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How to Sustainably Use Water Resources—A Case Study for Decision Support on the Water Utilization of Xinjiang, China

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Abstract: Global warming has led to a serious crisis on regional water resources. Establishing a decision support system (DSS) on the sustainable utilization of water resources for arid areas is an increasingly critical problem. Selecting Xinjiang as a case study, this paper developed a system dynamics (SD) model. Through the simulation operation of the model, we achieved the decision on sustainable utilization of water resources. The extensive economic development is the main factor restricting the sustainable utilization of water resources in Xinjiang. We propose to adjust the planting structure and implement water-saving irrigation in Xinjiang, especially the Tarim Basin and Turpan-Hami Basin. This research provides the sustainable utilization plan of water resources for Xinjiang and its sub-regions in the next 30 years. By 2050, we recommend that the reuse rate of urban domestic water consumption and industrial sewage should reach 75%; the rural domestic water quota should be 70 L/(person·day); water consumption per industrial output value of ten thousand Yuan should be 28 m^3; the irrigation water quota should be 5000 m^3/hectare in Xinjiang. This research can provide references for the decision on sustainable utilization of water resources in arid regions around the world.

Keywords: decision support; water resources; sustainable utilization; SD; Xinjiang; China

1. Introduction

Water is a crucial natural resource supporting life on Earth and underpinning equitable, stable, and productive societies and ecosystems [1]. Global warming has led to a general decline in water restoration on continents during the past century [2]. The excessive development and utilization of water resources, water pollution, and deterioration of the water environment disrupted the regional water cycle process, exacerbating water resources risks [3]. In China, this situation is even more pronounced in arid regions such as Xinjiang, where the environment is extremely harsh and water resources are extremely scarce [4,5]. It not only brings instability to water supply but also puts pressure on sustainable utilization of water resources [6–9]. In this context, there is an urgent need to assess and predict the trends and evolution of water resources and formulate appropriate policies for water resources management to deal with the increasing water crisis. Water resources management incorporates technical, political, legislative, and organizational components, which represent the natural entity of water resources management [10]. The technical part of water resources management

includes water supply management [11], water demand management [12], water allocation [13], policy objectives of water security [14,15], and decision support [16].

Information intended to inform sustainable management of water has been created from global to local scales, and many water DSS have been produced [17,18]. Generally, DSS are defined as knowledge resources that facilitate decisions for specific users or objectives through the integration of information on water and relevant drivers of change [18]. With the development of society and economy, the disturbance of natural water resources systems due to human activities has become more and more intense [19]. Therefore, the integrated management of a water resources-socioeconomic-environmental system has raised substantial attention and proved to be more suitable for the sustainable management of water resources [20–24]. The water DSS involves total water resources and water consumption, with complex content and wide coverage [17,18,25]. Currently, the decision-support tools that have been already developed mainly include optimization techniques [16,26–29], the conflict resolution technique (e.g., game theory) [28,30,31], and complex adaptive systems [32,33]. In addition, SD is another useful tool for water decision support and water resource management because of its strong ability to simulate the system complexity and evolutionary processes [34–43].

Global warming will result in possible increases in water disasters and water scarcity in arid areas in the future [44–46], although some DSS have been used in regional water resources management. However, to the best of our knowledge, there are still few studies that provide decision support for water use in Xinjiang, China. Xinjiang is the typical representative of the arid region in Central Asia, where the water resources are extremely scarce, uncertain, and unbalanced in time and space. Agriculture, industry, residents, and ecology are the main water-using sectors in Xinjiang, accounting for more than 96% of total water consumption [47–49]. In the current context of declining water reserves, irrigation water consumption is threatened, which, in turn, affects crop yields and food security [50–54]. Xinjiang has planted a large area of crops and is the main production area of the grain. Wheat, cotton, and corn are the main crops relying on irrigation. Irrigation water accounts for more than 90% of total water consumption [47–49]. Besides, Xinjiang is an important ecological barrier and its ecological environmental protection is an important guarantee for sustainable development in China [55]. While excessive irrigation water consumption leads to decreasing ecological water consumption and accelerates ecological crises [56–58]. Ecological water consumption accounts for less than 1% of total water consumption, and the contradiction between human activities and ecological water consumption has become increasingly prominent [57].

Affected by the geographical environment, water use structure, and local policies, the existing DSS are not well applicable to arid areas such as Xinjiang. There is an urgent need to develop DSS for water use in these areas. Therefore, the aim of this research is to develop DSS to better serve the sustainable utilization of water resources for arid areas such as Xinjiang. How do we achieve the sustainable utilization of water resources? To answer this question, it is necessary to simulate and predict the changes in water supply and demand under different scenarios, and to select a sustainable plan by comparing and analyzing the results of different scenarios. Through the simulation operation of the model, we can achieve the decision on sustainable utilization of water resources. This research can provide references for the decision on sustainable utilization of water resources in arid regions around the world.

2. Materials and Methods

2.1. Case Study

Xinjiang (34°–48° N, 73°–96° E) is located in the northwestern part of China (Figure 1). It covers an area of approximately 166×104 km^2 and accounts for 1/6 of the total land area in China [4]. Xinjiang is far from the ocean, dominated by a typical continental climate, with an average annual precipitation of less than 200 mm [5]. Water resources primarily result from precipitation and glacier snow meltwater in the mountainous regions [59]. Due to the special geographical environment and complex topography,

water resources in Xinjiang are scarce and unevenly distributed in time and space. Xinjiang has planted a large area of crops and is the main production area of the grain. The agricultural planting zone is mainly distributed in the oasis areas of piedmont plains, and wheat, cotton, and corn are the main crops relying on irrigation from surface water and groundwater. To quantitatively analyze the changes in water supply and demand, we divided the study area into Junggar Basin, Turpan-Hami Basin, Ili Valley Basin, and Tarim Basin [60].
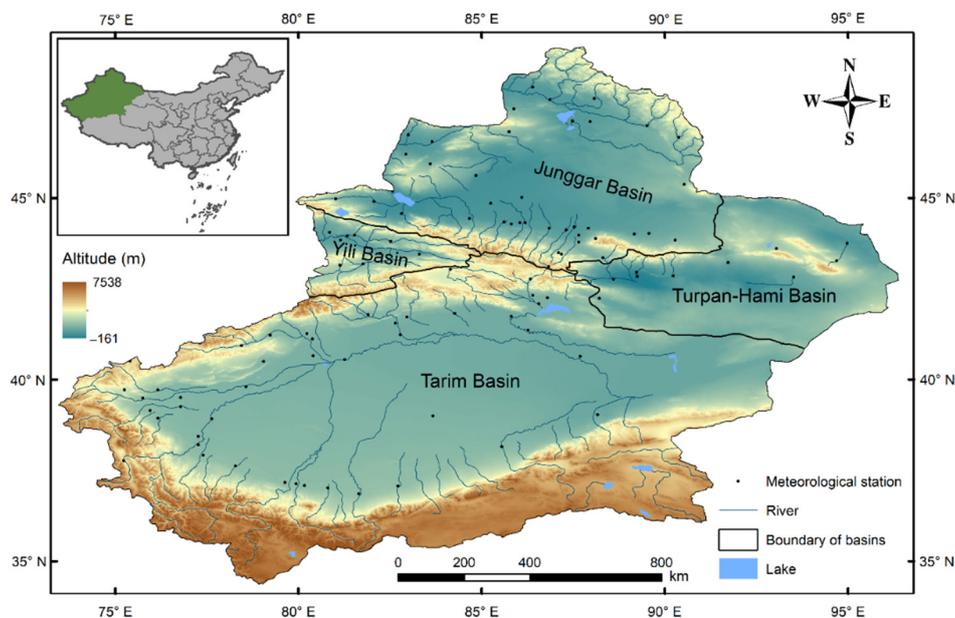

Figure 1. Study area description.

2.2. Materials

The data used in this study are mainly provided by the statistics Bureau of Xinjiang Uygur Autonomous Region and Xinjiang Water Resources Department [47–49,61–63]. To calculate the ecological water demand in the next 30 years, we used the land-use data products from ESA CCI (European Space Agency Climate Change Initiative) (http://maps.elie.ucl.ac.be/CCI/viewer/index.php) with a spatial resolution of 300 m × 300 m. According to Table 1, we integrate administrative divisions and corps data into four sub-regions in Xinjiang.

Table 1. Scope of sub-regions in Xinjiang.

Sub-Regions	Scope
Yili Basin	Counties (Cities) Direct Under Ili Prefecture except Kuytun City, Division 4 of Xinjiang Production and Construction Corps
Junggar Basin	Urumqi City, Karamay City, Shihezi City, Changji Hui Autonomous Prefecture, Tacheng Administrative Offices, Altay Administrative Offices, Bortala Mongol Autonomous Prefecture, Kuytun City, Division 5, 6, 7, 8, 9, 10, and 11 of Xinjiang Production and Construction Corps
Turpan-Hami Basin	Turpan City, Hami City, Division 12 and 13 of Xinjiang Production and Construction Corps
Tarim Basin	Bayangol Mongol Autonomous Prefecture, Kizilsu Kirgiz Autonomous Prefecture, Aksu Administrative Offices, Kashgar Administrative Offices, Hotan Administrative Offices, Division 1, 2, 3, and 14 of Xinjiang Production and Construction Corps

Table note: The data are provided by Statistics Bureau of Xinjiang Uygur Autonomous Region [48].

2.3. Methods

2.3.1. Principles of SD

The principle of SD models is decomposing the system layer by layer, starting with the mathematical description of the internal mechanism of the system [64,65]. Generally, we decomposed the system into multiple interrelated sub-systems as follows:

$$S = \{S_i \epsilon S | i \epsilon I\}, \tag{1}$$

where S is the entire system, S_i is the sub-systems, $i = 1, 2, \cdots, I$.

The sub-system is composed of basic units and first-order feedback loops. The first-order feedback loop includes state variables, rate variables, and auxiliary variables, which are represented by state equations, rate equations, and auxiliary equations, respectively. These equations, variables, functions, and constants can describe complex changes of the objective world [64,65]. The mathematical description is as follows:

$$\dot{L} = PR, \tag{2}$$

$$\begin{bmatrix} R \\ A \end{bmatrix} = W \begin{bmatrix} L \\ A \end{bmatrix}, \tag{3}$$

where $\dot{L}$ is the pure rate variable vector, P is the transition matrix, R is the rate variable vector, A is the auxiliary variable vector, W is the relational matrix, and L is the state variable vector.

Variables in SD models are mainly divided into state variables, rate variables, auxiliary variables, exogenous variables and constants. Except for constants and exogenous variables, the changes of other variables all result in internal and external feedback effects of the system [65,66], and the feedback mechanism can be represented by Equations (4)–(7):

$$dLEV/dt|t = RATIN(t) - RATOUT(t), \tag{4}$$

$$RATINT(t) = f_1(LEV(t), AUX(t), EXO(t), CON), \tag{5}$$

$$RATOUT(t) = f_2(LEV(t), AUX(t), EXO(t), CON), \tag{6}$$

$$AUX(t) = g(LEV(t), AUX^*(t), EXO(t), CON), \tag{7}$$

where LEV is the state variable, $RATIN$ is the input rates of the state variable, $RATOUT$ is the output rates of the state variable, AUX and AUX^* are auxiliary variables, EXO is the exogenous variable, and CON is the constant.

2.3.2. SD Model for Water Decision Support

It is promising to combine ecosystem measurements with variables related to social systems related to water security [55]. The SD model for decision support on water use includes water resources sub-system, population sub-system, agricultural sub-system, industrial sub-system, and ecological sub-system. According to the causality of sub-systems, we employed Vensim6.2 software to develop SD models for Xinjiang and its sub-regions. The model used 33 variables and constructed 21 mathematical equations. The simulation time of SD is 2008 to 2017, the forecast time is 2018 to 2050, and the forecast time step is one year. The system flow diagram (Figure 2) describes the internal structure and causality of sub-systems. In the water resources sub-system, the total water resources are the sum of surface water resources, groundwater resources, and reclaimed water, and the total water consumption is the sum of domestic water consumption, irrigation water consumption, industrial water consumption, and ecological water consumption. When the total water consumption exceeds total water resources, negative feedback will hinder population growth, economic development, and ecological water consumption. In the agricultural sub-system, we selected crop planting area as the state variable and

calculated irrigation water consumption by crop planting areas and irrigation water quota. In the industrial sub-system, we selected industrial output value as the state variable and calculate industrial water consumption by industrial output value and water consumption amount per unit output value of ten thousand Yuan. In the ecological sub-system, we selected ecological water consumption as the state variable and inputted its growth rate in the form of a table function. In population sub-system, we selected total population as the state variable and calculated domestic water consumption by rural population, urban population, rural domestic water quota, and urban domestic water quota. Taking into account the impact of water price on urban domestic water consumption [64], we added the water price change rate in the model, and its impact on urban domestic water quota can be expressed by Equation (8):

$$UDWQ = UDWQ_1 \times WPR^{\alpha}, \tag{8}$$

where *UDWQ* is the urban domestic water quota, $UDWQ_1$ is the urban domestic water quota in the last year, *WPR* is the water price change rate, and α is the elasticity coefficient.
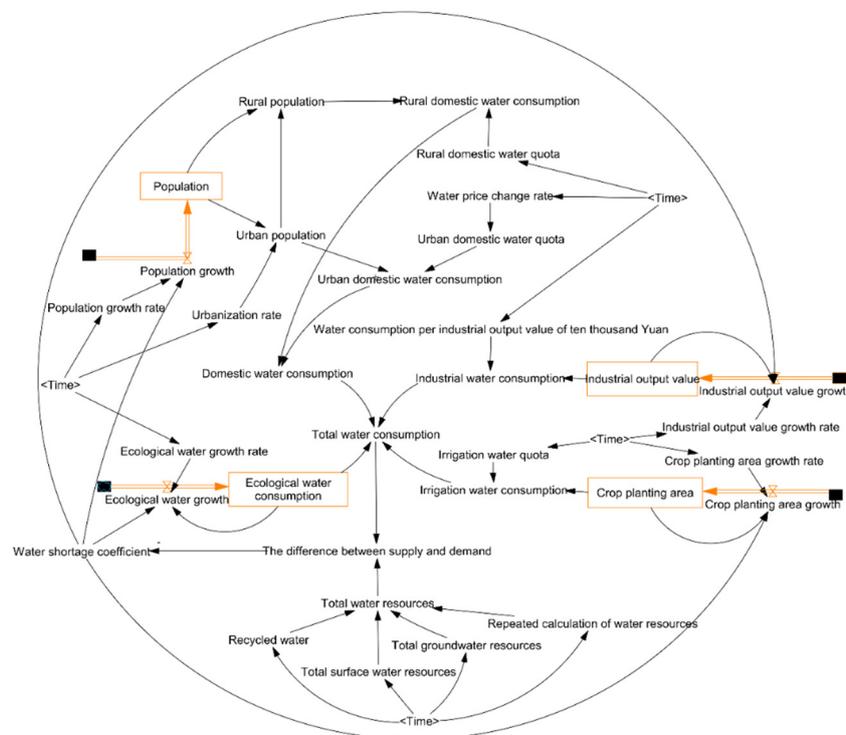

Figure 2. Flow diagram of SD model.

Water resources, agriculture, and industry are complex systems with highly nonlinear, high-order, multivariable, and multiple feedback. The SD model has advantages in simulating the relationship among these systems and is not sensitive to a small amounts of missing data. The SD model developed by this research includes agricultural subsystem, industrial subsystem, population subsystem, and ecological subsystem. According to relevant data, agriculture, industry, residents, and ecology are the main water-using sectors in Xinjiang, accounting for more than 96% of total water consumption [47–49]. By modeling historical data, the model can accurately predict future water changes. By changing the value of the decision variable, the model can accurately simulate water consumption under different scenarios and support decisions for water utilization. However, the SD model developed by this study also has some limitations, which are mainly manifested in two aspects. First, the impact of the service industry on water utilization is not considered in the model. This is because the service industry involves many variables, and relevant data is difficult to obtain. In addition, the service industry has a smaller impact on water consumption compared to agriculture and industry.

The second is the research scale. The SD model focuses on the decision support of water use for Xinjiang and its four sub-regions. It should be noted that there may also be some differences in water utilization in different districts and counties. Due to data limitations, the SD model in this research cannot provide good support for some districts and counties.

2.3.3. Model Validity Evaluation

As a simulation model of the actual system, the consistency between simulated results of SD models and objective reality is the premise of its feasibility. Model validity evaluation mainly includes intuitive test, historical test, and sensitivity test [37,66].

We employed the "Check Model" and "Units Check" provided by Vensim6.2 software to intuitively test SD models. In addition, we selected the variables with complete historical data as test objects, and calculated relative errors between simulated values and real values of these variables. The relative error can be calculated as follows:

$$E = (Y_i - \hat{Y}_i)/Y_i, \tag{9}$$

where E is the relative error, Y is the real data, and $\hat{Y}_i$ is the simulated data.

A strong SD model is insensitive to changes in most parameters [64]. The sensitivity can be calculated as follows [65]:

$$S_L = \left| \frac{\Delta L_t}{L_t} \times \frac{X_t}{\Delta X_t} \right|, \tag{10}$$

where t is the time, S_L is the sensitivity of the state variable L to the parameter X, L_t is the value of the state variable L at time t, X_t is the value of the parameter X at time t, ΔL_t is the change of state variable L at t, and ΔX_t is the change of parameter X at time t.

When parameter X_j changes, the sensitivity of state variables (L_1, L_2, $\cdots$, L_N) to X_j is expressed as (S_{L1}, S_{L2}, $\cdots$, S_{LN}), then the sensitivity of the model to parameter X_j can be calculated as follows:

$$S_{Xj} = \frac{1}{N} \sum_{i=1}^{N} S_{Li}, \tag{11}$$

We selected population growth rate, urbanization rate, water price change rate, rural domestic water quota, crop planting area growth rate, irrigation water quota, industrial output value growth rate, water consumption per industrial output value of ten thousand Yuan, and ecological water growth rate as main parameters, and selected domestic water consumption, irrigation water consumption, industrial water consumption, ecological water consumption, and total water consumption as main variables. We ran the model after increasing main parameters by 10% year by year in the forecast time (2018–2050), and calculated sensitivity values of the model to main parameters by Equations (10) and (11).

3. Results and Discussion

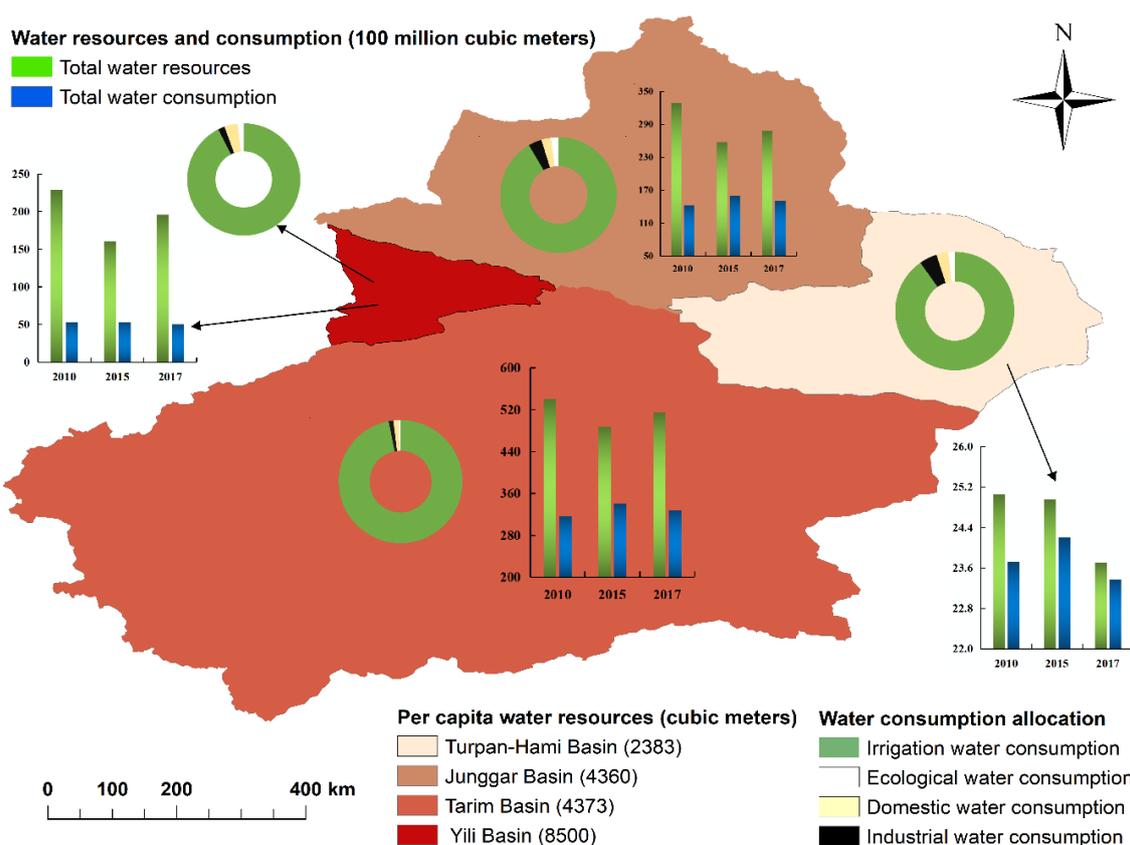### 3.1. Development and Utilization of Water Resources in Xinjiang

The basic characteristics of water resources in Xinjiang are scarcity, uncertainty, and unbalanced distribution in time and space [4,5]. Xinjiang accounts for one-sixth of the total land area in China, but its water resources account for only 4% (Figure 3a). The water resource in Xinjiang is 101.3 billion m^3 in wet years, 90.3 billion m^3 in regular years, and 72.6 billion m^3 in dry years [47–49,60–62]. With the development of social economy, the total water consumption in Xinjiang has been increasing from 48 billion m^3 in 2000 to 55.2 billion m^3 in 2017. The water consumption in 2017 accounted for about 61% of the water resource in normal years and 76% in dry years (Figure 3c). As the population increases, the per capita water resources have shown a decreasing trend, from 5255 m^3 in 2000 to 4144 m^3 in 2017 (Figure 3b). In addition, the extensive economic and social development in Xinjiang resulted in low utilization efficiency of water resources [49]. The irrigation water quota was 8500 m^3/hectare, the water consumption per industrial output value of ten thousand Yuan was 41 m^3, and the rural

domestic water quota was 89.5 L/(person·day) in Xinjiang in 2016 [49]. Affected by factors such as population density, crop planting structure, water-saving level, and water resource conditions, the water consumption indicators of the four sub-regions vary greatly. For example, the agricultural irrigation water quota reached 11000 m^3/hectare and the domestic water consumption of rural residents reached 130 L/(person·day) in the Turpan-Hami Basin. This was mainly due to the low level of water-saving, the large area of high water-consuming crops, and the living habits of rural residents in this basin [49]. In these areas, the per capita housing area, rural bathing habits, toilet flushing types, metering conditions of water meter, and water supply methods all contribute to high rural domestic water consumption in these areas [67]. From the perspective of water consumption structure, irrigation water consumption accounts for about 93% of total water consumption, while ecological water consumption is severely "squeezed", accounting for only 1% of total water consumption (Figure 3d). Under the constraints of scarce water resources, Xinjiang will face serious pressure in the future, and the contradiction between water supply and demand will become increasingly prominent [7,8].
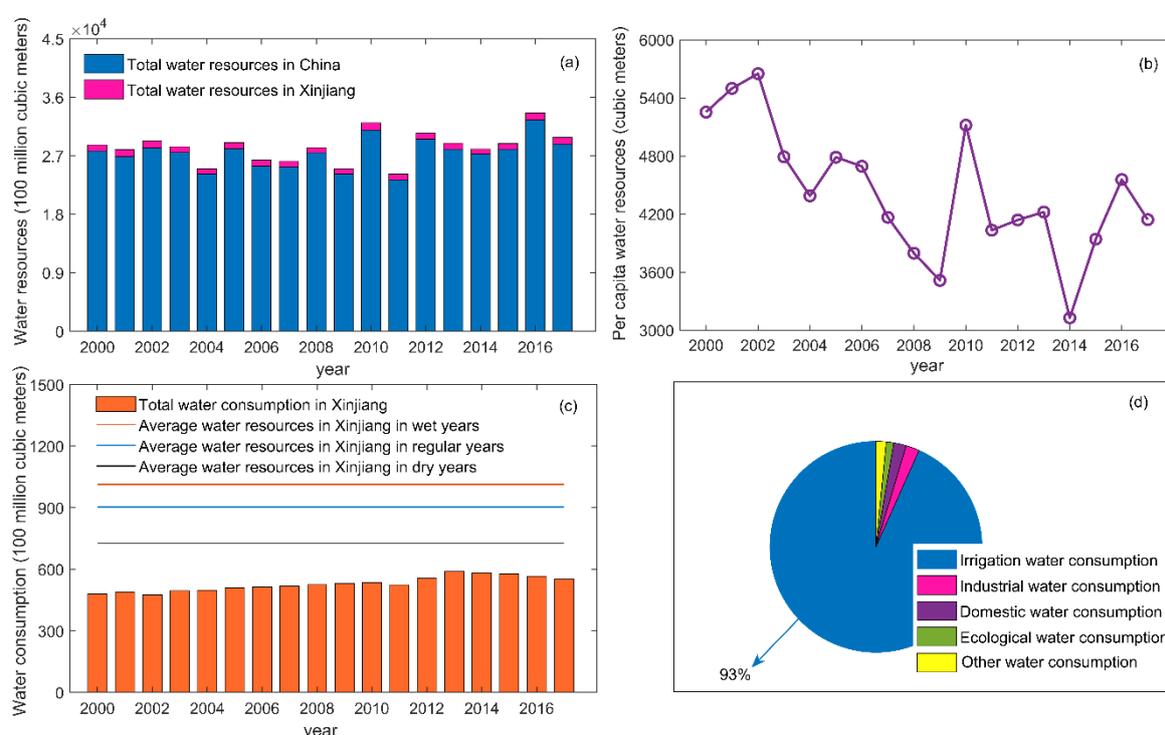
Figure 3. Development and utilization of water resources in Xinjiang. (**a**) is the comparison between water resources in Xinjiang and in China; (**b**) is the changes in per capita water resources; (**c**) is the changes in total water resources and water consumption; (**d**) is the allocation of water consumption.

Figure 4 reports the development and utilization of water resources in the sub-regions of Xinjiang. The total water resources in the four regions have shown a decreasing trend. The Yili Basin has the highest per capita water resources with 8500 m^3, followed by the Tarim Basin with 4373 m^3, the Junggar Basin with 4360 m^3, and the Turpan-Hami Basin with 2388 m^3. The Tarim Basin has the highest water consumption with 33.8 billion m^3, accounting for 67% of total water resources. The water consumption in the Junggar Basin is 15.8 billion m^3, accounting for 48% of its water resources. The water consumption in the Yili Basin is 5.2 billion m^3, accounting for 23% of its water resources. The Turpan-Hami Basin faced serious pressure on water resources, and its water consumption accounted for 98.6% of total water resources. The number and water storage of Karezes in the Turpan-Hami Basin are decreasing gradually and are on the verge of attenuation. Under the constraints of scarce water resources, the contradiction between water supply and demand will become increasingly prominent in the Turpan-Hami Basin and the Tarim Basin.

Figure 4. Development and utilization of water resources in sub-regions of Xinjiang (2016). The pie chart represents the allocation of water consumption, and bar chart represents the changes in water consumption and water resources.

3.2. Validity Evaluation of SD Models

SD needs to be sufficiently predictable that users can estimate what would happen if they were to establish particular rules [23]. We employed the intuitive test, historical test, and sensitivity test methods to evaluate the validity of SD models [65,66]. Intuitive test results show that the model has appropriate boundaries, reasonable structures, and correct units of variables, which meets the basic requirements of simulation. We selected the variables with complete historical data such as population, crop planting area, industrial output value, ecological water consumption, irrigation water consumption, and total water consumption as the test objects, and calculated the relative error between simulated values and real values of these variables. Figure 5 reported the historical test results of the main variables. It can be seen that simulated values of main variables are very close to actual values, and relative errors are less than 10%. Among them, relative errors between simulated values and actual values of variables such as population, industrial output value, crop planting area, ecological water consumption are less than 1%. To test the robustness of SD models, we performed the sensitivity test on main parameters. Table 2 showed that the sensitivity of the main parameters is lower than 0.4, indicating that SD models are insensitive to changes in most parameters. In summary, SD models can reflect the objective system well, which can be used to predict the changes in water supply and demand in Xinjiang and its sub-regions in the future.
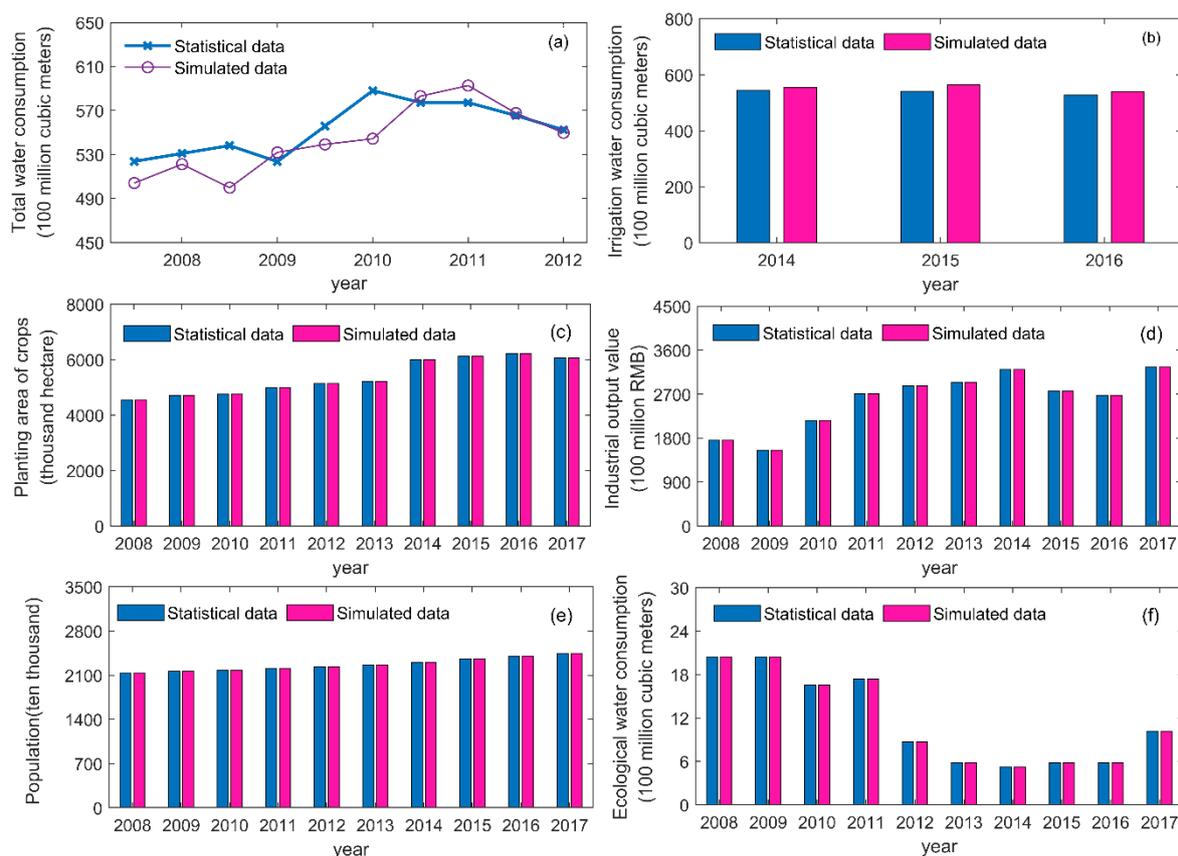
Figure 5. Historical test results of main variables. (**a–f**) are comparisons between simulated data and statistical data for total water consumption, irrigation water consumption, crop planting area, industrial output value, population, and ecological water consumption, respectively.

Table 2. Sensitivity test results of main parameters.

Parameters	Sensitivity
Population growth rate (%)	0.05
Urbanization rate (%)	0.10
Water price change rate (%)	0.01
Rural domestic water quota (L/(person·day))	0.03
Water consumption per industrial output value of ten thousand Yuan (m^3)	0.20
Industrial output growth rate (%)	0.10
Irrigation water quota (m^3/hectare)	0.39
Crop planting area growth rate (%)	0.27
Ecological water consumption growth rate (%)	0.24

3.3. Simulation and Prediction under Different Scenarios

By changing the value of the decision variable, the SD model can accurately simulate water consumption under different scenarios and support decisions for water utilization. We selected parameters with high sensitivity as decision variables, and designed different scenarios by changing the values of these parameters. Table 3 reported the values of decision variables under different scenarios for Xinjiang. The values of decision variables under different scenarios for sub-regions were provided in the Supplementary Materials (Table S1). It is noted that, out of the four scenarios reported in Table 3, only scenario 4 considers water-saving plans. For scenarios 1, scenario 2 and scenario 3, the water consumption indicators such as rural domestic water quota, irrigation water quota, and water consumption per industrial output value of ten thousand Yuan in the next 30 years are the same as the current indicators in Xinjiang [49]. Using debugged SD models, we simulated the changes in water

supply and demand in Xinjiang and its sub-regions in the next 30 years (2018–2050). Figures 6 and 7 reported future water consumption under different scenarios in Xinjiang and sub-regions, respectively.

Table 3. Values of decision variables under different scenarios for Xinjiang.

Scenario	Decision Variable	2020	2030	2040	2050
Scenario 1	Rural domestic water quota (L/(person·day))	89.5	89.5	89.5	89.5
	Water consumption per industrial output value of ten thousand Yuan (m^3)	40.7	40.4	40.2	40
	Irrigation water quota (m^3/hectare)	8500	8000	7500	7000
	Urbanization rate	0.520	0.610	0.680	0.730
	Crop planting area growth rate	0.040	0.030	0.020	0.010
	Industrial output value growth rate	0.030	0.015	0.010	0.006
	Ecological water consumption growth rate	0.120	0.050	0.020	0.010
Scenario 2	Rural domestic water quota (L/(person·day))	89.5	89.5	89.5	89.5
	Water consumption per industrial output value of ten thousand Yuan (m^3)	40.7	40.4	40.2	40
	Irrigation water quota (m^3/hectare)	8500	8000	7500	7000
	Urbanization rate	0.624	0.732	0.816	0.876
	Crop planting area growth rate	0.056	0.042	0.028	0.014
	Industrial output value growth rate	0.042	0.021	0.014	0.008
	Ecological water consumption growth rate	0.120	0.050	0.020	0.010
Scenario 3	Rural domestic water quota (L/(person·day))	89.5	89.5	89.5	89.5
	Water consumption per industrial output value of ten thousand Yuan (m^3)	40.7	40.4	40.2	40
	Irrigation water quota (m^3/hectare)	8500	8000	7500	7000
	Urbanization rate	0.520	0.610	0.680	0.730
	Crop planting area growth rate	0.040	0.030	0.020	0.010
	Industrial output value growth rate	0.030	0.015	0.010	0.006
	Ecological water consumption growth rate	0.320	0.280	0.240	0.180
Scenario 4	Rural domestic water quota (L/(person·day))	85	80	75	70
	Water consumption per industrial output value of ten thousand Yuan (m^3)	39	35	32	28
	Irrigation water quota (m^3/hectare)	8500	7300	6000	5000
	Urbanization rate	0.541	0.641	0.714	0.767
	Crop planting area growth rate	0.042	0.032	0.021	0.011
	Industrial output value growth rate	0.032	0.016	0.011	0.006
	Ecological water consumption growth rate	0.220	0.190	0.150	0.110

- Scenario 1

In scenario 1, the water consumption indicators such as rural domestic water quota, irrigation water quota, and industrial water quota in the next 30 years are the same as current situations. For rate variables such as urbanization rate, crop planting area growth rate, industrial output value growth rate, and ecological water consumption growth rate, we employed the trend forecasting method to predict future values of these variables. We named scenario 1 the regular development scenario. The prediction results of this scenario report that the total water consumption will continue to increase in Xinjiang in the next 30 years, and it will exceed the total water resources in dry years, regular years, and wet years in 2024, 2034, and 2041, respectively. The maximum water shortage will be 8.2 billion m^3 in wet years, 19.2 billion m^3 in regular years, and 36.9 billion m^3 in dry years (Figure 6a). The total water consumption will not be guaranteed and the contradiction between water supply and demand will become more prominent in the future under this scenario. Other studies [7–9] verified our results. We obtained water consumption for human activities by summing irrigation water consumption, industrial water consumption, and domestic water consumption. By 2050, both water consumption for human activities and ecology water consumption will show an increasing trend and will account for about 90 and 10% of total water consumption, respectively. By 2020, 2030, 2040, and 2050, water consumption

for human activities will reach 61.2, 78.3, 89.9, and 97.8 billion m³, ecological water consumption will reach 2.9, 7, 10, and 11.6 billion m³, and the total water consumption will reach 64.1, 85.3, 99.9, and 109.5 billion m³, respectively (Figure 6a). Under this scenario, water consumption in sub-regions will increase in the future. The total water consumption will be guaranteed in the Yili Basin, while a water shortage will occur and the contradiction between water supply and demand will be prominent in the Turpan-Hami Basin, Junggar Basin, and Tarim Basin after 2030 (Figure 7a). Xinjiang has formulated some short-term directives and measures [68,69] for the sustainable use of water resources. Under this scenario, the future water consumption for Xinjiang and the four sub-regions cannot be guaranteed, and serious water supply and demand conflicts will occur. Therefore, this scenario cannot achieve sustainable development, which is contrary to local directives and policies [68,69].
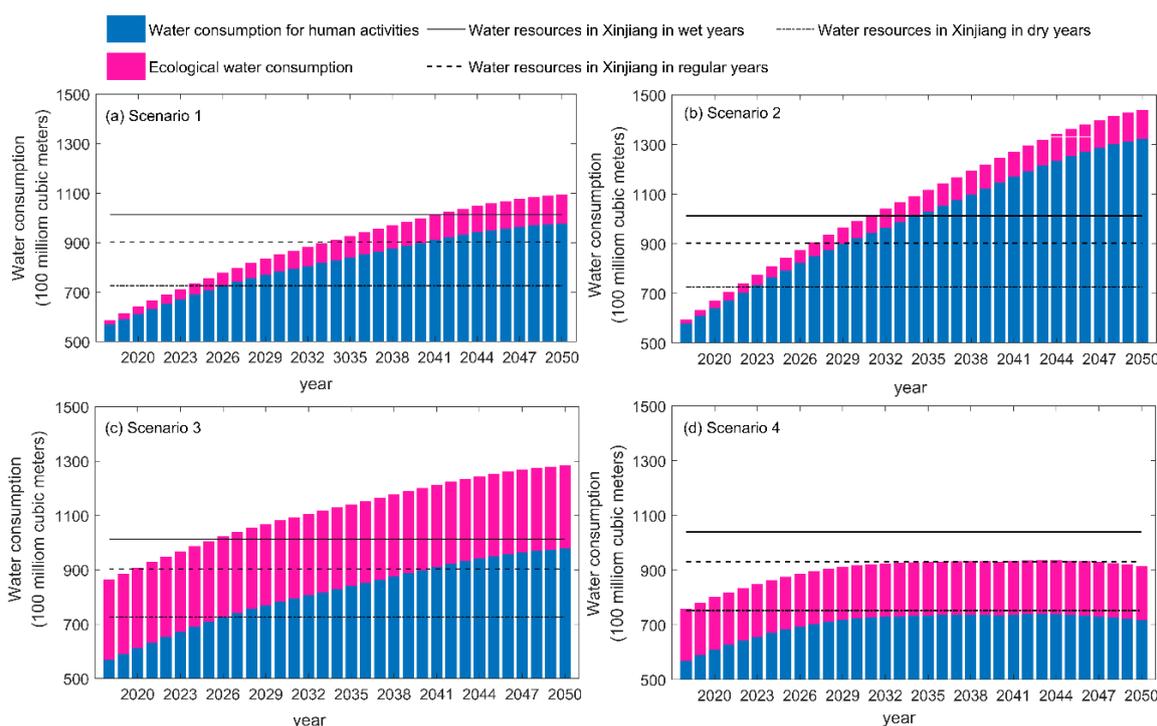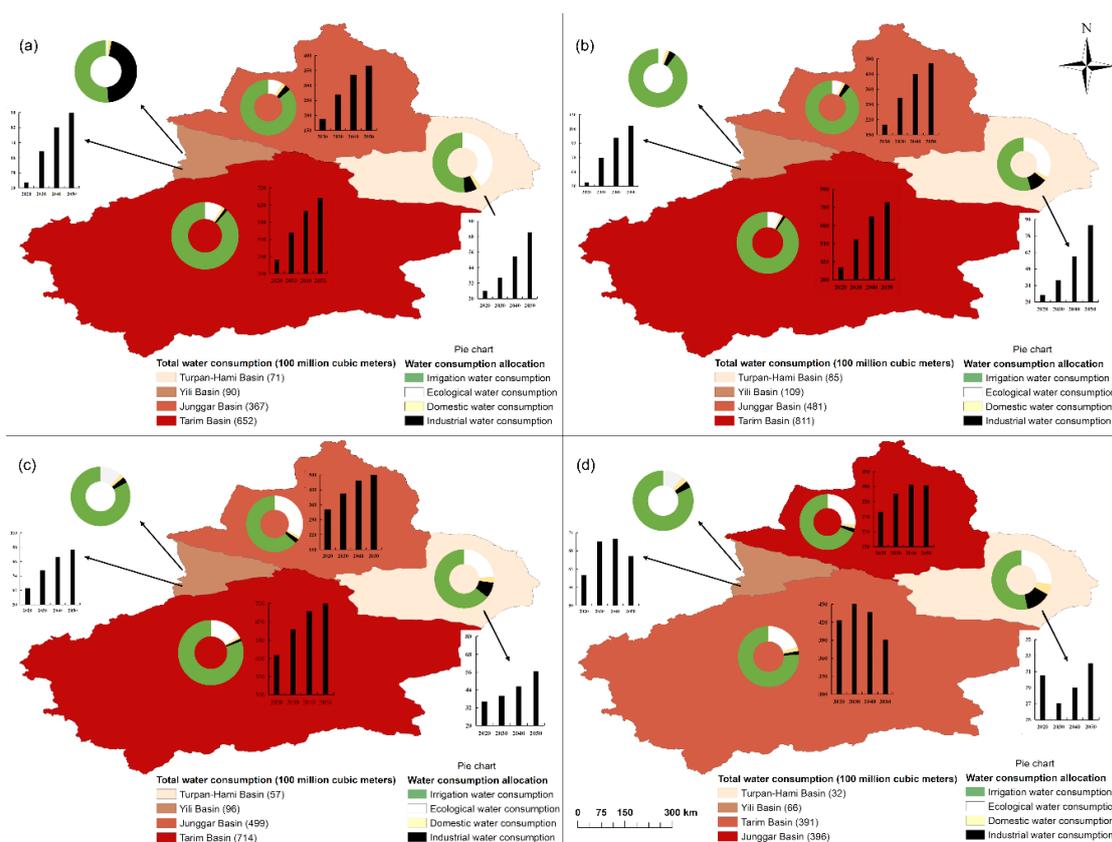

Figure 6. The future water consumption in Xinjiang under different scenarios. The blue rectangle represents water consumption for human activities and red rectangle represents ecological water consumption. (**a–d**) are water consumption under scenario 1, scenario 2, scenario 3, and scenario 4, respectively.

- Scenario 2

In scenario 2, the growth rate of crop planting area and industrial output value is 40% higher than the regular development scenario, and the urbanization rate is 20% higher than the regular development scenario. The water resources are allocated to economic development in priority in this scenario and we named it the economic priority scenario. Compared with scenario 1, Xinjiang will face a more serious pressure of water resources and more prominent contradiction between water supply and demand. Under this scenario, the total water consumption will continue to increase in the next 30 years, and it will exceed total water resources in dry years, regular years, and wet years in 2022, 2027, and 2031, respectively. The maximum water shortage will be 42.7 billion m³ in wet years, 53.7 billion m³ in regular years, and 71.4 billion m³ in dry years (Figure 6b). Both water consumption for human activities and ecology water consumption will show an increasing trend. Compared with regular development scenario, the proportion of water consumption for human activities will increase, accounting for about 93% of total water consumption, while the ecological water consumption will account for about 7% of total water consumption. By 2020, 2030, 2040, and 2050, water consumption for human activities will reach 64.1, 92.3, 114.6, and 132.4 billion m³, ecological water consumption will reach 3, 7, 10,

and 11.6 billion m^3, and total water consumption will reach 67.1, 99.3, 124.6, and 144 billion m^3, respectively (Figure 6b). Under this scenario, the total water consumption in sub-regions will increase in the future. The total water consumption can be guaranteed in the Yili Basin, while a water shortage will occur and the contradiction between supply and demand will be prominent in Turpan-Hami Basin, Junggar Basin, and Tarim Basin after 2025 (Figure 7b). According to local instructions and policies [68,69], economic development cannot be at the cost of destroying the ecological environment, and coordinated development of economy and ecology should be achieved. The disadvantage of this scenario is that excessive economic development in the future will result in a slow decline in the biomass of the ecosystem [46], which will aggravate the contradiction between human activities and the ecosystem and fail to achieve sustainable development. Therefore, this scenario is not suitable for future water utilization in Xinjiang.

Figure 7. The future water consumption in sub-regions of Xinjiang under different scenarios. The pie charts represent the allocation of water consumption, and bar charts represent the changes in total water consumption. (**a**–**d**) are water consumption under scenario 1, scenario 2, scenario 3, and scenario 4, respectively.

- Scenario 3

Xinjiang is an important ecological barrier and its ecological environmental protection is important guarantees for sustainable development in China [55], while excessive irrigation water consumption leads to decreasing ecological water consumption and accelerates regional ecological crises [56,57]. In scenario 3, ecological water demand is fully guaranteed, and population growth rate, urbanization rate, crop planting area growth rate, industrial output value growth rate, and water consumption indicators are the same as regular development scenario. We named this scenario the ecological priority scenario. Water resources in Xinjiang primarily result from precipitation and glacier snow meltwater in the mountainous regions. Generally, glacier snow meltwater flows out of mountainous areas and is utilized by humans in plain areas. The mountain ecosystem is a relatively closed and

self-sufficient ecosystem, which is rarely affected by human activities. Based on the land-use data of ESA CCI, we employed the area quota method [70] and the grey prediction method [71] to calculate the ecological water demand in non-mountainous areas of Xinjiang in the next 30 years. The water demand quotas of different vegetation types are determined by the relevant data of the main references [70–73]. Under the ecological priority scenario, the total water consumption will continue to increase in Xinjiang in the next 30 years, and it will exceed the total water resources in dry years, regular years, and wet years in 2018, 2021, and 2026, respectively. The maximum water shortage will be 27.1 billion m^3 in wet years, 38.1 billion m^3 in regular years, and 55.8 billion m^3 in dry years (Figure 6c). The pressure of water resources under this scenario is higher than the regular development scenario and lower than the economic priority scenario. Compared with regular development scenario, the proportion of ecological water consumption will increase, accounting for about 27% of total water consumption, while water consumption for human activities will account for about 73% of total water consumption. By 2020, 2030, 2040, and 2050, water consumption for human activities will reach 61.2, 78.3, 89.9, and 97.8 billion m^3, ecological water consumption will reach 29.6, 29.9, 30.2, and 30.5 billion m^3, and total water consumption will reach 90.8, 108.2, 120.1, and 128.4 billion m^3, respectively (Figure 6c). Defining sustainable transition pathways of social-ecological systems still remains challenging in the context of global change because of highly non-linear interactions between the social and the ecological systems [23,46]. Under this scenario, ecological water demand will be fully guaranteed, while it squeezes water consumption for human activities. Therefore, this scenario cannot achieve the coordinated development between human activities and the ecosystem and is contrary to local directives and policies [68,69].

- Scenario 4

The extensive economic development has caused low water utilization efficiency [49], and water-saving is the key to solving the contradiction between water supply and demand in Xinjiang. Israel is a global leader in water-saving irrigation and sewage treatment by increasing revenue and reducing expenditure and rationally planning water resources [74]. Xinjiang has similar climatic conditions with Israel, but water-saving technology is seriously lagging behind Israel [75,76]. According to relevant plans [68,69] and considering the current water consumption indicators, we formulated scenario 4. By 2050, the reuse rate of urban domestic water consumption and industrial wastewater will reach 75%, and the irrigation and industrial water quota in Xinjiang will be the same as the current level in Israel. Under this scenario, urbanization rate, crop planting area growth rate, and industrial output value growth rate are 5% higher than scenario 1. Besides, the ecological water demand is 65% guaranteed and the remaining 35% is supplied by precipitation. The prediction results under this scenario reported that the total water consumption will be stable first and decline after 2030 in Xinjiang because we considered the water-saving plan determined according to relevant plans. In wet years, a water remain will occur and remaining water resources will exceed 12 billion m^3. In regular years, the total water demand will be guaranteed. By 2050, water consumption for human activities and ecology water consumption will occupy about 80% and 20% of total water consumption, respectively. By 2020, 2030, 2040, and 2050, water consumption for human activities will reach 61.1, 72.4, 73.5, and 71.7 billion m^3, ecological water consumption will reach 19.2, 19.4, 19.6, and 19.8 billion m^3, and the total water consumption will reach 80.3, 91.9, 93.2, and 91.5 billion m^3, respectively (Figure 6d). Under this scenario, the total water consumption can be guaranteed in the Yili Basin and Tarim Basin. By 2020, 2030, 2040, and 2050, the total water consumption will reach 42.3, 46.2, 43.7, and 39.1 billion m^3 in the Tarim Basin, 29, 36.3, 39.5, and 39.6 billion m^3 in the Junggar Basin, 3.1, 2.7, 2.9, and 3.2 billion m^3 in the Turpan-Hami Basin, and 6, 7.1, 7.2, and 6.6 billion m^3 in the Yili Basin, respectively (Figure 7d). Under this scenario, future water demand for human activities and ecological system in Xinjiang will be guaranteed, and coordinated development between economy and ecological system can be achieved. Therefore, this scenario is the best plan for achieving sustainable use of water resources in the future. Xinjiang has formulated some short-term directives and measures [68,69] for the sustainable use of

water resources. This scenario is consistent with local policy perspectives, and it can provide references for future water use plans and the formulation of related directives.

3.4. Decision Support on Sustainable Use of Water Resources

The above analysis results show that the contradiction between water supply and demand will be prominent, and not possible to achieve sustainable development in Xinjiang in the future under scenario 1, scenario 2, and scenario 3. Under scenario 4, the economic development level will be higher than the current level; ecological water demand will be guaranteed by 65%; the total water demand will be guaranteed, which will achieve sustainable development. Therefore, scenario 4, which harmonizes economy, ecology, and water conversation, will be the best plan for sustainable utilization of water resources in Xinjiang in the future. The extensive social and economic development is the main factor restricting the utilization of water resources in Xinjiang. Irrigation water consumption accounts for more than 90% of the total water consumption in Xinjiang [49]. Reducing irrigation water demand is the guarantee for the sustainable utilization of water resources in Xinjiang [6]. Scenario 4 proposes to expand the scale of water-saving facilities and focus on the development of water-saving irrigation technologies, especially the Tarim Basin and Turpan-Hami Basin (Table 4). By 2050, the reuse rate of urban domestic water consumption and industrial sewage in Xinjiang will reach 75%. By 2020, 2030, 2040, and 2050, the rural domestic water quota will be 85, 80, 75, and 70 L/(person·day), water consumption per industrial output value of ten thousand Yuan will be 39, 35, 32, and 28 m^3, and irrigation water quota will be 8500, 7300, 6000, and 5000 m^3/hectare in Xinjiang, respectively. In addition, scenario 4 proposes to control the development speed of agriculture and industry. By 2020, 2030, 2040, and 2050, the crop planting area growth rate will be 0.042, 0.032, 0.021, and 0.011, the industrial output value growth rate will be 0.032, 0.016, 0.011, and 0.006, respectively. For the sub-regions, the Turpan-Hami Basin and Junggar Basin will face serious water shortages in the future. To realize the sustainable use of water resources in the sub-region, scenario 4 proposes that the rural domestic water quota will be 75 L/(person·day) in the Yili Basin and Junggar Basin, 110 L/(person·day) in the Turpan-Hami Basin, and 50 L/(person·day) in the Tarim Basin; the water consumption per industrial output value of ten thousand Yuan will be 54 m^3 in the Yili Basin, 21 m^3 in the Junggar Basin, 43 m^3 in the Turpan-Hami Basin, and 40 m^3 in the Tarim Basin; the irrigation water quota will be 5000 m^3/hectare in four basins by 2050 (Table 4).

It should be noted that the scenario designs can also have more detailed considerations. For example, for high water-consuming crops such as cotton, different planting ratios can be set to predict changes in future water consumption. According to the existing research, the water demand of cotton in each growth stage is relatively high. After the blooming stage, the water content of the 0–80 cm soil layer needs to reach 70–80% of the field water holding capacity. The average water consumption of cotton is more than 10,500 m^3/hectare [77]. The current planting area of cotton is 2.49 million hectares, accounting for about 40% of the total crop planting areas in Xinjiang [62]. If the planting area of cotton is reduced by 10%, water resources will decrease by 2.61 billion m^3 in Xinjiang. Studies [78] have shown that it is no longer suitable to grow cotton in large areas in Xinjiang. In the above four scenarios, we did not consider the planting structure of crops. In the long term, we recommend adjusting planting structure and implementing water-saving irrigation in Xinjiang. For example, strictly controlling the cultivation area of high water-consuming crops, and encouraging to plant low water-consuming and greater salinity tolerance crops under the premise of ensuring national food security and regional food production planning goals. It is possible to increase the cost of water-consuming crops to make farmers unwilling to plant these crops and increase prices to make textile companies more willing to choose chemical fibers. For water-scarce regions, making more efficient utilization of available water by increasing the efficiency of agricultural irrigation become increasingly important [79]. Studies have shown that the water consumption of low-pressure sprinkler irrigation is 60% less water consumption than ordinary flood irrigation [80]. We recommend adopting drip irrigation and low-pressure sprinkler irrigation according to local conditions and improving canal

seepage control standards. It is noted that financial limitations on infrastructure leave some cities in great water stress. In financially limited regions, increased investment will be needed to create adequate water-saving infrastructure [79]. In addition, the centralized irrigation of crops can reduce the loss of irrigation water [80]. Therefore, we recommend that transforming the personal operation of the planting industry into a large-scale centralized operation. Research confirms that climate change and urban growth will intensify water competition between cities and agriculture [23,79,81]. Therefore, investments in improving agricultural water use could thus serve as an important global change adaptation strategy, especially in arid areas [3,19].

Table 4. Sustainable utilization plan of water resources for Xinjiang and its sub-regions in the next 30 years.

Region	Decision Variable	2020	2030	2040	2050
Xinjiang	Rural domestic water quota (L/(person·day))	85	80	75	70
	Water consumption per industrial output value of ten thousand Yuan (m^3)	39	35	32	28
	Irrigation water quota (m^3/hectare)	8500	7300	6000	5000
	Urbanization rate	0.541	0.641	0.714	0.767
	Crop planting area growth rate	0.042	0.032	0.021	0.011
	Industrial output value growth rate	0.032	0.016	0.011	0.006
	Ecological water consumption growth rate	0.220	0.190	0.150	0.110
Yili Basin	Rural domestic water quota (L/(person·day))	105	95	85	75
	Water consumption per industrial output value of ten thousand Yuan (m^3)	70	67	60	54
	Irrigation water quota (m^3/hectare)	7500	7000	6000	5000
	Urbanization rate	0.420	0.473	0.536	0.599
	Crop planting area growth rate	0.032	0.021	0.011	0.005
	Industrial output value growth rate	0.042	0.032	0.021	0.011
	Ecological water consumption growth rate	2.120	2.790	4.950	5.050
Junggar Basin	Rural domestic water quota (L/(person·day))	105	95	85	75
	Water consumption per industrial output value of ten thousand Yuan (m^3)	29	26	23	21
	Irrigation water quota (m^3/hectare)	6200	6000	5500	5000
	Urbanization rate	0.788	0.861	0.903	0.935
	Crop planting area growth rate	0.042	0.032	0.011	0.005
	Industrial output value growth rate	0.032	0.021	0.011	0.001
	Ecological water consumption growth rate	0.120	0.190	0.250	0.310
Turpan-Hami Basin	Rural domestic water quota (L/(person·day))	130	130	120	110
	Water consumption per industrial output value of ten thousand Yuan (m^3)	50	50	48	43
	Irrigation water quota (m^3/hectare)	10000	7000	6000	5000
	Urbanization rate	0.840	0.861	0.882	0.893
	Crop planting area growth rate	0.011	0.021	0.021	0.032
	Industrial output value growth rate	0.021	0.024	0.043	0.062
	Ecological water consumption growth rate	0.420	0.150	0.080	0.050
Tarim Basin	Rural domestic water quota (L/(person·day))	65	60	55	50
	Water consumption per industrial output value of ten thousand Yuan (m^3)	50	49	45	40
	Irrigation water quota (m^3/hectare)	9600	8000	6300	5000
	Urbanization rate	0.399	0.452	0.515	0.567
	Crop planting area growth rate	0.035	0.021	0.011	0.005
	Industrial output value growth rate	0.032	0.021	0.011	0.006
	Ecological water consumption growth rate	0.290	0.163	0.067	0.039

4. Conclusions

Global warming has led to a serious crisis on regional water resources. Establishing DSS on sustainable use of water resources for arid areas is an increasingly critical problem. Selecting Xinjiang as the target, this paper developed a SD model. Through the simulation operation of the model,

we achieved the decision on sustainable utilization of water resources. The main conclusions of this study are as follows: (1) The extensive economic development is the main factor restricting the sustainable utilization of water resources in Xinjiang. Water-saving will be the key to solving the contradiction between water supply and demand in the future. (2) To realize the sustainable use of water resources, this paper proposes to expand the scale of water-saving facilities and focus on the development of water-saving irrigation technologies, especially the Tarim Basin and Turpan-Hami Basin. By 2050, the reuse rate of urban domestic water consumption and industrial sewage in Xinjiang will reach 75%. By 2050, the rural domestic water quota will be 70 L/(person·day), water consumption per industrial output value of ten thousand Yuan will be 28 m^3, and irrigation water quota will be 5000 m^3/hectare in Xinjiang, respectively. At the same time, Xinjiang should control the development speed of agriculture and industry. By 2050, the crop planting area growth rate will be 0.011 and the industrial output value growth rate will be 0.006. It is noted that some short-term directives and measures have been formulated for the sustainable use of water resources in Xinjiang [68,69]. For example, the local directive stipulates that the irrigation water quota should be 8350 m^3/hectare in 2020 [68]. This research suggests that this indicator should be 8500 m^3/hectare in 2020 by fully considering the actual local conditions and water-saving potential. This research is consistent with local policy perspectives, so it can provide references for future water use plans and the formulation of related directives. (3) For the sub-regions, the Turpan-Hami Basin and Junggar Basin will face serious water shortages in the future. In order to realize the sustainable use of water resources, this paper proposed that the rural domestic water quota will be 75 L/(person·day) in the Yili Basin and Junggar Basin, 110 L/(person·day) in the Turpan-Hami Basin, and 50 L/(person·day) in the Tarim Basin; the water consumption per industrial output value of ten thousand Yuan will be 54 m^3 in the Yili Basin, 21 m^3 in the Junggar Basin, 43 m^3 in the Turpan-Hami Basin, and 40 m^3 in the Tarim Basin; the irrigation water quota will be 5000 m^3/hectare in four basins by 2050. (4) To achieve the goals above, we recommend the following: (a) Adjust the planting structure and strictly control the cultivation area of high water-consuming crops. (b) Adopt drip irrigation and low-pressure sprinkler irrigation according to local conditions and improve canal seepage control standards. (c). Transform the personal operation of the planting industry into a large-scale centralized operation. (d). Formulate rewards and punishments of water use to encourage rural and urban residents to save water.

As next steps, we plan to introduce more variables into the SD models and obtain more data through field surveys to more accurately estimate regional water consumption. For example, we can add variables related to the service industry into the model to better simulate changes in water consumption. In addition, we plan to develop a model based on climate change data such as Earth system data products to simulate and predict changes in total water resources, and combine it with the results of this article to provide better decision support. Finally, the scale of this study is four sub-regions of Xinjiang. Downscaling to districts and counties can provide better supports for decision on regional water utilization.

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