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Article

Simulation Study on the Different Policies of Jiangsu Province for a Dynamic Balance of Water Resources under the Water–Energy–Food Nexus

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Abstract: In order to promote the efficient use of resources and the sustainable development of the economy in Jiangsu Province, it is particularly important to ease the contradiction between water supply and demand on the basis of realizing the coordinated development of the water–energy–food (WEF) nexus. With the aim of a dynamic balance of water resources, this paper used system dynamics (SD) to build a WEF nexus SD model that focused on studying the specific supply-and-demand mechanism of water resources in each subsystem. Then, Jiangsu Province was taken as an example to perform simulation research on the regional water dynamic balance to explore effective policies for increasing water supply and decreasing water demand. The results showed that the imbalance of water resources will remain severe in the next few years. To relieve the imbalance, it will be helpful to promote the energy utilization of straw, improve the irrigation efficiency, adjust the crop planting structure, and require residents to strictly follow the water quota. An important advancement in this study is the simulation of the water resources supply-and-demand mechanism in each subsystem from the perspective of the WEF nexus.

Keywords: water–energy–food nexus; water resource dynamic balance; system dynamic; scenario simulation

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1. Introduction

Water, energy, and food are important basic resources for the survival and development of human beings, and they are also necessary conditions and important supports for the sustainable development of society. Water resources are also an important part of the environmental system. There is a close and intricate relationship among water, energy, and food; they coordinate with each other to form a multi-variable coupling, reciprocal, dynamic system, and the coordinated development of them will play a positive role in human survival and development under the widely accepted background of global warming, which is associated with climate change and vegetation phenology [1]. However, as a province that has abundant water resources, consumes a large quantity of energy, and also is a major food-producing region, Jiangsu Province has faced an increasingly serious problem of imbalance in the supply and demand of water resources under the influence of discordant development of the water–energy–food nexus in the context of population growth, resource shortages, and environmental degradation. To be specific, the total amount of water resources in Jiangsu is abundant, whereas the utilization rate for water resources and water quality are not high, and the per capita share of water resources are not large, which in turn leads to an aggravation of the contradiction between the supply and demand of domestic water. Moreover, large amounts of water are consumed in the process of energy production and food irrigation, which also deepens the imbalance of water resources in Jiangsu. Therefore, it is particularly important to alleviate the contradiction between water supply and demand in Jiangsu and maintain the balance between water supply and demand on the basis of effectively coordinating the relationship between water, energy, and food.

Current research on the dynamic and balanced development of regional water resources are generally conducted in terms of total amount management, water supply capacity, water resources allocation, and sustainability of water supply and demand. With respect to total water resources management, a dynamic equilibrium model to control the total amount of water resources was used to carry out research on the dynamic balance management of water resources [2]. With respect to water supply capacity, the principle of the three supply and demand balances of water resources was applied to solve the problem of the imbalance between water supply and demand [3]. With respect to water resources allocation, the problem of water supply-and-demand balance can be solved by rationally optimizing the allocation of water resources. Specifically, some methods like prospect theory, two-stage stochastic programming method, and improved grey prediction theory were used to optimize the allocation of water resources [4–6]. Additionally, some studies focused on agriculture and analyzed the regional agricultural water resources supply–demand balance to improve irrigation water consumption efficiency [7]. In addition, some studies focused on the ecological environment and studied the imbalance of water resources encountered in sustainable urban management [8]. With respect to the sustainability of water supply and demand, some studies estimated the sustainable level of water supply and demand for planning the water system in preparation for future development [9,10]. What is more, many studies chose specific industries as research objects and studied their dynamic balance of water supply and demand [11,12]. Among them, there is a study linking water resources to energy and food, and it analyzes the sustainability of energy and water use during food production based on the optimal allocation of agricultural irrigation water [13].

In recent years, the concept of the water–energy–food nexus has been continuously enriched, and research into this nexus has gradually deepened. Many noted practical nexus modelling tools have been proposed, such as the water supply model, power generation and environment (WPE) model, agent-based modeling (ABM) framework, and water–energy–food (WEF) nexus simulation optimization (WEFSiM-opt) model [14–16]. Current research on the WEF nexus is generally conducted in terms of efficiency analysis, coordinated development, risk control, and sustainable development assessment. With respect to efficiency analysis, the structural path analysis method and data envelopment analysis method were used to study the input–output efficiency of the WEF nexus to improve the efficiency of resource utilization [17,18]. With respect to coordinated development, analysis of the coupling and coordination degrees of the WEF nexus was carried out to measure the level of coordinated development of the WEF nexus, thereby optimizing its coordinated development capability and enhancing the coordinated security guarantee capability [19–21]. With respect to risk regulation, technologies such as remote sensing and integrated resource management were used in safety and risk prevention of the WEF nexus to enhance its risk management and control capabilities [22]. With respect to sustainable development assessment, a step-by-step methodological approach was proposed for sustainability assessment [23].

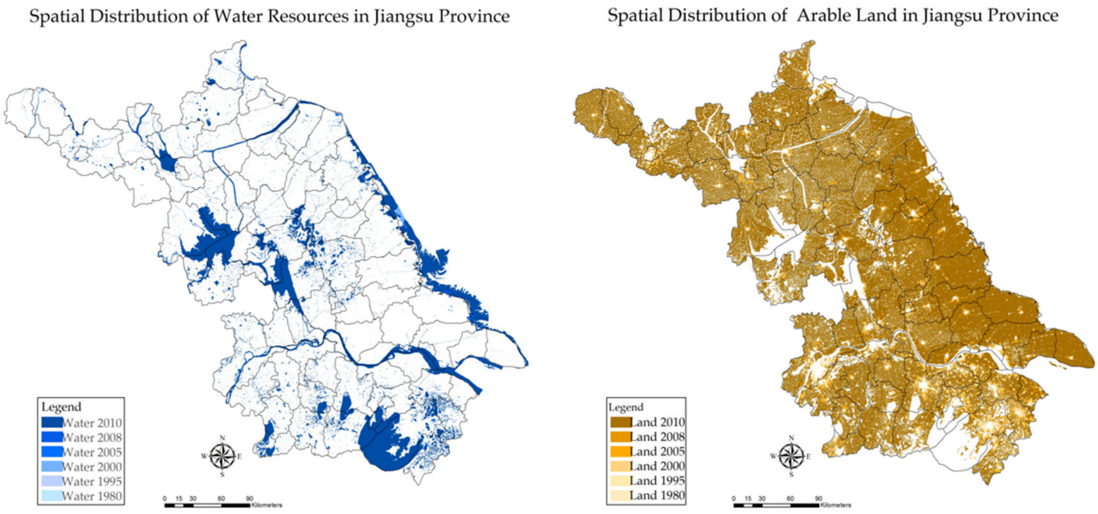
It has been concluded that most of the research on the dynamic balance of water resources is mainly from a macro perspective or within a single industry. What is more, on the study of the balance of water resources, little consideration has been given to the inefficient use of water in different production activities and the necessity of synergy development between different industries. Given the above research, this paper was the very first work to analyze the coordinated development of the water–energy–food nexus and explore effective, relevant policies for the water used in energy and food production to maintain the balance between supply and demand. Therefore, with the aim of the dynamic balance of water resources, this paper fully considered the intricate connections between WEF and used the principles and methods of system dynamics to build a WEF nexus system dynamics (SD) model. To be specific, the WEF nexus SD model combined the external social system, economic system, and eco-environmental system and focused more on studying the specific supply and demand mechanism of water resources in each subsystem. After building the model, a simulation study on the different policies of dynamic balance of Jiangsu Province's water resources was performed to explore effective relevant policies for increasing water supply and decreasing water demand to maintain the balance between supply and demand. In terms of study area, this study selected Jiangsu Province as the research object with the aim of exploring how to coordinate the relationship between water, energy, and food in economically developed regions, and exploring how to make their water resources balanced so as to better promote the efficient use of resources and the sustainable development of the society and economy.

2. Materials and Methods

2.1. Study Area

Jiangsu Province is located on the eastern coast of mainland China, bounded by 30°45′–35°20′ N and 116°18′–121°57′ E, with a total area of 102,600 km^2. In terms of topography, the landforms of Jiangsu are relatively simple, dominated by plains, which account for 69% of the province's area. In terms of climate, Jiangsu is located in the transition zone between the subtropical monsoon climate and the warm temperate monsoon climate. The annual average temperature of Jiangsu is between 13 and 16 °C, and the average annual rainfall of Jiangsu is about 1000 mm [24]. In terms of economy, Jiangsu's regional economic comprehensive competitiveness ranks first in mainland China. By the end of 2019, Jiangsu's permanent population was 80.70 million, regional GDP reached 9963.15 billion yuan, and regional development and people's livelihood index ranked at the forefront of the country [25].

In terms of water resources, Jiangsu Province spans the two major river systems, the Yangtze River and the Huai River, and has dense river networks and abundant water resources. The average total amount of water resources in the province for many years has been 32.3 billion m^3. The total amount of water resources in Jiangsu is considerable, but the per capita share of it is not large. The transit water resources are sufficient, but the local water resources are insufficient. Water pollution is serious, and the quality of water resources is not high. The spatial distribution of water resources in Jiangsu Province is shown in Figure 1a, which reflects the current distribution of water resources and the geographical distribution laws of water resources in Jiangsu Province. Water resources mainly include rivers, lakes, reservoirs, ponds, and tidal flats [26]. In terms of energy, Jiangsu Province is a large energy-consuming province, of which the total energy consumption of the province in 2018 reached 314.3041 million tce (tce is the English abbreviation for tons of standard coal equivalent) [27]. However, Jiangsu is a province with low energy production, and its energy resources are relatively scarce. Consequently, the energy utilization situation in Jiangsu Province has obvious characteristics, such as the prominent contradiction between energy supply and demand and the unreasonable energy consumption structure. In terms of food, as a major agricultural province, Jiangsu Province's capability for a food security guarantee is continuously strengthened to ensure the balance of food supply and demand in the province. The sown area of food crops in the province is 5381 thousand hectares, and the total output of food crops reached 37.062 million tons in 2019 [25]. According to the "Jiangsu Statistical Yearbook", the main food crops grown in Jiangsu Province are wheat, rice, corn, and soybeans; the planting area of these four crops in Jiangsu Province accounted for about 95–97% of the total food crop planting area, and the total output of these four food crops accounted for about 96–98% of the province's total food crops output in recent years. The spatial distribution of arable land in Jiangsu Province is shown in Figure 1b, which reflects the current status of arable land distribution and geographical distribution law of arable land in Jiangsu Province. Arable land is divided into paddy fields and dry land [26].



(**a**) (**b**)

Figure 1. Water resources and arable land in Jiangsu Province: (**a**) Spatial distribution of water resources in Jiangsu Province; (**b**) Spatial distribution of arable land in Jiangsu Province.

2.2. Study Method

The water–energy–food nexus is a dynamic mutual feedback system formed by the combination of multiple factors, and more predictions need to be made about the development of the security status of water resources, energy, and food. Moreover, these predictions are made on the basis of continuous communication and feedback between various factors inside and outside the system. Therefore, this paper used system dynamics to build an SD model of the water–energy–food nexus with the goal of a dynamic balance of water resources.

System dynamics is an approach proposed by Professor Forrest of the Massachusetts Institute of Technology in the 1950s. It is mainly used to study information feedback in dynamic systems and analyze the interaction between various time-varying variables in the system [28]. Models built by using the principles of system dynamics can be used for mid-term and long-term simulation and prediction of the system and its future development trends. The steps of system dynamics to solve practical problems are generally as follows: determine the research problem; build a model that has been validated on the basis of clear model boundaries and structure; and finally set up different scenarios for policy simulation research according to the research needs and select the best option to improve the solution of actual problems. In terms of specific operation, there are many software programs and languages for creating and modeling SD models, among which, Vensim software has the ability to graphically illustrate the SD model, has a very good data set analysis function, and has high authenticity. The characteristics mentioned above are obviously different from other system dynamics software packages and languages, so this study selected the Vensim PLE v8.0.9 software package for modeling and simulation (Producer: Ventana Systems, Inc. Harvard, MA, USA) [29].

2.3. Conceptual Structure Analysis of the System

The operation processes of water resources development and utilization, energy development, and food production in the WEF nexus system not only depend on their own internal structure, but also are affected by external environmental variables. The input of external factors such as population size, urbanization level, and economic development level in the social and economic systems into the WEF nexus system will affect the production volume and production structure of WEF, thereby changing internal system of the WEF. In turn, the WEF nexus system will produce pollution during resource production that will be exported to the external eco-environment system, which will have an impact on climate and ecology, thereby affecting the water–energy–food supply quality. Therefore, during construction of the WEF nexus SD system, it was necessary to consider the complex correlation between the water–energy–food system and external systems such as society, economy, and eco-environment. Particularly, the WEF nexus SD system in this study addresses the problem of fuzzy boundaries between water, energy, and food subsystems and focuses on delineating the mechanism of water supply and demand in the energy subsystem, food subsystem, social subsystem, economic subsystem. and eco-environmental subsystem, which is different from previous studies [30–33]. The construction framework of the WEF nexus SD model is shown in Figure 2.

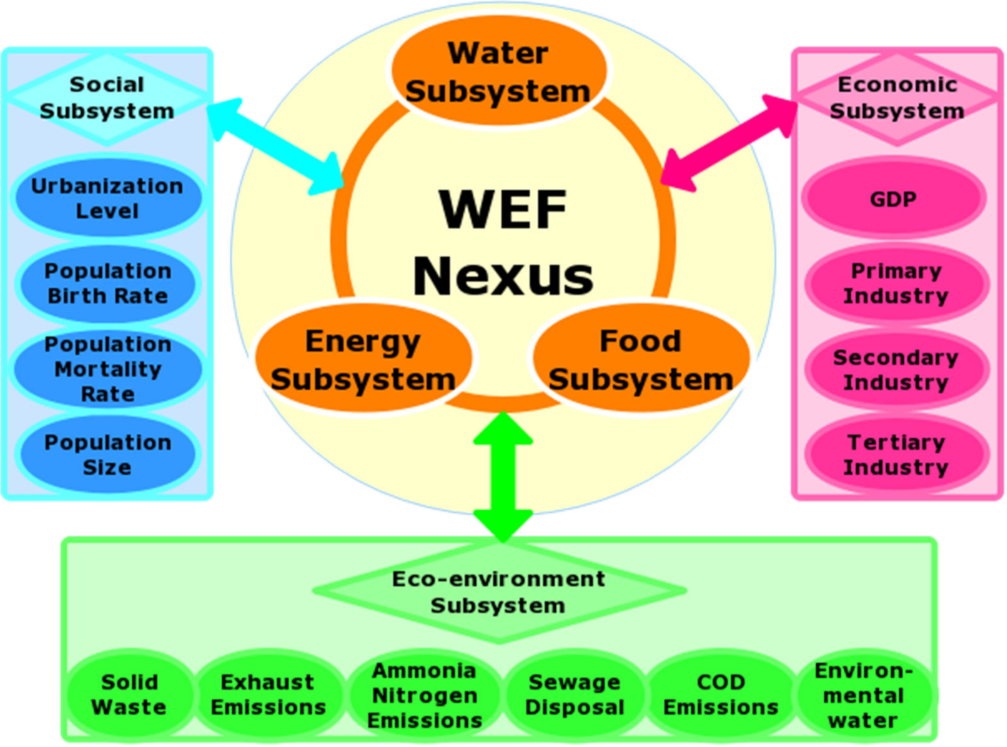


Figure 2. Framework of the water–energy–food (WEF) nexus system dynamics (SD) model.

2.3.1. Conceptual Structure of the Water Subsystem

As the core system of the research model, the water resource subsystem is composed of two parts: water supply and water demand. With respect to water demand, the demand for water resources is divided into production water, ecological water, and domestic water. With respect to water supply, available water resources come from the local surface water supply, groundwater supply, and recycled water supply. All in all, the water subsystem specifically reflects the dynamic balance of water resources through the close relationship between total water demand and total water supply. The causal loop diagram of the specific water subsystem is shown in Figure 3. The external social, economic, and eco-environment subsystems are also included in it. To be specific, the main social factor that affects the WEF nexus is total population, and the main economic factor is gross domestic product (GDP). Furthermore, the eco-environmental subsystem mainly consists of two aspects: ecological water demand and water pollution. Figure 3 illustrates the situation of domestic water consumption (B1, B2) and production water consumption (B3–B5). In addition, Figure 3 shows the circulation process of water resources in the social–eco-environmental coupling system (R1, R2) and the economic–eco-environmental coupling system (R3–R5).

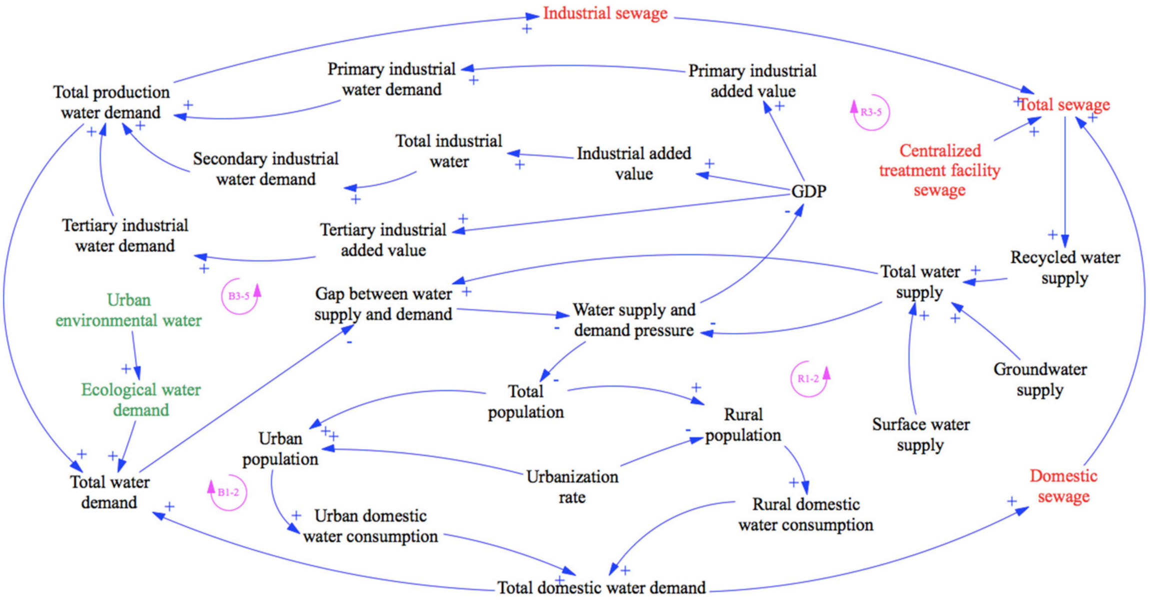


Figure 3. Water subsystem causal loop diagram.

2.3.2. Conceptual Structures of the Energy and Food Subsystems

This study built the WEF nexus SD model with the goal of dynamic balance of the water resources by improving the scientific and efficient use of water in the process of energy and food production, therefore, we focused on the energy subsystem and the food subsystem in this study of how the water is used in energy and food production.

The energy subsystem selects primary energy and power energy as the research objects and main elements of this subsystem. Primary energy is specifically divided into raw coal, crude oil, and natural gas, and primary energy production water is classified into general industrial production water, which constitutes industrial water, and power industry water. The causal loop diagram of the specific energy subsystem is shown in the right half of Figure 4, which delineates the mechanism of water use in the energy subsystem.

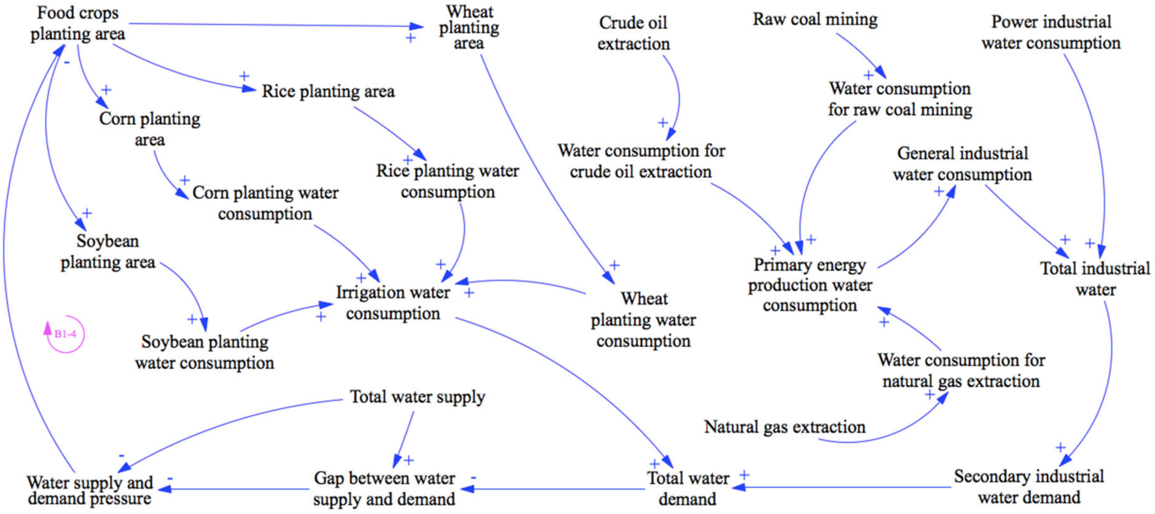


Figure 4. Causal loop diagram of the energy and food subsystems.

The food subsystem selects the four main food crops of wheat, rice, corn, and soybean as the research objects according to the planting structure and scale of food crops. What is more, the production of these four main foods plays an absolute role in the water consumption by irrigation.

Additionally, the water requirement of each food crop is determined by the planting area of the food crop and the water consumption per hectare of the food crop planting. The causal loop diagram of the specific food subsystem is shown in the left half of Figure 4, which delineates the mechanism of water use in the food subsystem. Figure 4 illustrates water consumption for the irrigation situation of the four major food crops (B1–B4).

2.4. Model Building

2.4.1. Model Building of the Water Subsystem

The data on water resources were mainly from the "Jiangsu Statistical Yearbook" (2011 to 2019), the "Jiangsu Water Resources Bulletin" (2010–2018), and the "Jiangsu Environmental Status Bulletin" (2010 to 2018). Some years' data on water resources are missing, so this study used the average method to interpolate and fill in the gaps.

In this subsystem, the gap between water supply and demand (GWSD) is the state variable to measure the dynamic balance of water resources, which is defined as follows:

$$GWSD = TWS - TWD \tag{1}$$

where TWS represents the total water supply that is the sum of the groundwater supply, surface water supply, and recycled water; TWD represents the total water demand that is the sum of the total production water demand, ecological water demand, and domestic water demand.

2.4.2. Model Building of the Energy Subsystem

Energy data mainly came from the "Jiangsu Statistical Yearbook" (2011 to 2019), the "Chinese Energy Statistical Yearbook" (2017), and some websites such as the Guanyan Network, International Energy Network, International Solar Photovoltaic Network, International Gas Network, China Industry Competitive Intelligence Network, and China Industry Information Network. The data of power industries' water consumption came from the "Jiangsu Water Resources Bulletin" (2010 to 2018). The water demand data on various energy industries were derived from the "Jiangsu Industrial Water Quota" and Xiang's research [34]. The main parameter values of the energy subsystem are shown in Table 1.

Table 1. Main parameter values of the energy subsystem.

Constant Variable	Unit	Parameter Value
Water consumption per unit raw coal mining	m^3/t	0.75
Water consumption per unit crude oil extraction	m^3/t	5
Water consumption per unit natural gas extraction	m^3/m^3	0.002

In this subsystem, total industrial water consumption (TIWC) was the main component of the secondary industrial water demand, which is defined as follows:

$$TIWC = PIWC + GIWC \tag{2}$$

where $PIWC$ represents power industries' water consumption; $GIWC$ represents the general industrial water consumption, which mainly consists of water consumption for natural gas extraction, raw coal mining, and crude oil extraction.

2.4.3. Model Building of the Food Subsystem

The food data were mainly from the "Jiangsu Statistical Yearbook" (2011 to 2019). Data for the water consumption per hectare from food crop planting is derived from Xu's research [35]. The main parameter values of the food subsystem are shown in Table 2.

Table 2. Main parameter values of the food subsystem.

Constant Variable	Unit	Parameter Value
Wheat planting's water consumption per hectare	m^3/hm^2	1814.09
Rice planting's water consumption per hectare	m^3/hm^2	4632.68
Corn planting's water consumption per hectare	m^3/hm^2	1214.39
Soybean planting's water consumption per hectare	m^3/hm^2	1034.48

In this subsystem, irrigation water demand (IWD) is the main component of the primary industrial water demand, which is defined as follows:

$$IWD = IWC/IWCC \tag{3}$$

where *IWC* represents irrigation water consumption, which includes water consumption of the four major food crops planting; *IWCC* represents the irrigation water consumption coefficient.

In addition, in this subsystem, there is a level variable, food crop planting area (FCPA), that is defined as follows:

$$FCPA = \int (FAG)dt + A_i \tag{4}$$

where *FAG* represents food crops planting area growth; A_i represents initial food crops planting area.

2.4.4. Model Building of the External Subsystems

Data on society and economy mainly came from the "Jiangsu Statistical Yearbook" (2011 to 2019). The ecological water demand in Jiangsu mainly comes from urban environmental water consumption, so the ecological water demand in this study was replaced by the urban environmental water consumption. In terms of sewage treatment, due to the lack of data, this article assumed that all the recycled water in Jiangsu Province comes from sewage treatment. What needs to be explained is that the sewage reuse rate is the ratio of the total amount of sewage to the recycled water.

In the social subsystem, total domestic water demand (TDWD) is the main component of total water demand, which is defined as follows:

$$TDWD = RDWC + UDWC \tag{5}$$

where *RDWC* represents the rural domestic water consumption; *UDWC* represents the urban domestic water consumption.

In addition, in this subsystem, there is a level variable, total population (TP), that is defined as follows:

$$TP = \int (PG)dt + P_i \tag{6}$$

where *PG* represents population growth; P_i represents initial population.

In the economic subsystem, total production water demand (TPWD) is the main component of total water demand, which is defined as follows:

$$TPWD = PIWD + SIWD + TIWD \tag{7}$$

where *PIWD*, *SIWD,* and *TIWD* represent the primary, secondary, and tertiary industrial water demands. In this study area, the primary industrial water is obtained from agricultural water, and the secondary industrial water is obtained from industrial water.

In addition, in this subsystem, there is a level variable, GDP, that is defined as follows:

$$GDP = \int (GDPG)dt + G_i \tag{8}$$

where *GDPG* represents GDP growth; G_i represents initial GDP.

In the eco-environmental subsystem, recycled water (RW) is the main component of total water supply, which is defined as follows:

$$RW = TS \times SRR \tag{9}$$

where TS represents total sewage; SRR represents the sewage reuse rate.

2.4.5. Model Building of the WEF Nexus

Firstly, according to the administrative divisions of China, the geographical space of the whole Jiangsu Province was taken as the system boundary. In consideration of the current situation and development trends of Jiangsu Province, this system selected 2010 as the historical benchmark year, 2019 as the forecast benchmark year, 2010–2018 as the historical examination period, and 2019–2023 as the simulation and prediction period. Additionally, the simulation step set by the model was 1 year.

Then, the system dynamics model of the WEF nexus was built with the system dynamics Vensim software. Fully considering the internal correlation of the WEF nexus and combining the factors related to water resources in the external social subsystem, economic subsystem, and eco-environmental subsystem, the water subsystem was selected as the model core, and then the stock and flow diagram of the WEF nexus was created by integrating and modifying the above-mentioned subsystems, which not only show the type and property of each variable, but also show the specific situation of each variable changing over time. The specific stock and flow diagram is shown in Figure 5.

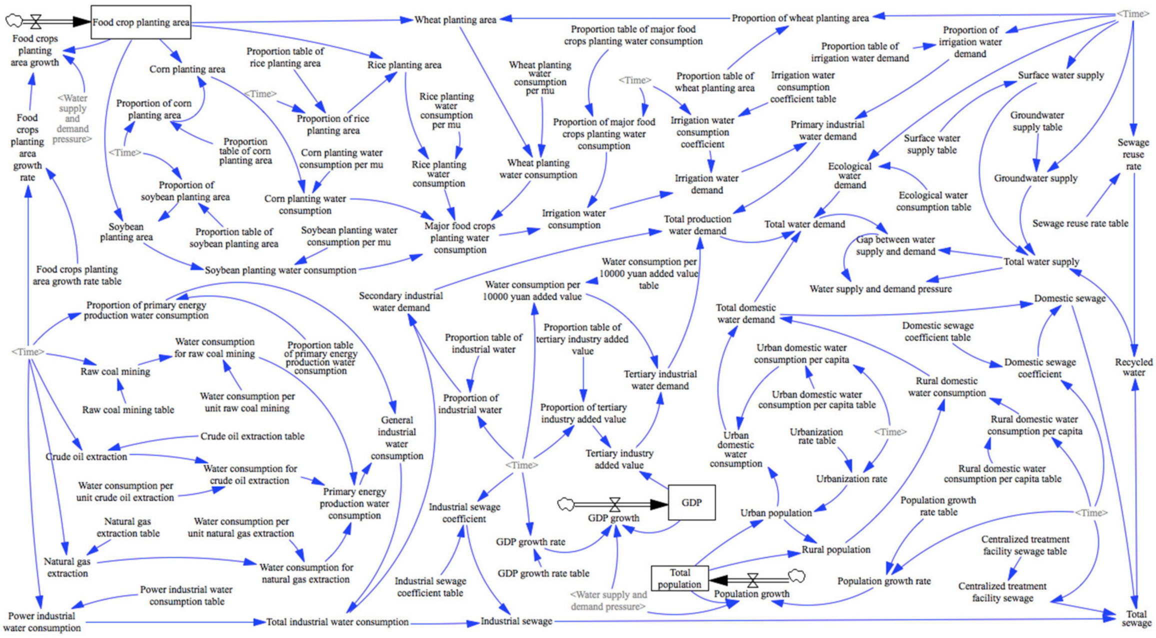


Figure 5. WEF nexus stock and flow diagram.

2.5. Model Verification

The establishment of the WEF nexus SD model in the process of studying the dynamic balance of water resources in Jiangsu Province is a process that abstracts the real system. In order to verify the coincidence of the WEF nexus SD model and the real system and test whether the information obtained through the model can reflect the changing law of the real system, it was necessary to verify, validate, and accredit the WEF nexus SD model. The verification of an SD model generally includes visual examination, operation examination, historical examination, and sensitivity degree analysis.

2.5.1. Visual Examination and Operation Examination

Visual examination is a method to test whether the boundary of the model, the causal relationship, and the expression of equations are reasonable, whether the definitions of valuable are correct and whether the dimensions are consistent. Operation examination refers to verifying the correctness of the expression of the SD model and judging the rationality of the SD model based on the operation results according to the error detection and tracking functions in the Vensim PLE v8.0.9 software package. In the process of using the Vensim software to construct the WEF nexus SD model, correctness of the SD model expression and rationality of the SD model were verified. The result shows that the SD model established in this study is complete in structure and effective in operation, which meets the requirements of visual examination and operation examination.

2.5.2. Historical Examination

A historical examination of the WEF nexus SD model was performed by comparing simulated data in the Vensim software with historical data to verify the coincidence of the WEF nexus SD model and the real system. During this examination, five typical variables were selected as historical inspection indicators of the model, and historical data from 2010 to 2018 were selected to perform the historical examination. Then, the error between the simulated data and historical data of each typical variable was calculated. The calculation formula of the error was as follows:

$$Error = \frac{|\hat{x} - x|}{x} \tag{10}$$

where *Error* represents the error of each typical variable; $\hat{x}$ represents the simulation data; x represents the historical data.

The errors of the five typical variables during the historical examination period were made into a boxplot, shown in Figure 6, by using R language software. The result vividly shows that all the relative errors between the simulated data and historical data of these five typical variables do not exceed 2%, which is much lower than the 10% that is the standard for judging whether the examination qualified the set in most other system dynamics papers. Given that the typical variables' simulated data are highly consistent with the historical data, the historical examination of the SD model was qualified.

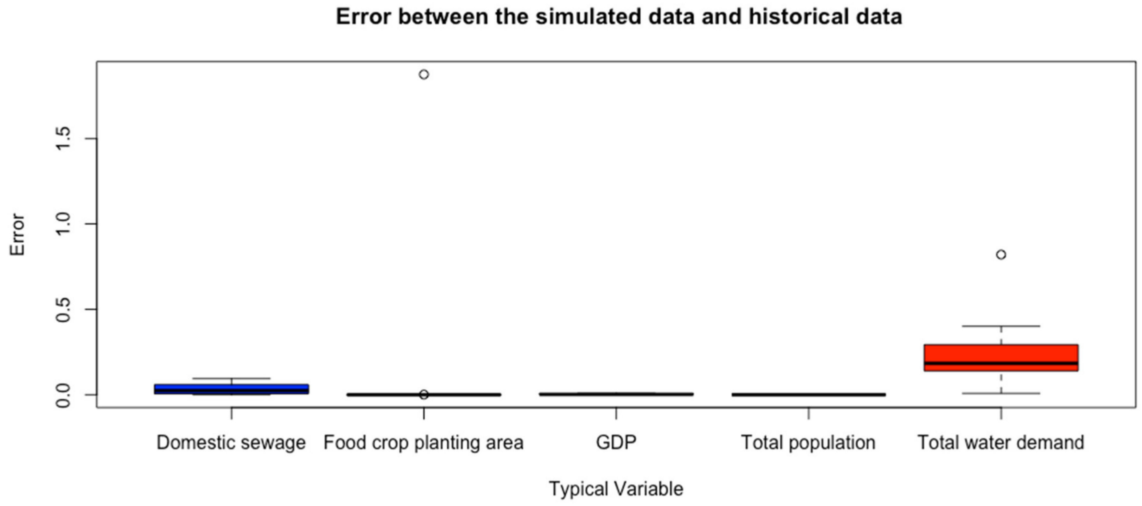


Figure 6. Historical examination result of the WEF nexus SD model.

2.5.3. Sensitivity Degree Analysis

Sensitivity degree analysis is an important method to verify the validity of a model, and a model with good stability and effectiveness should have a low sensitivity degree. Sensitivity analysis of the

WEF nexus SD model was completed to analyze the impact of parameter changes on the output of the model state variables by adjusting the parameters in this model. The calculation formula of the sensitivity degree is as follows [36]:

$$S_V = \left| \frac{\Delta V_{(y)}}{V_{(y)}} \frac{P_{(y)}}{\Delta P_{(y)}} \right| \tag{11}$$

where S_V represents the sensitivity degree of the state variable V to the parameter P; y represents the year; $V_{(y)}$ and $P_{(y)}$ represent the value of state variable V and parameter P in year y; and $\Delta V_{(y)}$ and $\Delta P_{(y)}$ represent the amount of change of state variable V and parameter P in year y.

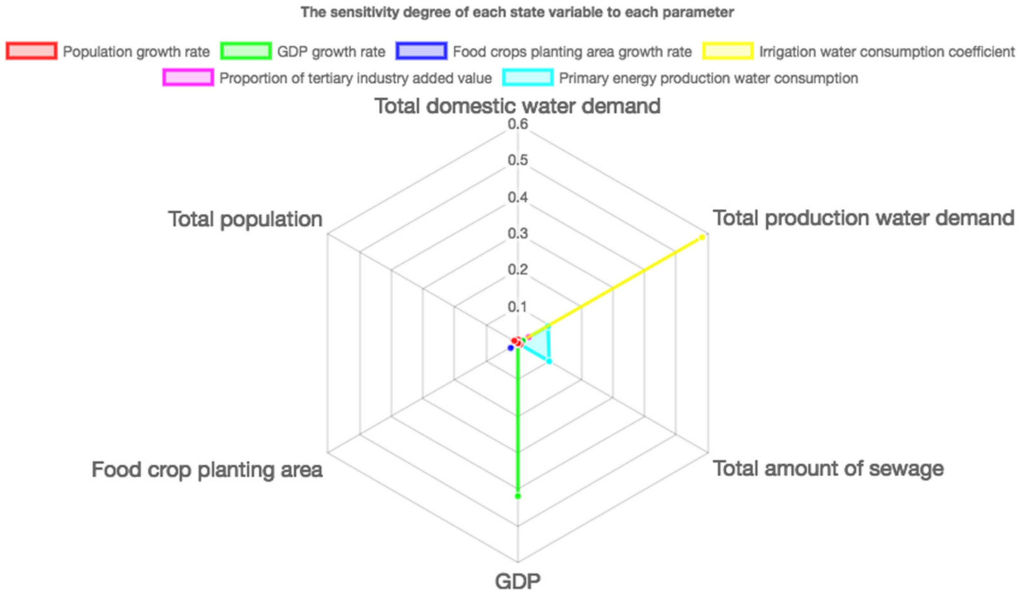
For the n state variables ($V_1, V_2, \ldots, V_n$), the average sensitivity degree of any parameter P in the year y is defined as follows:

$$S = \frac{1}{n} \sum_{i=1}^{n} S_{V_i} \tag{12}$$

where S represents the average sensitivity degree for the n state variables to the parameter P; n represents the number of state variables; and S_{V_i} represents the sensitivity degree of state variable V_i.

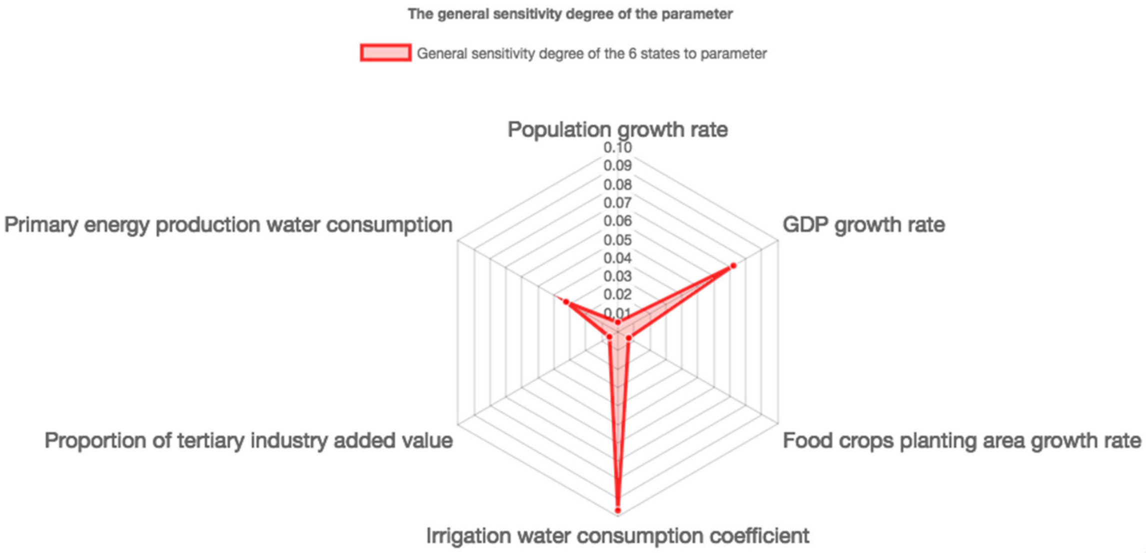
This study selected six parameters and six state variables from the WEF nexus SD model, and then analyzed them according to the method that each parameter was increased by 10% each time to analyze its impact on the sixvariables. Specifically, the sensitivity degree of each state variable to six parameters was calculated according to Equation (11). Then, the average sensitivity degree of each parameter was separately calculated according to Equation (12). The sensitivity degree analyses result is shown in Figure 7. From this figure, it can be seen that the sensitivity degrees of all parameters are lower than 10% or even lower than 1%, which shows that the WEF nexus SD model has a low sensitivity degree to most of the parameters, and the SD model has a strong stability.

After the above visual inspection, operation inspection, historical inspection, and sensitivity analysis, it can be seen that the WEF nexus SD model based on Vensim software designed in this paper is effective and also can be used for the simulation of the dynamic balance of water resources in Jiangsu Province based on the WEF nexus.



(**a**)

Figure 7. *Cont.*



(**b**)

Figure 7. Sensitivity degree analyses result: (**a**) The sensitivity degree of each state variable to each parameter; (**b**) The general sensitivity degree of the parameter.

3. Simulation and Results

This study set up six different scenarios for simulation research on the dynamic balance policies of water resources. The design ideas of each scenario are shown in Table 3. To sum up, scenarios 2, 3, 4, and 5 are from the perspective of decreasing water demand by savings on energy production water consumption, food production water consumption, and domestic water consumption, whereas scenario 6 is from the perspective of broadening water sources to increase water supply.

Table 3. Design ideas of the scenarios.

Scenarios	Adjusted Target Subsystem	Design Ideas
Scenario 1	None	Status quo
Scenario 2	Energy	Promoting the energy utilization of straw
Scenario 3	Food	Increasing the irrigation water consumption coefficient
Scenario 4	Food	Adjusting the crop planting structure
Scenario 5	Society	Requiring residents to strictly follow the water quota
Scenario 6	Eco-environment	Increasing the sewage reuse rate

3.1. Scenario 1

This scenario analyzed the water supply and demand in Jiangsu in the next five years if the current development trend is maintained. This scenario chose 2019 as the base year for the system model prediction, chose 2019–2023 as the simulation period, and used the SD model to predict the development trend of the WEF nexus. With respect to method, this paper used a double-exponential model with good short-term forecasting ability, which is also called Holt index smoothing in R language software, to predict the values of all input variables during the simulation period, which were inputted to the Vensim software to perform the WEF nexus system dynamics simulation.

Simulation results of scenario 1 are shown in Figure 8. In the next five years, the province's irrigation water demand, total industrial water consumption, and ecological water demand will all decrease year by year. In contract, tertiary industrial water demand and total domestic water demand will increase year by year. Overall, the total water demand will be in a downward trend. However, the continuous reduction in the surface water and groundwater will lead to a decrease in the total water supply year by year, which will make Jiangsu Province face the risk of a shortage of water resources in the next five years, and the gap between water supply and demand will grow.

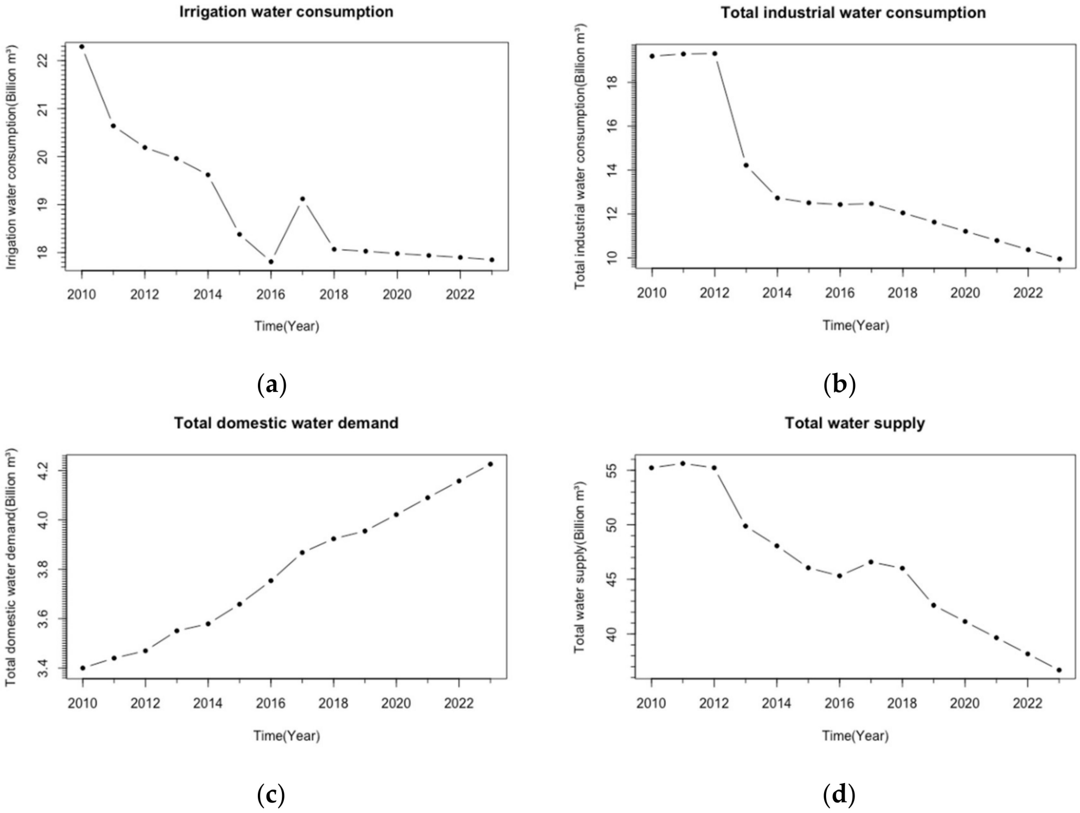


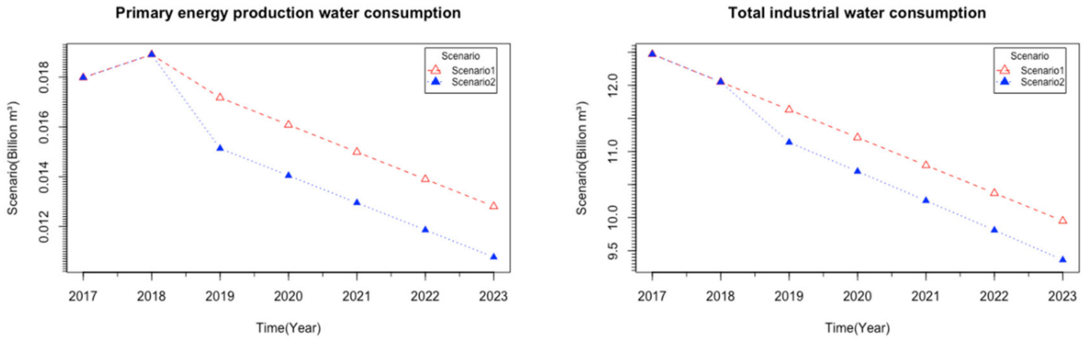
Figure 8. Scenario 1 simulation results: (**a**) Trend of irrigation water demand; (**b**) Trend of total industrial water consumption; (**c**) Trend of total domestic water demand; (**d**) Trend of total water supply.

3.2. Scenario 2

This scenario considered promoting the energy utilization of straw to save on water production for energy production. In this scenario, straw crops are turned into biomass energy to replace the original traditional fossil energy; however, there must be enough straw returned to the field to ensure that the soil fertility of crops is not reduced. This method can reduce the amount of water used in energy extraction and production so as to achieve the purpose of saving industrial water.

The scenario design process was as follows: According to the data released by the Jiangsu Science and Technology Department, the comprehensive utilization rate of straw in Jiangsu Province reached 92% in 2017. Therefore, in this scenario, the comprehensive utilization rate of straw in Jiangsu Province from 2019 to 2023 was assumed to be 100%, that is, all straw would be effectively used. Then, the part of the increase in straw resources caused by the increase in the comprehensive utilization rate of straw was all used for energy. The data processing was as follows: Bsased on the food crop straw/grain ratio calculated by Liu and conversion factors from physical units to coal equivalent of various energy given in the "Chinese Energy Statistical Yearbook", standard coal equivalents converted from various straw crops in Jiangsu were calculated [37]. In addition, conversion factors from physical units to coal equivalent of straw crops other than soybean, cotton, corn, rice, and wheat were calculated according to the fireweed's conversion factors from physical units to coal equivalents. Taking the food crop production of Jiangsu Province in 2018 as a reference, it was calculated that increasing the comprehensive utilization rate of straw in Jiangsu Province from 92% to 100% could increase the standard coal equivalents converted from various straw crops by 1941390.487 tce. Then, this part of the biomass energy would be solidified into fuel to replace the raw coal for thermal power generation, because the biomass solidification molding process does not consume water. It was calculated that this can save 2.7179 million tons of raw coal. In this scenario, the data of the SD model made the adjustment that the amount of the raw coal mining in the simulation period was reduced by 2.7179 million tons.

Scenario 2 simulation results are shown in Figure 9. Compared with the scenario 1 simulation results, the water consumption of primary energy production in Jiangsu will decrease from 0.1281 m^3 to 0.1077 m^3 by 2023. To conclude, using biomass energy as a renewable energy source to replace non-renewable energy from raw coal for thermal power generation can reduce the amount of raw coal mining so as to reduce the amount of water consumption for raw coal and then reduce the amount of water consumption for primary energy production and total industrial water consumption in Jiangsu.



(**a**) (**b**)

Figure 9. Scenario 2 simulation results: (**a**) Trend of primary energy production water consumption; (**b**) Trend of total industrial water consumption.

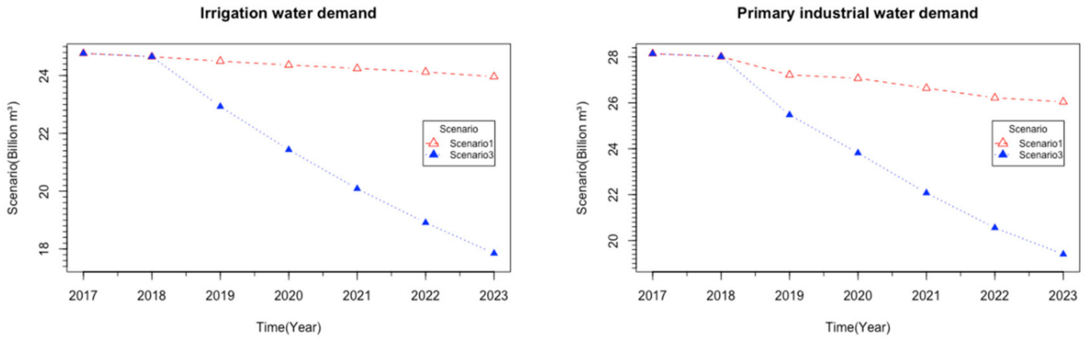
3.3. Scenario 3

In this scenario, the irrigation water consumption coefficient was selected as the decision variable for regulating and controlling irrigation water demand, and the value of the irrigation water consumption coefficient was increased to reduce the irrigation water demand. What needs to be explained is that the irrigation water consumption coefficient is the ratio of water that cannot return to surface water bodies and underground aquifers during irrigation and transportation due to gross irrigation water consumption. The higher the irrigation water consumption coefficient, the higher the utilization rate of farmland irrigation water. When the irrigation water consumption coefficient reaches 1, there will be no unnecessary loss of water resources in the process of farmland irrigation water delivery and water consumption, which is the most ideal state of irrigation. Therefore, in this scenario, it was assumed that the optimal state of farmland water-saving irrigation could be reached in 2023, and the irrigation water consumption coefficient was increased by 0.0534 year by year during the 5 years from 2019 to 2023.

Scenario 3 simulation results are shown in Figure 10. Compared with the scenario 1 simulation results, by 2023, the irrigation water demand will decrease from 23.9593 billion m^3 to 17.85 billion m^3. In addition, primary industrial water demand will decrease following the change of irrigation water demand. To conclude, the utilization rate of irrigation water can be improved by increasing the irrigation water consumption coefficient to reduce the irrigation water demand and alleviate the water supply pressure in Jiangsu Province.

3.4. Scenario 4

In this scenario, the proportion of rice planting area, the proportion of wheat planting area, and the proportion of corn planting area were selected as the decision variables for regulating and controlling irrigation water consumption. With the expected ultimate purpose of reducing irrigation water consumption, this scenario considers adjusting the food crops planting structure according to the actual situation of food crop cultivation in Jiangsu Province.

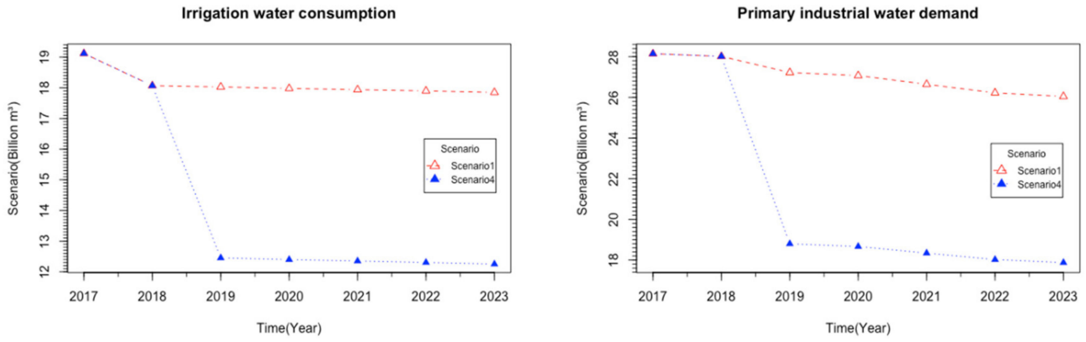


(**a**) (**b**)

Figure 10. Scenario 3 simulation results: (**a**) Trend of irrigation water demand; (**b**) Trend of primary industrial water demand.

The scenario design process was as follows: According to Xue's research on the relationship of major food supply and demand in Jiangsu Province, it can be found that food supply in Jiangsu has generally been in a state of supply exceeding demand in recent years [38]. Specifically, the supply of rice and wheat has exceeded demand, whereas corn is in short supply. Additionally, according to the water consumption per unit mass of the main food crops in China, the order of the water consumption per unit mass of rice, wheat, corn, and soybeans is soybean > wheat > rice > corn [39]. Based on the above facts, the food planting structure was appropriately adjusted to reduce the irrigation water consumption. The rice planting area and wheat planting area were appropriately reduced, and the lands vacated by these adjustment were used for corn planting, which has relatively small water consumption, ensuring enough supply of water to rice and wheat. It is worth mentioning that the planting area of the other food crops remained unchanged in this scenario because of low proportion. Combined with Xue's research data, this scenario sets the ratio of the food crop planting structure in the SD model simulation period as rice area/wheat area/corn area = 19:21:54.

Scenario 4 simulation results are shown in Figure 11. Compared with the scenario 1 simulation results, by 2023, irrigation water consumption will decrease from 17.8497 billion m^3 to 12.252 billion m^3. In addition, primary industrial water demand will decrease following the change of irrigation water consumption. To conclude, the irrigation water consumption can be effectively reduced by a reasonable adjustment of the food crop planting structure in Jiangsu, so that the primary industrial water demand is reduced, and the water supply pressure in Jiangsu can be effectively relieved.



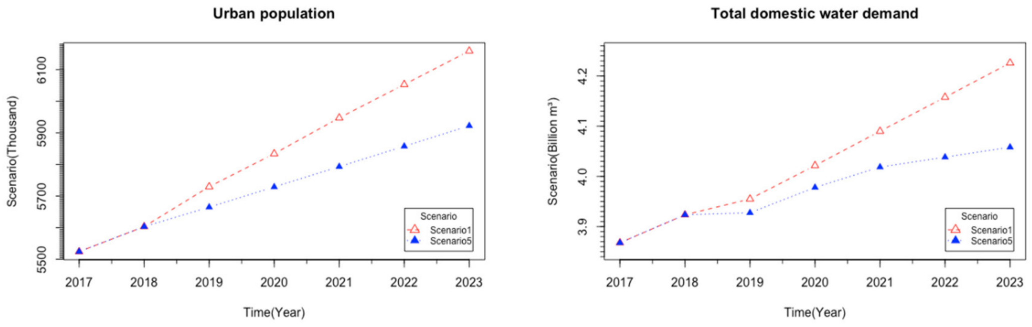
(**a**) (**b**)

Figure 11. Scenario 4 simulation results: (**a**) Trend of irrigation water consumption; (**b**) Trend of primary industrial water demand.

3.5. Scenario 5

For the expected ultimate purpose of saving domestic water, this scenario selected the population growth rate, urbanization rate, rural domestic water consumption per capita, and urban domestic water consumption per capita as the decision variables for regulating and controlling total domestic water demand. According to the "Jiangsu 13th Five-Year Plan for Population Development", the urbanization rate of Jiangsu will continue to slow down during the "13th Five-Year Plan" period, and the population urbanization rate will increase by about 0.6 to 0.8 percentage points annually. Therefore, this scenario set the annual growth rate of the urbanization rate during the simulation period as 0.6 percentage points. In addition, this scenario assumed that all residents in Jiangsu use water resources strictly in accordance with the resident domestic water quota. The quota of urban domestic water consumption per capita was set as 150 L/(person · day) and the quota of rural domestic water consumption per capita was set as 100 L/(person · day), which were obtained from the "Urban Life and Public Water Quota of Jiangsu Province (Revised in 2012)".

The scenario 5 simulation results are shown in Figure 12. Compared with the scenario 1 simulation results, the urban population decreased from 61.5837 million to 59.2182 million and the urban domestic water consumption also declined, which led to the decrease of the total domestic water demand in Jiangsu. Moreover, by 2023, the total domestic water demand will decrease to 4.05796 billion m^3. To conclude, requiring residents to strictly follow the water quota can effectively save the domestic water consumption.



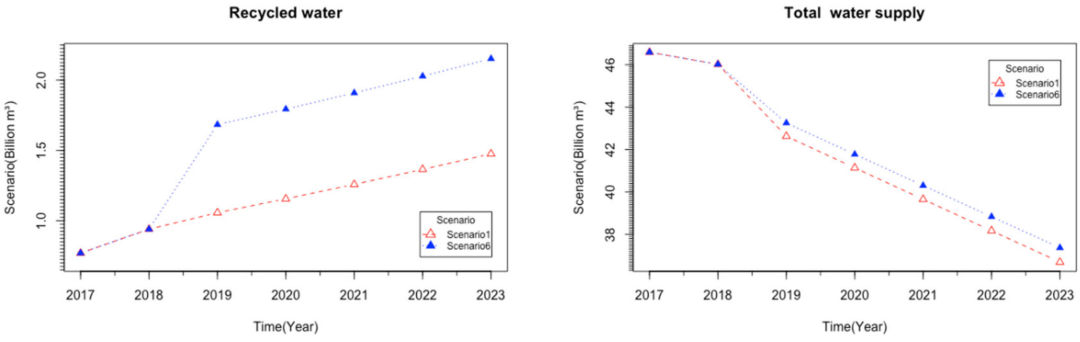
(**a**) (**b**)

Figure 12. Scenario 5 simulation results: (**a**) Trend of urban population; (**b**) Trend of total domestic water demand.

3.6. Scenario 6

The expected ultimate purpose of this scenario was to increase the supply of water resources and enhance the supply capacity of water resources, the methods of which include improving the capacity of natural water resources development and utilization, improving the sewage reuse rate, and so on. Considering the availability of data, this scenario selected the sewage reuse rate as the decision variable for regulating and controlling the recycled water supply. Furthermore, this scenario increased the supply of water resources by converting more domestic sewage and industrial sewage to water that meets certain quality standards and can be used at certain occasions. With respect to the data processing, this scenario referred to the data from the "Thirteenth Five-Year Plan for National Urban Sewage Treatment and Recycling Facilities Construction Plan", which set the following goals: The water utilization rate of the Beijing-Tianjin-Hebei area is not less than 30%, the water utilization rate of water-scarce cities is not less than 20%, and other cities and counties strive to reach 15%. According to the goals above, in this scenario, it was assumed that a sewage reuse rate of Jiangsu Province of not less than 30% can be reached in 2023. Therefore, this scenario's data processing was as follows: The annual sewage reuse rate was increased by 10 percentage points based on the data of scenario 1 during the 5 years from 2019 to 2023. Then, the sewage reuse rate of Jiangsu Province in 2023 will reach 31.8217%, which will meet the hypothetical goal.

The scenario 6 simulation results are shown in Figure 13. Compared with the scenario 1 simulation results, the total water supply of Jiangsu will increase from 36.689 billion m^3 to 37.3654 billion m^3 by 2023, caused by the increase of the recycled water. To conclude, increasing the sewage reuse rate can effectively increase the water supply, so that the water shortage of water resources in Jiangsu will be alleviated.



(**a**) (**b**)

Figure 13. Scenario 6 simulation results: (**a**) Trend of recycled water; (**b**) Trend of total water supply.

4. Discussion

This study explored effective ways to achieve a dynamic balance of water resources by setting up six different scenarios from the perspective of increasing water supply and decreasing water demand. This paper selected the gap between water supply and demand as the state variable to measure the dynamic balance of water resources in Jiangsu. If the gap between water supply and demand is positive, supply exceeds demand, otherwise, supply exceeds demand. The comparison of the simulation results of the gap between water supply and demand in the six scenarios are shown in Figure 14. To conclude, the results show that the imbalance of water resources will remain severe in the next few years, and it will be helpful in relieving the imbalance to take measures from the perspectives of regulating the water consumption from food production, energy production, and domestic water consumption, and regulating the water resource supply. According to the above analysis, some suggestions about regulating and controlling water supply and demand are included.

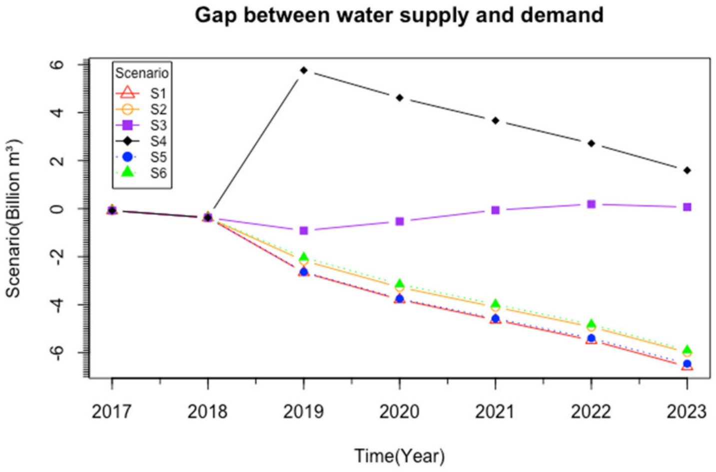


Figure 14. Comparison of the simulation results from scenarios 1–6.

4.1. *Regulation and Control of Water Consumption for Food Production*

Compared with the other scenarios, scenarios 3 and 4, which both aim to save water consumption from food production, have the best effects of relieving the contradiction of water resources supply and demand in Jiangsu. Scenario 4 adjusts the planting structure of food crops, the gap between water supply and demand becomes positive, and the situation of supply exceeding demand emerges. To conclude, increasing the effective utilization rate of irrigation water and appropriately adjusting the food crop planting structure can effectively reduce the water consumption from food production and alleviate the pressure of water supply in Jiangsu Province.

According to the above analysis, some suggestions about regulating and controlling the water consumption for food production are put forward. Firstly, in terms of agricultural water conservancy projects, Jiangsu Province needs to strengthen the construction of agricultural water-saving projects and improve the farmland water conservancy infrastructure, etc. Secondly, in terms of water-saving technologies, Jiangsu Province needs to promote high-efficiency water-saving technologies such as agricultural water sprinkler irrigation, seepage irrigation, drip irrigation, micro irrigation, inrush irrigation, gravity irrigation, and dry–wet alternate irrigation, etc., and deepen the research and promotion of agronomic water-saving and bio-physiological water-saving technologies to improve the irrigation water consumption coefficient so as to reduce unnecessary water loss during irrigation. Thirdly, in terms of the food planting structure, according to the actual food demand and irrigation water demand in Jiangsu, the planting of crops that consume a lot of water in the process of planting should be appropriately reduced and replaced by crops that consume less water. Last but not least, in terms of a management system, the quantitative management of irrigation water demand should be strengthened, and the "Jiangsu Agricultural Irrigation Water Quota" should be constantly adjusted and improved according to the latest development of farmland irrigation in Jiangsu so as to guide agricultural production more accurately. In addition, agricultural water price management mechanisms should be established and improved.

4.2. Regulation and Control of Water Consumption for Energy Production

The effect of relieving the contradiction of water resources supply and demand in Jiangsu made by scenario 2, which aims to save water consumption from energy production, is not as good as scenarios 3 and 4. However, the positive effects of reducing the water consumption for energy production and water resource pollution by replacing traditional energy with eco-friendly biomass energy are still obvious.

According to the above analysis, some suggestions about regulating and controlling the water consumption for energy production are put forward. Firstly, in terms of fuel and gas production, the production of biomass solid-shaped fuel and biomass gas that does not consume water in the production process should be actively promoted. The energy utilization of straw crops also should be promoted. Straw resources can be gasified into high-value biomass gas by pyrolysis gas and other technologies. Furthermore, straw resources solidified and compressed into shaped fuel by related mechanical equipment and the solidified and compressed straw can be further carbonized to increase the calorific value of straw fuel. Secondly, in terms of secondary energy power production, Jiangsu Province should strive to develop air-cooling technology and build high-capacity and high-parameter units to gradually ban DC direct cooling thermal power generation, which consumes a large amount of water. Due to the coastal advantage, the nuclear power generation industry should be actively developed so as to reduce the use of freshwater resources in the power generation process. In addition, Jiangsu Province should continue to develop wind power and solar power industries and increase the development of biomass power generation industries so as to use biomass such as straw crops, domestic waste, and biogas to generate electricity.

4.3. Regulation and Control of Domestic Water Consumption

In the next few years, domestic water consumption and industrial and domestic sewage discharge will rise. Compared with other scenarios, scenario 5, which aims to save domestic water consumption, has a small effect on relieving the contradiction of water resources supply and demand in Jiangsu. Obviously, the task of saving domestic water and controlling water pollution is arduous.

According to the above analysis, some suggestions about regulating and controlling domestic water consumption are put forward. Firstly, Jiangsu Province should establish a water-saving and pollution-proof society, ensuring the quality of water resources does not decrease and the safety of drinking water for residents is guaranteed. Relevant authorities should also strengthen water-saving publicity work to raise residents' awareness of water-saving and reducing unnecessary water pollution and waste of water resources in ordinary life. In terms of system construction, the strictest management system should be implemented in the process of water resources management, the accountability mechanism for supervision should be established and strengthened, and the transformation from qualitative management of water resources to quantitative management of water resources should be promoted. What is more, water consumption quota standards such as "Urban Life and Public Water Quota" and pollution discharge standards such as "Village Domestic Wastewater Treatment Water Pollutant Discharge Standards" should be constantly adjusted and improved to better assist the public in scientifically formulating water pollution prevention plans so as to put water and pollution prevention work into the whole process of life and production of urban and rural residents. Last but not least, it is necessary for Jiangsu Province to optimize the industrial layout and strictly control the industries or enterprises with high water consumption and high pollution that settle in Jiangsu.

4.4. Regulation and Control of the Water Resources Supply

The above analyses looked at how to promote the dynamic and balanced development of water resources from the perspective of regulating and controlling water resources demand. From the simulation results of scenario 6, with the purpose of increasing the supply of water resources, it can be seen that proper development of water resources can alleviate the contradiction between water supply and demand in Jiangsu.

According to the above analysis, some suggestions about regulating and controlling the water resources supply are put forward. Firstly, it is necessary to strive to improve the sewage reuse rate, fully develop and use recycled water, and apply sewage recycling technology to the secondary industries like construction or agricultural production that do not have high requirements for production water quality. All methods mentioned above can recycle water resources and actively protect the ecological environment. Secondly, it is also necessary to strengthen the collection and reuse of rainwater and floodwater. Water storage projects such as reservoirs, rivers, and ditches should be constructed to improve the ability of saving rain and flood waters. In terms of mitigating the contradiction between urban development and the ecological environment, it is essential to pay attention to the collection and reuse of rainwater in buildings and to take some measures like improving the water storage space system in buildings and increasing the construction of multifunctional rainwater regulation and storage facilities. Last but not least, in terms of water resources management, it is essential to improve the development and utilization of surface water resources, and increase pollution control so as to improve the status quo of water resources and increase the amount of water resources available on the surface that meet the water quality standards.

5. Conclusions

With the aim of a dynamic balance of water resources, this paper used the principles and methods of system dynamics that can depict a complex relationship network to build a WEF nexus SD model that combined the external social system, economic system, and eco-environment system. In particular, this study focused on studying the specific supply and demand mechanisms of water resources in each subsystem. Then, this paper set up six scenarios for the simulation study: maintaining the current trend, promoting the energy utilization of straw, increasing the irrigation water consumption coefficient, adjusting the food crop planting structure, saving domestic water, and improving the sewage reuse rate.

Many conclusions can be drawn from our work. Firstly, the WEF nexus SD model, constructed by integrating the energy system and the food system on the basis of a single system of water resources and combining external social, economic, and eco-environmental systems, can be effectively applied to the analysis of Jiangsu's water resources dynamic balance. Secondly, it is necessary to pay attention to the synergy of water, energy, and food during the study of the dynamic balance of water resources. This synergy is embodied in the results that show that using biomass energy can not only maintain energy security, improve the energy structure to alleviate the pressure of energy supply, and reduce the water consumption for energy production, but it can also in turn promote agricultural development and increase farmers' income so as to make farmers be more willing to grow crops with higher efficiency and less water consumption, such as corn. It is worth mentioning that water consumption for agricultural production is decreased at the same time. Thirdly, taking no improvement measures of alleviating the water supply and demand contradiction and maintaining the current development trend of the WEF nexus will result in the consequence that Jiangsu's water resources will not be able to achieve a dynamic balance, water shortages will occur, and the contradiction between supply and demand will gradually deepen. It is helpful for relieving imbalance to promote the energy utilization of straw, improve the irrigation efficiency, adjust the crop planting structure, require residents to strictly follow the water quota, and improve sewage recycling. Furthermore, simulation studies on the different policies of Jiangsu's dynamic water balance from the perspective of the water–energy–food nexus is helpful for promoting the efficient use of resources and the sustainable development of the economy in Jiangsu, and they also have deep theoretical and practical significance.

There are some important contributions of this study. First and foremost, this study had a new research perspective that the dynamic balance of the water resources was studied from the perspective of the synergy of water, energy, and food, which further enriches the research perspectives on water resources balance based on the previous research [2,3]. Secondly, this study had an improved method of model establishment on that it not only combined a single water system with energy and food systems, but also fully integrated external systems such as social, economic, and eco-environmental systems. This improvement of the WEF nexus SD model was made on the basis of the water–energy–food nexus in Cyprus [40]. Last but not least, this study had a new research object-screening method that centered on the water system and focused more on studying the specific supply and demand mechanism of water resources in the energy, food, social, economic, and eco-environmental systems, which is different from the study of the SD model WEF nexus in Beijing [41].

However, the SD model itself is an abstraction and simplification of real problems. Because data are difficult to quantify and collect, many factors will be reduced in the process of building the WEF nexus SD model. This reduces the effectiveness of using system dynamics to solve practical problems.

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