately. Long-term separate management makes the conflict between the two sources increasingly prominent (Zhang *et al.* 2019).

El Gafy *et al.* (2017) used a system dynamic model platform to develop a methodology for analysis of WEFN in a case study from Egypt considering crop production and consumption under different scenarios. Water and energy footprints of crop production and consumption, the national water and energy saving balance due to trade of agricultural commodities, virtual water and energy import and export, and a WEFN index were evaluated using the developed framework. Results showed the importance of considering the WEFN when developing national strategies. Zhang *et al.* (2019) evaluated the structural dynamics of the WEFN in arid areas from the water footprint perspective and the risk characteristics. The results showed that agricultural products account for the maximum values of water footprints higher than water footprints of energy consumption. Moreover, the water–energy risk coupling degree of the WEF system was comparatively significant, which means that it is facing the dual pressures of internal water shortage and external energy dependence. Ravar *et al.* (2020) developed a spatiotemporal disaggregated simulation model based on WEFN approach to assess water and food supply security considering ecosystem provisioning services in the Gavkhuni Basin in central Iran. Population, water, agriculture and energy modules were the main components of the simulation mechanism. The proposed policies were the most effective in changing the status of the WEF system and meeting the environmental demand. The results showed that the security of water supply and the status of energy subsystem in the basin were highly dependent on the food sector.

El-Gafy & Apul (2021) analyzed the concept WEFN based on environmental, economic and social aspects as well as life cycle assessment-based thinking. A set of environmental footprint assessment, life cycle assessment and socio-economic assessment indicators was proposed using a developed multidimensional dynamic system. The proposed model was applied to predict the corn production in the Western Lake Erie Basin-USA from 2016 to 2030. The prediction was based on scenarios for population, land, yield, crop use and crop production costs. This matrix could help to develop strategies for managing the nexus in the basin. Gao *et al.* (2023) developed a new relationship of the WEFN system by integrating the water footprint, which can identify water demand, water source type, water pollution rate and pollution type. Based on this link, a suitable WEFN system feedback model for arid regions was developed using a system dynamics approach. Taking Ningxia, China, as a case study, six future scenarios were designed and the development process of the WEFN system was simulated under different development scenarios to investigate the impact of different policies on WEFN. The resource-saving scenario and energy production restructuring adjustment scenario could effectively reduce the energy security problems caused by the rapid economic development.

WEF is affecting the sustainable development in China. The production of energy affects the quality of water resources, which in turn affects food production. The three resources interact and constrain each other. This article constructed a dynamic model for the sustainable development system of WEF, analyzed the water resource subsystem, energy subsystem and food subsystem, and their correlations, and simulated and predicted the relevant factors of the WEF system.

2. WATER, ENERGY AND FOOD NEXUS

2.1. Conceptual description

Resources and environment are the foundation of human survival, and reasonable and sustainable development while ensuring the quality of life is conducive to the long-term use of resources. However, with the increase in population and unreasonable use of resources, the ecological environment is getting worse and resources are facing shortages. Human survival cannot do without water and food, and the development of technology cannot do without the use of energy.

Development speed in China is very fast, but the rapid economic growth has caused great damage to the environment. China is facing a shortage of water resources. Water consumption per capita is below the world average, and the warming climate is also causing precipitation to decline. Many regions in China are facing water resource shortages.

Energy is the foundation of economic development, and economic development relies on resources such as oil and coal. However, oil and other resources are very scarce, and its economic development requires long-term import of energy. Moreover, the large-scale usage of fossil energy generates a lot of harmful gases and other pollutants, which cause great damage to the environment.

Food is the material foundation for human survival, but the increase in population requires more food supply, and the yield of food is related to social stability. In order to achieve sustained and stable development, it is necessary to adhere to sustainable development strategies. Sustainable development is a model based on the synergistic development of society, economy, population, resources and environment, which satisfies the needs of economic development without impacting on subsequent development. China has a large population and a great demand for resources. It is necessary for China to realize the sustainable development of WEF.

Water resources in China are not abundant and are very low per capita due to its large population base. This article obtains the water resources situation of some regions in China in 2003 from the National Bureau of Statistics. The water resource situation is shown in Table 1.

In Table 1, data statistics were collected on water resources in seven regions of China. Overall, water resources in southern China were relatively abundant, while water resources in northern China were relatively scarce. The total water resources in Jiangxi were 136.27 billion cubic meters, Beijing 1.84 billion cubic meters and Tianjin 1.06 billion cubic meters.

China is a major energy consumer, and its oil reserves are very scarce, which depends on imports. Economic growth cannot do without the use of energy, mainly relying on fossil fuels such as coal and oil. However, energy reserves are not very sufficient, and the use of energy causes serious environmental damage.

Food is the foundation of human survival, including rice, beans, coarse grains, etc. China has a very large population and a great demand for food. With the improvement of Chinese lives, meat products have been added to their dietary structure, which has led to the need to spend more agricultural feed on the aquaculture industry. Data from China National Bureau of Statistics show that water use from 2000 to 2023 is listed in Table 2.

In Table 2, the water use situation in China from 2000 to 2023 is described, and statistics are made on agricultural water use, industrial water use and domestic water use. The proportion of agricultural water was very large, with agricultural water accounting for over 60%.

Table 1 | Water resources balance in China

Region	Total water resources (100 MCM)	Surface water resources (100 MCM)	Groundwater resources (100 MCM)	Precipitation (100 MCM)	Availability of water resources (m^3/capita)
Beijing	18.4	6.1	14.8	76.1	127.8
Tianjin	10.6	6.2	4.8	69.9	105.1
Hebei	153.1	46.5	135.8	1,049.4	226.7
Shanxi	134.9	89.2	86.0	1,033.3	408.2
Anhui	1,083.0	1,038.1	252.3	2,037.5	1,699.1
Fujian	806.6	805.4	284.4	1,426.6	2,319.9
Jiangxi	1,298	1,365	346	2,238	3,119
China	27,460	26,250	8,299	60,415	2,131

Table 2 | Water use in China from 2000 to 2003

Water distribution	2000–2010	2011–2015	2016–2020	2021–2023
Proportion of agricultural water use	68.8%	68.7%	68.0%	64.5%
Proportion of industrial water consumption	20.7%	20.5%	20.8%	22.1%
Proportion of domestic water consumption	10.5%	10.8%	11.3%	11.9%

The production of food requires a lot of water resources for irrigation, and the use of energy to some extent pollutes water resources. Balancing the relationship between the three is the key to achieving sustainable development in China. Sustainable development is to ensure that human activities are within the ecological carrying capacity.

2.2. Construction of system

As the world population increases, the demand for resources becomes greater, and factors such as shortage of energy reserves and climate deterioration make the supply and demand for WEF unbalanced. The analysis of the sustainable development system of WEF is crucial for maintaining social stability, as the three types of resources are interrelated.

System dynamics is a method of studying the structure and function of a system, identifying the factors that affect the system from within and simulating its development laws. The WEF system is very complex, and the correlation between various subsystems is strong. Using system dynamics to analyze the flow relationship between different resources is beneficial for studying the sustainable development of the WEF system.

The WEF sustainable development system consists of three subsystems, and the research variables of the water resource subsystem mainly include various types of water resource consumption, such as agricultural water use. The energy subsystem is mainly composed of various forms of energy consumption and environmental pollution caused by energy use. The food subsystem mainly analyzes the production and use process of food.

Human daily life cannot do without the use of water. Whether it is laundry, cooking or drinking water, clean water resources are necessary. Irrigation in agriculture also requires water resources, and the growth of crops cannot be separated from water sources. In addition, the use of energy in industry also requires water. The supply of water resources is the foundation of social stability. The rapid growth of population has led to an increase in demand for water resources. The water resources subsystem causal loop is illustrated in Figure 1.

In Figure 1, the cycle of water resource consumption is described based on the WEF system. Economic development requires a large amount of water resources to support which is mainly used for industrial use, domestic use and agricultural irrigation. Domestic wastewater and industrial wastewater require sewage treatment. Energy is the foundation of economic development. The proportion of different forms of energy and the efficiency of energy utilization are analyzed. During the use of non-clean energy, many pollutants are generated, polluting the atmosphere and water sources. Therefore, it is necessary to manage the environmental pollution generated by energy use effectively.

In the agricultural subsystem, the storage capacity of food is composed of food production and foreign trade imports. Agricultural water is used to achieve food cultivation, and the productivity and water resources invested in food production are analyzed. The supply and demand of food determines the area of food grown, and food indirectly affects the amount of water used, population, etc. The dynamic model dynamically connects the influencing factors in the system and analyzes the results under different connection methods. The factors contained within the WEF system are very diverse and can form the following circuits. Economic development leads to energy use, which leads to industrial wastewater. Wastewater discharge enhances wastewater treatment capacity, thereby reducing population death and promoting economic growth. This is a positive feedback loop that enhances economic growth capabilities through wastewater treatment. The population increase causes an increase in the use of domestic use, resulting in a large amount of domestic wastewater, which causes environmental pollution and leads to an increase in the mortality rate of the population. Increasing food production can cause the total inventory to increase, leading to a decrease in market food prices and subsequent reduction in food planting area, thus leading to a reduction in food production.

The rapid growth of the population causes the speed of economic development to become faster, and economic development requires a large amount of energy use, which in turn generates a large amount of pollutants, leading to an increase in the population mortality rate. From these circuits, it can be observed that many factors affect the entire WEF system, and different subsystems are interconnected. By simulating the system loop, the development form of the system can be predicted, thereby achieving sustainable development of the WEF system.

2.3. Dynamics model

In evaluating the correlation between water and agriculture, there is a fundamental factor that plays an important role in the economy as a strategic component. This situation on a global geopolitical scale and in developed countries, where the need for oil and gas is increasing, has forced the world to pay attention to a category called energy security and to adopt a solution on how to provide it.

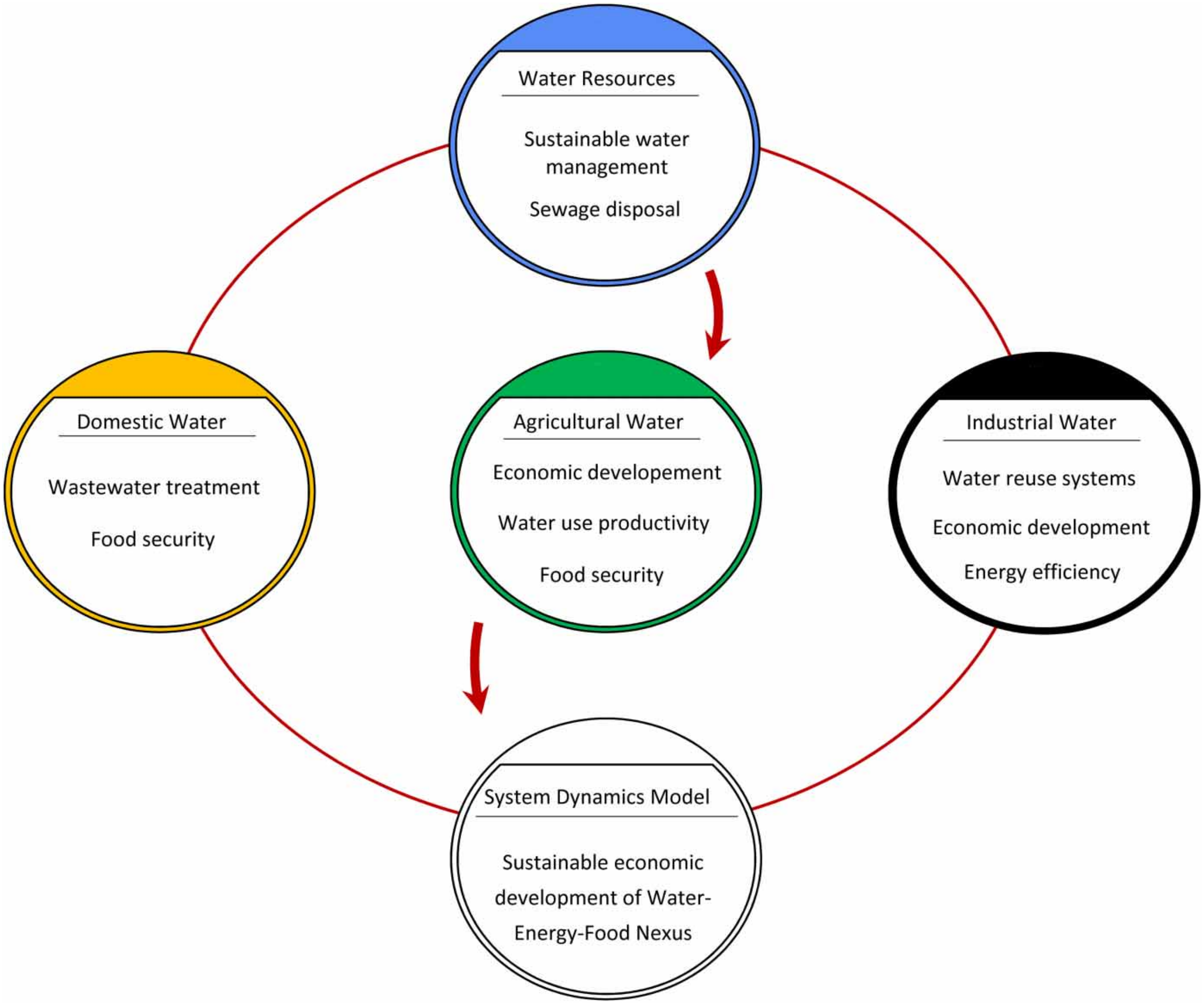


Figure 1 | Causal cycle diagram of water resources subsystem.

Identifying different aspects of energy security and its relationship with water and agriculture is of special importance. Therefore, the structure of the dynamic model of water, agriculture and energy are shown in Figure 2.

After explaining the conceptual model of WEFN, quantitative relationships were developed for comparable evaluation. The economic productivity of water at time t in the agricultural sector is calculated as follows:

$$P_a = \frac{\sum_{c=1}^{m} [B - C]_c}{\sum_{c=1}^{n} W} \tag{1}$$

where P_a is the economic productivity of water in the agricultural sector (USD/m^3), B is the value of the yield produced (USD/ha) and C is the cost of production (USD/ha) and W is the amount of water used in the agricultural sector (m^3/ha).

Another parameter evaluated was the efficiency of energy saving in the agricultural sector, which was calculated as follows:

$$P_e = \frac{\sum_{c=1}^{m} [B - C]_c}{\sum_{c=1}^{n} E} \tag{2}$$

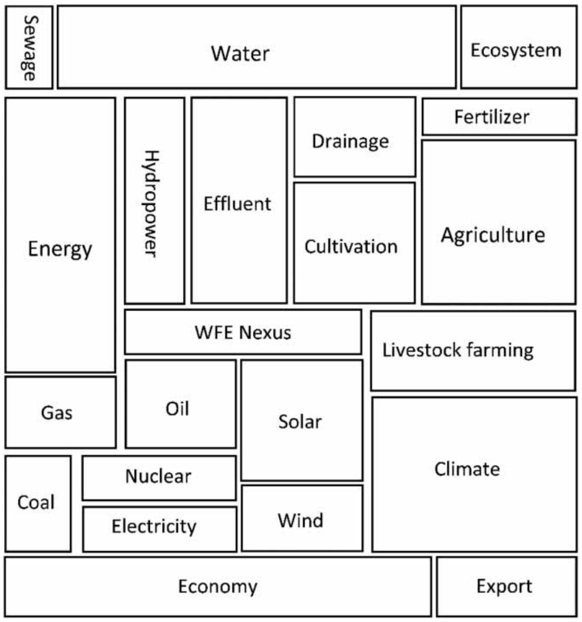


Figure 2 | Dynamic nexus between agriculture, water and energy.

where P_e is the economic productivity of energy in the agricultural sector (USD/J) and E is the amount of energy used for agricultural production (J/ha).

Based on this concept, the WEFN index can be presented based on the economic efficiency of this nexus as follows:

$$P_{\text{Nexus}} = \sum_{i=1}^{n} w_i[x - \min(x)]_i / \sum_{c=1}^{n} [\max(x) - \min(x)]_i / \sum_{i=1}^{n} w_i \tag{3}$$

where P_{Nexus} indicates the WEF linkage index from the point of view of productivity, i shows the weight of each index compared to the total index. In the developed equation, variable x is standardized.

2.4. Indicator analysis

Indicator analysis is a mechanism to establish a framework for evaluating the role of water and energy resources in the nexus system. The problem is established as a nonlinear programming. The specific modeling steps are as follows.

Decision variables: Decision variables refer to variables that can be adjusted to optimize water resources, such as the amount of water allocated to each consumer.

Constraints: Constraints refer to the conditions that must be met in allocating water resources, such as the supply–demand balance of each water resource, and the guarantee rate of water resources (Rahmani *et al.* 2022).

Objective function: The objective function refers to the optimal goal of water resource allocation, such as minimizing total costs, maximizing water resource utilization efficiency, etc. P_{Nexus} was evaluated as an objective function to optimize the water and energy parameters.

Mathematical modeling: Decision variables, constraints and objective functions are converted into mathematical expressions, establishing linear programming problems or mixed integer linear programming problems. The mathematical model is solved using the Push-Relabel algorithm.

The Push-Relabel algorithm is the algorithm with the highest asymptotic efficiency and fastest implementation among maximum flow algorithms. It can solve the maximum flow problem in a network, which is to find the maximum flow from the source point to the sink point in a given network.

In summary, the Push-Relabel algorithm is widely used in wastewater discharge and water resource allocation problems, which can help decision-makers to formulate scientific and reasonable plans to improve the efficiency of wastewater and water resource utilization and reduce pollution and damage to the environment.

It introduces several new concepts: $H = (C, R)$ is set as a flow network with a source point of d and a sink point of u, given a capacity of v and a flow of g.

Preflow: A function g of $C \times C \rightarrow T$ satisfies capacity limitations and the following properties:

$$\sum_{c \in C} g(c, i) - \sum_{c \in C} g(i, c) \geq 0, i \in C - \{d\} \tag{4}$$

i represents an intermediate node, which means that the flow allowed to flow in during the algorithm process is greater than the flow allowed to flow out.

Excess flow: the portion of flow that a node inflow exceeds outflow, namely:

$$r(i) = \sum_{c \in C} g(c, i) - \sum_{c \in C} g(i, c) \tag{5}$$

The algorithm allows nodes to temporarily store traffic and if $r(i) > 0$, it is called node i overflow.

Node height: Each node has a height of j. The height of the source node is defined as $|C|$. The height of the sink point is set as 0 and the initial height of the intermediate node is set as 0, which continuously increases during the calculation process. The flow can only flow from high to low and nodes with high heights push the flow towards nodes with low heights.

Active point: a node that simultaneously meets the following conditions:

$$r(i) > 0 \text{ and } i \in V - \{d, u\} \tag{6}$$

Node i is an intermediate node and has overflow, which requires basic operations.

The Push-Relabel algorithm includes two basic operations, namely the 'push' operation and the 'relabel' operation. To obtain maximum traffic, both operations are performed in an uncertain order and under certain circumstances.

Overall, the network flow algorithm is a very vital algorithm that has been extensively used in many practical problems.

3. RESULTS

3.1. Error analysis

With the rapid growth of population and excessive use of resources, the climate and environment have deteriorated, posing serious challenges to sustainable development strategies. Rapid economic development in China relies on the use of energy and the supply of water and food, which are important resources for achieving sustainable development. However, there is a close correlation between the three resources. For example, economic development requires the supply of energy, and the extensive use of energy causes water pollution, which reduces food production.

To achieve the sustainable development of the WEF system, this article establishes a system dynamics model to simulate, predict and analyze resources. This article selects historical data from China from 2000 to 2022 for analysis, which is related to water resources, energy and food. The selected indicators include (1) food security, (2) energy supply, (3) water resource consumption, (4) population growth, (5) gross domestic product and (6) environmental pollution. If there is data loss for certain years in the selected historical resource data, SPSS software can be used to fit the missing variables.

This article uses a system dynamics model to analyze the WEF system. When the model has high simulation accuracy, it can be used to predict the development trend of resources. To verify the validity of the model, some of the indicators affecting the WEF system are analyzed in this paper. The simulation errors of the system dynamics model are shown in Figure 3. The error of the model is primarily a test of whether the fitted results meet the criteria for historical data development. When the error is within 5%, it indicates that the prediction results of the model have reference significance.

In Figure 3, the model simulation errors are optimized and described. Six related indicators in the WEF system were analyzed for simulation error, and the error of all indicators was less than 5%, indicating that the model has high-precision simulation capability. Among them, the fitting analysis of water resource consumption was the most accurate, with an error of only 0.75%, and the simulation error of population growth was 4.6%. The system dynamics model constructed in this study has the ability to simulate data changes in the WEF system, and can be applied to actual scenarios in China. By

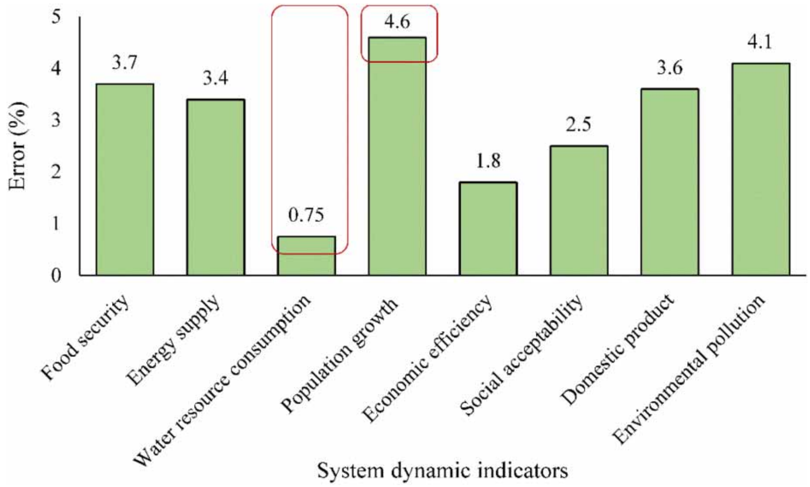


Figure 3 | Simulation error of the system dynamics model.

predicting and analyzing changes in WEF resources, reasonable control can be achieved, thereby achieving sustainable development of resources (Poças *et al.* 2020; Negi *et al.* 2021).

3.2. Water resource consumption

Water resources are considered as one of the main components of human life and survival. Health, livelihood, food security and urbanization development are closely related to water supply. There are dry parts, especially in the northern plains of China. Rational use of water resources is the basis for achieving sustainable development. Figure 4 shows the trend of changes in water consumption in three sectors: domestic, agricultural and industrial, which are directly related to energy and food security. The results for the years 2022 to 2025 are obtained based on dynamic analysis. Naij showed that in the coming years, the development of industries should be accompanied by increasing productivity in order to be able to respond to dry conditions.

3.3. Water and energy productivity

Economic development by providing the required water in the industrial sector is a higher priority. Although agriculture is not considered an acceptable option for future development from an economic point of view, it can play a role in food security, which is an essential factor. Investment in agriculture is one of the components of sustainable development. Figure 5

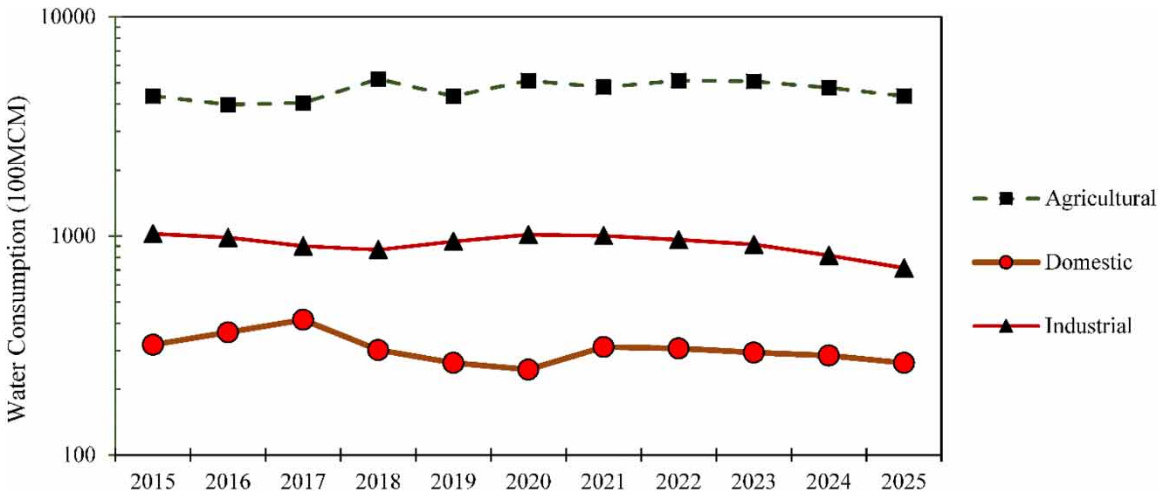


Figure 4 | Prediction results of water resource consumption.

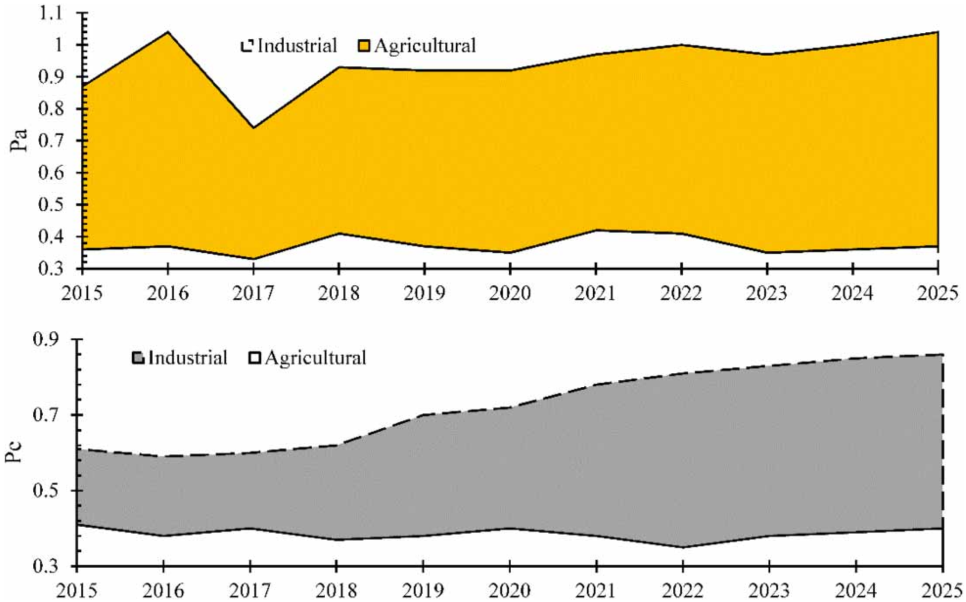


Figure 5 | Water (Pa) and energy productivity (Pe) for developing industrial and agricultural sections.

shows the comparison of economic productivity in industries and agriculture. The economic efficiency of water in agriculture and energy efficiency in industry are the most important parameters that can be focused on for their planning. Past research has shown that industrial development without considering food security will not lead to sustainable development.

4. CONCLUSIONS

Creating a logical connection between the processes involved in a planning system can lead to sustainable development indicators. Analyzing conceptual models based on dynamic rules will provide the necessary flexibility in decision making. Today, food security, water resources and energy supply have common approaches, which are the main structure of economic and social development of people. Unplanned energy use reduces water quality and food production and creates economic failure. To achieve the sustainable development of the WEFN, a system dynamics model has been built and the cyclical processes of various factors in the WEF system have been analyzed. This paper used a system dynamics model to predict changes in China from 2015 to 2025. The prediction results showed that industrial and domestic water consumption in China is steadily decreasing and energy consumption is constantly increasing. Food stocks were constantly increasing and imported food was also increasing. China economy was improving, but the risk of water and energy shortages was increasing year by year. This paper analyzes future economic growth through simulation forecasting. However, the energy usage is not reasonable enough. To achieve sustainable development of the Chinese economy, China needs to strongly develop clean energy and improve the use of energy and water resources. One of the limitations of this research is the short-term forecasting period, which in future research should increase the accuracy of forecasts by adding economic indicators and micro-scale information of water and energy resources.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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