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Analysis of the Cooperative Carrying Capacity of Ulan Suhai Lake Based on the Coupled Water Resources–Water Environment–Water Ecology System

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Abstract: In order to maximize the carrying benefits of Ulan Suhai Lake and utilize the important role of the Inner Mongolia plateau lake basin in restoring its ecology and conserving water, the carrying capacity of the water resources, water environment, and water ecology of Ulan Suhai Lake was determined using system theory and synergy theory, and a 17-item evaluation index system of the three levels of the water resources, water environment, and water ecology (including the ice-covered period) was established using hierarchical analysis. In addition, a system dynamics model of the synergistic carrying capacity of the water resources–water environment–water ecology of Ulan Suhai Lake was constructed. A principal component analysis was conducted on the indicators of the Ulan Suhai Lake survey; six main sensitive factors were selected, and five simulation scenarios (status continuation mode, development continuation mode, conservation continuation mode, comprehensive mode I, and comprehensive mode II) were designed to regulate the configuration, taking into account the actual local development needs. Using 2014 as the base year and 2014–2020 as the validation period, a dynamic simulation analysis of the carrying capacity of the Ulan Suhai Lake from 2014 to 2050 was carried out. The results show that Ulan Suhai Lake has a poor carrying capacity level and a fragile carrying state. Three of the five simulated scenarios lead to severe water shortages, while the others affect economic growth. Considering these aspects, it was found that comprehensive mode I performed better, and for the configuration of this scheme, the following countermeasures, and suggestions to enhance the carrying capacity of the Ulan Suhai Lake are proposed. The rate of change in the industrial water use should be reduced by 20%, the discharge coefficients of the domestic and industrial wastewater should be reduced by 10% and 50%, respectively, the effective utilization coefficient of agricultural irrigation should be increased to 0.71, and the wastewater treatment rate should be increased by 30%. These measures can ensure the protection of the water resources while ensuring economic development.

Keywords: collaborative bearing capacity; analytic hierarchy process; SD model; simulation prediction; Ulan Suhai Lake

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1. Introduction

The term "bearing capacity" refers to the maximum load that the research subject can withstand without significant deformation or destruction [1,2]. At present, the main methods of researching the water resource and water environment carrying capacity are the ecological footprint method [3], principal component analysis [4], backpropagation (BP) neural network model [5], routine prediction method [6], fuzzy comprehensive evaluation [7], the multiple objective decision-making method [8], and system dynamics method [9–11]. Most scholars have researched the carrying capacity as part of the theory of sustainable development, not through separate studies. For example, Harris et al. proposed that in areas with more agricultural water usage, the water resource carrying capacity could represent an important reference standard for the development potential of the region [12].

The carrying capacity of water resources in Xinjiang was first studied in the middle and late 1980s [13]. Chang Yuting [14], Tian Pei [15], and Zhao Xiaoqing et al. [16] used the water footprint model, variable weight technique for order of preference by its similarity to the ideal solution (TOPSIS) model, and system dynamics (SD) model to comprehensively evaluate the carrying capacities of regional water resources. Of course, the carrying capacity is studied based on the establishment of an index system. Most previous studies on the carrying capacity have been limited to the water resources carrying capacity or water environment carrying capacity, and most of these studies ignored the water ecology indicators [17,18]. Although some studies have emphasized the importance of quantifying the water ecology, most of the indicator data were for water resources [19]. As a result, previous research includes studies of only the water resources carrying capacity, water environment carrying capacity, or water ecology carrying capacity, without linking the water resources, water environment, and water ecology in carrying capacity research. Less research related to the synergistic carrying capacity has been conducted, which cannot comprehensively and systematically define the carrying capacity.

Ulan Suhai Lake has directly affected the regional water quality and water ecological safety due to the long-term acceptance of receding farmland water from the Hetao irrigation district, urban domestic sewage, and industrial sewage [20]. Moreover, the water pollution in Ulan Suhai Lake has intensified, and its ecological function has degraded [21], leading to a serious ecological crisis [22].

Therefore, to maximize the carrying benefits of Ulan Suhai Lake and utilize the important role of the Inner Mongolia plateau lake basin in restoring its ecology and conserving water, the carrying capacity of the water resources, water environment, and water ecology of Ulan Suhai Lake was established using system theory and synergy theory to carry out synergistic carrying capacity assessment and calculations. In addition, the functional configuration of the coupled water resources, water environment, and water ecology system of Ulan Suhai Lake was simulated under multiple scenarios. Then, a synergistic regulation scheme for the different subsystems was developed to assess the synergistic carrying capacity of Ulan Suhai Lake under the current and future changing environment. The water resource, water environment, and water ecology indicators were selected, the analytic hierarchy process method was used to calculate the weights, and a water resource, water environment, and water ecology subsystem model was established. Synergy theory was used to combine the various subsystems and establish a calculation model of the collaborative bearing capacity of Ulan Suhai Lake.

In order to further predict the dynamic development of the future bearing capacity of Ulan Suhai Lake, a dynamic system model was constructed, the value of the decision-making variable was changed, and five scenarios were designed to dynamically simulate the main indicators and the collaborative bearing capacity of the system. These five scenarios were the status continuation mode, development continuation mode, conservation continuation mode, comprehensive mode I, and comprehensive mode II. Then, the optimal control scheme was selected according to the corresponding bearing capacity of each scheme.

2. Materials and Methods

2.1. Overview of the Study Area and Data Sources

Ulan Suhai Lake, located at 40°36′–41°03′ N, is a freshwater lake in China. It is an important part of the drainage system of the Hetao irrigation district in Inner Mongolia and is located at the end of the Hetao Plain (Figure 1). According to the thematic mapper TM satellite remote-sensing images acquired from 2018 to 2020, the specific data sources of land use in Ulan Suhai Lake are shown in Table 1, reference [10,11,23]. The lake freezes at the end of November and thaws from late March to April. Ulan Suhai Lake is an important water body for domestic sewage, industrial sewage, and agricultural retreat water in the Hetao irrigation district. It was mildly eutrophic from 2015 to 2017 and has remained moderately eutrophic since 2018 [24], with a high diversity of phytoplankton pollution indicator species [25]. Currently, the government departments responsible for Ulan Suhai Lake strictly adhere to the "three zones and three lines" rule, strictly control the ecological environment zoning according to the "three lines and one list" rule, implement the 14th Five-Year Plan for the ecological environmental protection and management of the Ulan Suhai Lake basin with high standards, and adopt seasonal and environmental protection measures in the protected area. The plan includes a seasonal fishing ban in the protected area and prohibits fishermen from fishing in the core area and buffer zone. Ulan Suhai Lake is currently in a subhealthy state [26].

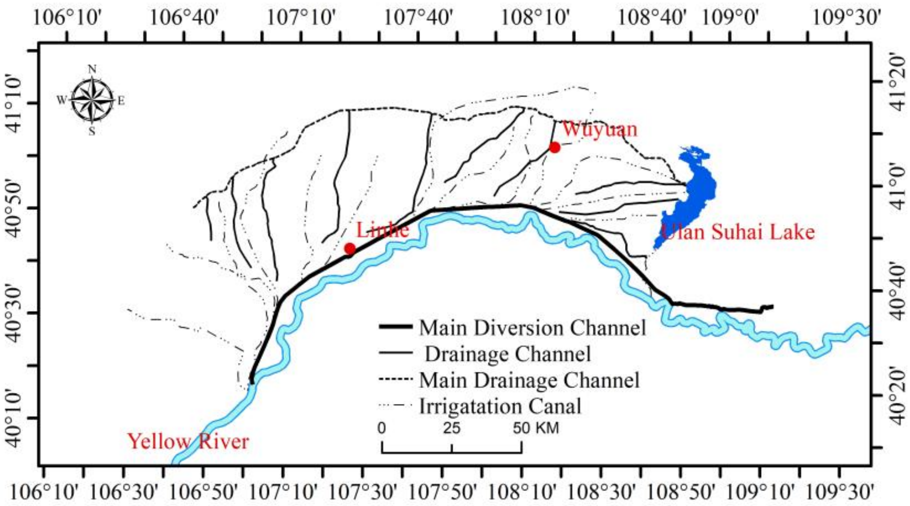

Figure 1. The irrigation and drainage system in Hetao.

Table 1. Land use in Ulan Suhai Lake.

Land Use in Ulan Suhai Lake					
Average Water Depth (m)	**Maximum Storage Capacity (Million m^3)**	**Water Area (km^2)**	**Reed Growth Area (km^2)**	**Area of the Open Water Area (km^2)**	**Aquatic Weed Covered Area (km^2)**
2.21	300	337.78	205.27	105.22	27.34

The index data used in this study were mainly obtained from the Inner Mongolia Autonomous Region Statistical Yearbook (2014–2020), the Bayannaoer City Statistical Yearbook (2014–2020), the Bayannaoer City Water Resources Bulletin (2014–2020), the Resource and Environmental Science Statistical Data (2014–2020), and the Bayannaoer City Water Supplies Bureau, the Bayannaoer City Ecological Environmental Protection Bureau, and other departments (2014–2020). The specific sources of the data are described in Table 2.

Table 2. Index Data Source.

Data Source	
Indicators	**Historical Data Sources**
Total water resources	Bayannaoer City Water Resources Bulletin
Total basin water use	Bayannaoer City Water Resources Bulletin
Industrial water consumption	Bayannaoer City Water Resources Bulletin
Ecological environmental water consumption	Bayannaoer City Water Resources Bulletin
Effective utilization coefficient of farmland irrigation	Bayannaoer City Water Resources Bulletin
Total wastewater discharge	Bayannaoer City Ecological Environmental Protection Bureau

Table 2. *Cont.*

Data Source	
Indicators	**Historical Data Sources**
Industrial COD and NH_3-N discharge	Bayannaoer City Ecological Environmental Protection Bureau
Agriculture COD and NH_3-N discharge	Bayannaoer City Ecological Environmental Protection Bureau
Urban COD and NH_3-N discharge	Bayannaoer City Ecological Environmental Protection Bureau
Pollutant distribution ratio of the lake during ice-covered period	Water environment team inspection
Ratio of lake district up to the standard for water quality	Water environment team inspection
Biodiversity	Water environment team inspection
Water area eutrophication	Water environment team inspection
Duration of ice-covered period	Yellow River Conservancy Commission of the Ministry of Water Resources
Regional wetland area	Bayannaoer City Statistical Yearbook
Forest area	Bayannaoer City Statistical Yearbook
Grassland area	Bayannaoer City Statistical Yearbook
Area of zone	Bayannaoer City Statistical Yearbook
Regional water area	Bayannaoer City Statistical Yearbook
Total population	Bayannaoer City Statistical Yearbook
Natural growth rate	Bayannaoer City Statistical Yearbook
Product of primary industry	Bayannaoer City Statistical Yearbook
Value of industrial industry	Bayannaoer City Statistical Yearbook
Value of agriculture industry	Bayannaoer City Statistical Yearbook
Speed of urbanization	Bayannaoer City Statistical Yearbook

2.2. Research Methods

2.2.1. Indicator Selection and Bearing Capacity Calculation

a. Indicator Selection

The bearing capacity is a large and complex system. The main purpose of studying the carrying capacity is to ensure a good ecological environment. With the water resources, water environment, and water ecology as the limiting factors, the relationships between these subsystems result in the bearing capacity reflecting the safety of the water intake in this area. Consequently, it is necessary to consider the bearing capacity of the coupled water resource–water environment–water ecology system and their coupling mechanism. Based on the research goals of this study, the indicators were selected based on the principles of scientificity, operability, and screening coordination [27]. The indicators for the Ulan Suhai Lake investigation were analyzed using the analytic hierarchy process, and then, the factor load matrix was rotated using the orthogonal rotation method with maximum variance. The rotated load value greater than 0.6 was taken as the bearing capacity evaluation index [28]. A total of 17 specific indicators were selected to form the bearing capacity evaluation system index for Ulan Suhai Lake (Table 3).

Table 3. Indicators of collaborative bearing capacity evaluation system.

Rule Hierarchy	Index Hierarchy	Type
Water resources carrying capacity (A)	Development and utilization rate of water resources (A1)	Pressure type
	Per capita water resources (A2)	Support type
	Water use amount per 10,000 yuan of industrial value added (A3)	Pressure type
	Ecological environment water consumption rate (A4)	Pressure type
	Per capita water area (A5)	Support type
	Effective utilization coefficient of farmland irrigation (A6)	Support type

Table 3. *Cont.*

Rule Hierarchy	Index Hierarchy	Type
Water environment carrying capacity (B)	Wastewater discharge intensity (B1)	Pressure type
	Industrial pollution intensity index (B2)	Pressure type
	Agricultural pollution intensity index (B3)	Pressure type
	Urban pollution intensity index (B4)	Pressure type
	Ratio of lake district up to the standard for water quality (B5)	Support type
	Pollutant distribution ratio of the lake during ice-cover period (B6)	Pressure type
Water ecology carrying capacity (C)	Submerged plant coverage ratio (C1)	Support type
	Water area eutrophication index (C2)	Pressure type
	Duration of ice-covered period (C3)	Support type
	Water conservation index (C4)	Support type
	Biodiversity index (C5)	Support type

b. Indicator weight calculation and collaborative bearing capacity calculation

In this paper, the hierarchical analysis method is used to weight the indicators. The specific steps have been described by Yang Qian et al. [29]. The calculation of the bearing capacity was conducted as follows.

(1). Data standardization

In this paper, the Z-score method is used to standardize the original data. The specific steps are as follows.

(a) Determine the expectation $\overline{X}$ and standard deviation of each indicator S.

$$\overline{X} = \frac{\sum_{i=1}^{n} X_i}{n} \tag{1}$$

$$S = \sqrt{\frac{\sum_{i=1}^{n} \left(X_{\overline{I}} - \overline{X}\right)^2}{n-1}} \tag{2}$$

(b) Carry out standard treatment.

$$E_{\overline{z}} = \left(X_{\overline{i}} - \overline{X}\right)/S \tag{3}$$

where $E_{\overline{z}}$ is the standardized value, and $X_{\overline{i}}$ is the actual value, n is the total number of indicators, $i - 1,2,3 \ldots$ n, X is the raw data of the indicator.

(2). Establish the calculation model of the minute bearing capacity and determine the bearing capacity.

$$E_j = \sum_{i=1}^{m} w_{\overline{i}} \cdot E_{\overline{i}} \tag{4}$$

where E_j is the sub-carrying capacity of the water resources, water ecology, and water environment, $E_{\overline{i}}$ is the standardized value of the ith index, $w_{\overline{i}}$ is the weight of the ith index, m is the number of indicators, and j is the number of subsystems.

(3). Establish a collaborative bearing capacity calculation model to determine the bearing capacity.

$$E = \left[\sum_{1}^{3} \left(w_j E_j\right)^2\right]^{1/2} \tag{5}$$

where E is the collaborative bearing capacity value, w_j is the weight of the jth sub-bearing capacity, and E_j is the value of the jth sub-bearing capacity.

(4). According to previous studies, determine the level and state of the carrying capacity (Table 4).

Table 4. Bearing capacity level and state judgment table.

Value of Bearing Capacity	0–0.2	0.2–0.5	0.5–0.8	0.8–1
Bearing level State	Inferior Collapse	Poor Fragile	General General	Good Good elasticity

2.2.2. Construction of System Dynamics Model

a. Parameterization and structural analysis of system dynamics model

In this study, Bayannur City in Inner Mongolia was defined as the system boundary of the carrying capacity model, 2014–2050 was the simulation time, of which 2014–2020 was the test phase, 2021–2050 was the simulation prediction phase, the step length was 1 year, and 2018 was the base year. The initial values of the indicators were the data for the base year, which were used to predict the values of the indicators in 2021–2050 and to predict the collaborative bearing capacity of Ulan Suhai Lake. After a large number of literature element frequency statistics and in reference to the related studies [30–33], the collaborative bearing capacity was divided into the carrying capacity of each subsystem, i.e., the water resources, water environment, and water ecology. The water resources subsystem included the population, the total water resources, water use amount per 10,000 yuan of industrial value added, and the effective utilization coefficient of farmland irrigation. The water environment subsystem included the socioeconomic indicators, wastewater discharge intensity, pollutant emission intensity, and distribution ratio of the pollutants during the ice-covered period. The water ecology subsystem indicators included the lakewater quality, eutrophication status, biodiversity, and length of ice-cover period.

b. Construction of system dynamics model

In this study, the spatial boundary of the system was defined as Bayannur City in the Inner Mongolia Autonomous Region; the temporal boundary was 2014–2050, the historical test period was 2014–2020, and the forecasting regulation period was 2021–2050. The iteration interval was 1a, with 2014 as the base year, and the initial values of the variables were simulated using the relevant actual data for 2014 for the regulation period. First, before running the simulation using the model, the equations and their units in the model were checked for errors, and if there was an error, the error was corrected and rechecked according to the prompt message. Second, the relevant parameters of the model were simulated and run many times, and the behaviors of the key variables were compared to analyze the causes and trends. Finally, in order to verify whether the model could accurately reflect the actual synergistic carrying capacity operation, 2014–2020 was selected as the historical testing time period to determine the matching degree (mse) between the simulated and actual values.

In order to study the collaborative bearing capacity of Ulan Suhai Lake and analyze its change trend, the SD model was established based on the selected indicators and the SD principle. The model mainly comprised nine state variables and 71 model parameters. The model had horizontal variables, auxiliary variables, and constant variables. The model involves more variables. The main parameter equations are listed in Table 5. The model was then used to predict the trends of the carrying capacity of Ulan Suhai Lake from 2021 to 2050 under five scenarios: the status continuation mode, development continuation mode, conservation continuation mode, comprehensive mode I, and comprehensive mode II. The model was divided into three subsystems, each of which consisted of several variables and equations, and each subsystem was linked via the synergy theory.

Table 5. Principal parameters and their equations.

Per Capita Water Resources = Total Water Resources/Total Population
Per capita domestic water consumption = total water consumption/total population
Development and utilization rate of water resources = total water supply/total water resources
Total water resources = volume of groundwater resources + volume of surface water resources
Wastewater discharge intensity = total wastewater discharge/regional gross domestic product
Agricultural water consumption = farmland irrigation water use + forest, animal husbandry, and fishery storage water consumption
Total amount of sewage discharge = quantity of industrial wastewater effluent + quantity of domestic sewage effluent
Total water supply = reclaimed water volume + groundwater supply + surface water supply
Variability of volume of industrial water used = volume of industrial water used * variation ratio of industrial water used
Water use amount per 10,000 yuan of industrial value added = total water consumption/gross industrial output value
Added value of primary industry = product of primary industry * rate of primary industry increase
Added value of secondary industry = product of secondary industry * rate of secondary industry increase
Added value of tertiary industry = product of tertiary industry * rate of tertiary industry increase
Urban pollutant emission intensity = (urban COD and NH_3-N discharge)/value of tertiary industry
Agriculture pollutant emission intensity = (agriculture COD and NH_3-N discharge)/value of primary industry
Industrial pollutant emission intensity = (industrial COD and NH_3-N discharge)/value of industrial industry
Water resources carrying capacity= water use amount per 10,000 yuan of industrial value-added carrying capacity + per capita water area carrying capacity + per capita water resources carrying capacity + effective utilization coefficient of farmland irrigation carrying capacity + development and utilization rate of water resources carrying capacity + ecological environment carrying capacity
Water environment carrying capacity = agriculture pollutant emission intensity carrying capacity + urban pollutant emission intensity carrying capacity + industrial pollutant emission intensity carrying capacity + wastewater discharge intensity carrying capacity + pollutant distribution ratio of the lake during ice-covered period carrying capacity + ratio of lake district up to the standard for water quality carrying capacity
Water ecology carrying capacity = duration of ice-covered period carrying capacity + water area eutrophication index carrying capacity + water conservation index carrying capacity + submerged plant coverage ratio carrying capacity + biodiversity index carrying capacity
Collaborative bearing capacity = $[(0.4126 * \text{water resources carrying capacity})^2 + (0.3275 * \text{water environment carrying capacity})^2 + (0.2599 * \text{water ecology carrying capacity})^2)^{1/2}$

2.2.3. Scenario Plan Design

Based on previous studies [34–36] and taking into account the current situation of the water resource utilization and socioeconomic development in Bayannur City, the population growth rate, urbanization rate, rural water consumption per capita, urban water consumption per capita, domestic wastewater discharge coefficient, sewage treatment rate, effective irrigation area, domestic wastewater discharge coefficient, and industrial wastewater coefficient were selected as the decision parameters. Five scenarios (i.e., the status continuation mode, conservation continuation mode, development continuation mode, comprehensive mode I, and comprehensive mode II) were developed to simulate the collaborative bearing capacity of Ulan Suhai Lake from 2021 to 2050 and to find out the changes in the collaborative bearing capacity under the existing socioeconomic development conditions. In the scenario design, the different scenarios were simulated by adjusting the values of the decision parameters, which were mainly based on the 13th Five-Year Plan for Population Development in the Inner Mongolia Autonomous Region, the 13th Five-Year Plan for National Economic and Social Development in the Inner Mongolia Autonomous Region, the Plan for Ecological Protection and High-Quality Development in the Yellow River Basin in the Inner Mongolia Autonomous Region, the Inner Mongolia Autonomous Region Water Resources Bulletin 2018–2020, and the Inner Mongolia Autonomous Region Water Quota Standards. The main parameters are listed in Table 6.

Table 6. Main parameters of the scenario modes.

Parameters	Status Continuation Mode	Development Continuation Mode	Conservation Continuation mode	Comprehensive Mode I	Comprehensive Mode II
Population growth rate (‰)	2.61	5.61	4.61	2.61	2.61
Urbanization rate (%)	54.2	75.6	54.2	54.5	59.5
Per capita rural water consumption (Liters/person/day)	85	120	75	80	75
Per capita urban water consumption (Liters/person/day)	116	150	90	105	116
Wastewater treatment rate (%)	75	75	100	95	95
Farmland irrigation quota (m^3/hm^2)	475	495	445	460	475
Water consumption of forest, animal husbandry, and fishery (million m^3)	2.375	2.85	1.875	2.075	1.875
Domestic sewage discharge coefficient	0.7	0.76	0.6	0.6	0.56
Industrial sewage discharge coefficient	0.51	0.55	0.43	0.46	0.43
Rate of primary industry increase (%)	6	9	3	4	4
Variation ratio of industrial water use (%)	1.2	1.4	0.8	1	0.9
Rate of tertiary industry increase (%)	11	24	11	13	13

The status continuation mode assumes the development of the existing development trend and takes the parameter values in 2014 as the initial values of all of the parameters for the simulation of the collaborative bearing capacity during 2021–2050. The development continuation mode is based on the status continuation mode, strengthening the protection of water resources, and the strict control of agriculture, industry, and domestic water use to ensure the sustainable use of water resources. The conservation continuation mode is based on the continuation of the status continuation mode, but only the ecological red line is guaranteed, and the economy is rapidly developed in accordance with the objectives of the 13th Five-Year Plan for the Inner Mongolia Autonomous Region. Comprehensive mode I and comprehensive mode II consist of a combination of economic development and water conservation, ensuring that economic development is maintained at a medium to high rate while focusing on water resource efficiency.

3. Results and Discussion

3.1. Weight and Bearing Capacity Value

The weights and combined weights of each index in each subsystem using the AHP are presented in Table 7, the standardized values obtained using Equations (1)–(3) are presented in Appendix A (Table A1), and the bearing capacity results for each system calculated using Equations (4) and (5) are presented in Figure 2.

Table 7. Weight results of chromatography analysis.

Target Hierarchy	Criterion Hierarchy	Criterion Hierarchy Weight	Index Hierarchy	Index Weight	Combination Weight
Bearing capacity A	Water resources carrying capacity B1	0.4126	Development and utilization rate of water resources (A1)	0.199	0.082
			Per capita water resources (A2)	0.240	0.099
			Water use amount per 10,000 yuan of industrial value added (A3)	0.213	0.088
			Ecological environment water consumption rate (A4)	0.105	0.043
			Per capita water area (A5)	0.126	0.052
			Effective utilization coefficient of farmland irrigation (A6)	0.117	0.048
	Water environment carrying capacity B2	0.3275	Wastewater discharge intensity (B1)	0.117	0.038
			Industrial pollution intensity index (B2)	0.199	0.065
			Agricultural pollution intensity index (B3)	0.240	0.078
			Urban pollution intensity index (B4)	0.213	0.070
			Ratio of lake district up to the standard for water quality (B5)	0.126	0.041
			Pollutant distribution ratio of the lake during ice-covered period (B6)	0.105	0.034
	Water ecology carrying capacity B3	0.2599	Submerged plant coverage ratio (C1)	0.237	0.062
			Water area eutrophication index (C2)	0.133	0.035
			Duration of ice-covered period (C3)	0.133	0.035
			Water conservation index (C4)	0.295	0.077
			Biodiversity index (C5)	0.202	0.052

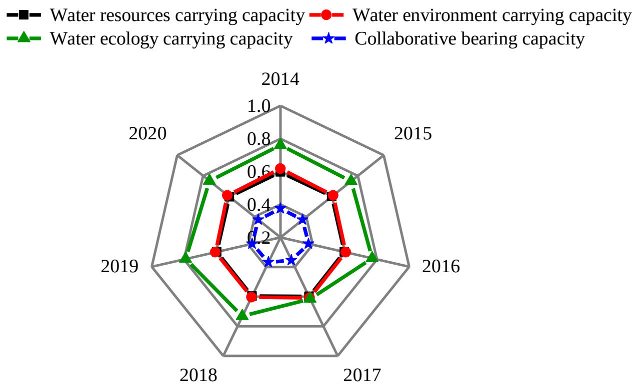

Figure 2. Bearing capacity of each system.

3.2. Validation of the Model

In this study, 2014–2020 was taken as the validation period of the model. The simulated and actual values were compared, and it was found that the model has an error of within ±10% and is effective [37]. Thus, it could be used to predict the collaborative bearing capacity of Ulan Suhai Lake from 2021 to 2050. In this study, three subsystems were selected to verify the bearing capacity. The results and errors are presented in Table 8. The relative errors between the simulated and actual values of the three subsystems were found to be within ±10%, indicating that the accuracy of the model was good, and it could be used for the subsequent simulation and prediction analysis.

Table 8. Comparison of simulated and actual carrying capacity of Ulan Suhai Lake from 2014 to 2020.

Year	Water Resources Carrying Capacity				Water Environment Carrying Capacity			
	Actual Value	Simulated Value	Residual	Mse	Actual Value	Simulated Value	Residual	Mse
2014	0.597	0.596	−0.001	$2.066*10^{-6}$	0.617	0.622	0.005	$2.153*10^{-4}$
2015	0.598	0.597	−0.001		0.609	0.622	0.013	
2016	0.598	0.597	−0.001		0.606	0.622	0.016	
2017	0.598	0.598	0.000		0.607	0.622	0.015	
2018	0.596	0.598	0.002		0.603	0.622	0.019	
2019	0.596	0.598	0.002		0.604	0.622	0.018	
2020	0.596	0.598	0.002		0.610	0.621	0.012	
Year	**Water Ecology Carrying Capacity**				**Collaborative Bearing Capacity**			
	Actual Value	**Simulated Value**	**Residual**	**Mse**	**Actual Value**	**Simulated Value**	**Residual**	**Mse**
2014	0.761	0.764	0.003	$1.165*10^{-3}$	0.375	0.376	0.001	$2.356*10^{-5}$
2015	0.748	0.728	−0.020		0.372	0.371	−0.001	
2016	0.770	0.785	0.015		0.375	0.379	0.005	
2017	0.614	0.569	−0.045		0.355	0.352	−0.002	
2018	0.731	0.680	−0.051		0.368	0.365	−0.003	
2019	0.788	0.842	0.053		0.376	0.388	0.011	
2020	0.751	0.741	−0.010		0.372	0.373	0.001	

3.3. Model Prediction Analysis

In this study, 2014 was taken as the simulation base year, and the prediction time was 2021–2050. Based on the simulation results obtained using the constructed dynamic system model, the trends of the six main influencing factors (i.e., the total population, total water consumption, domestic water consumption, agricultural water consumption, per capita water resources, and the total amount of sewage discharge) of the Ulan Suhai Lake system from 2021 to 2050 are shown in Figure 3.

The model (Figure 3d) predicts that agricultural water consumption slowly increases during 2021–2050 because Ulan Suhai Lake is in the Hetao irrigation district, in which the water resources are required and used for crop irrigation. With the increase in the urbanization level, the per capita water resource utilization remains low [38] and domestic water consumption slowly increases (Figure 3c), which is consistent with the population growth rate. The per capita water resources exhibit a decreasing trend [39], but they remain positive (Figure 3b), which means that this increase is not caused by the decrease in the total water resources and is most likely related to the rapid growth of the total population. With the growth of urbanization and the population increase, the sewage volume also increases dramatically (Figure 3e). The growth of the sewage discharge causes domestic sewage pollution in the villages and towns to become an important source of water pollution in the region. In addition, Ulan Suhai Lake is an important component of the drainage system of the Hetao irrigation district in Inner Mongolia (Figure 1). Ulan Suhai Lake has been receiving chemical fertilizer and pesticide residues from the Hetao irrigation district and discharging them into urban domestic sewage and industrial sewage for a long time [20], which has aggravated the water pollution in Ulan Suhai Lake for a long time and has directly threatened the ecological water security of the Yellow River. With the rapid development of living standards, and the pressure on water resources increases, the main problem of which being how to address the maximum rate of water usage in the case of a limited water supply.

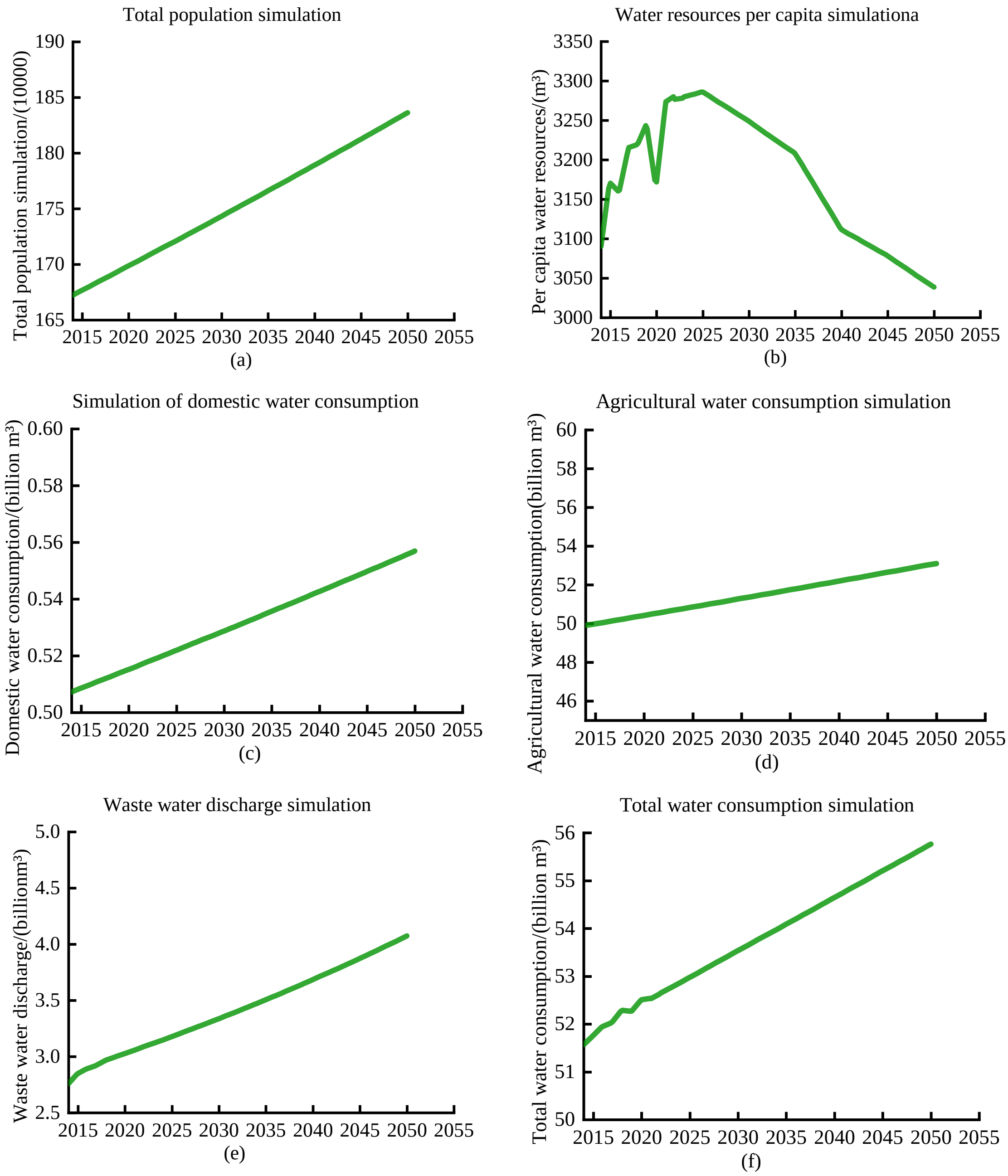

Figure 3. Variation trends of the main indexes of the carrying capacity system of Ulan Suhai Lake from 2014 to 2050. (**a**) Total population simulation; (**b**) Water resources per capita simulation; (**c**) Simulation of domestic water consumption; (**d**) Agricultural water consumption simulation; (**e**) Waste water discharge simulation; (**f**) Total water consumption simulation.

3.4. Model Scenario Simulation Analysis

The six main influencing factors (i.e., the total population, total water consumption, domestic water consumption, agricultural water consumption, per capita water consumption, and the total amount of sewage discharge) in the Ulan Suhai Lake system from 2021 to 2050 were simulated under different scenarios. The change trends of these indicators are shown in Figure 4.

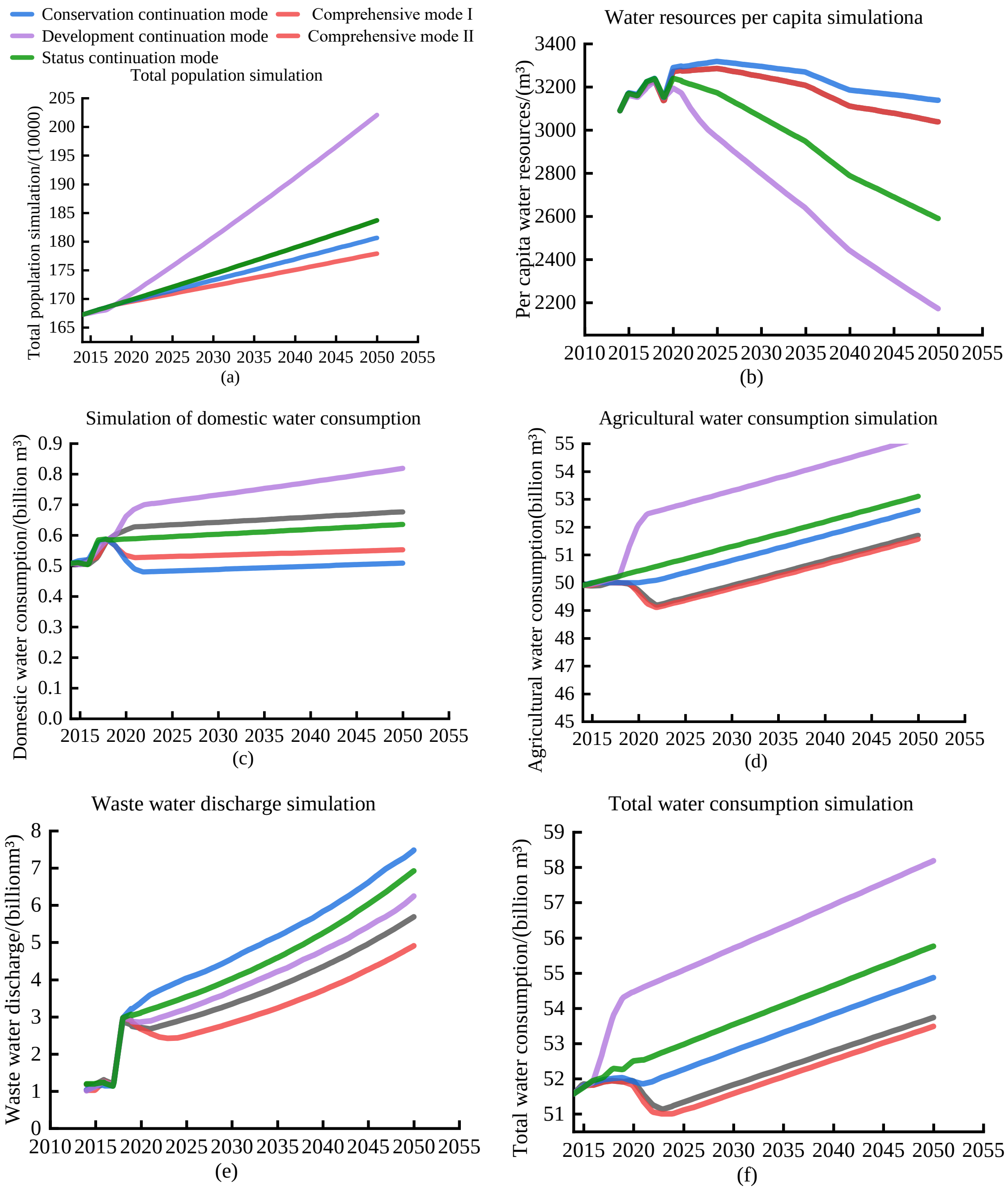

Figure 4. Change trends of the main indicators under the various scenarios. (**a**) Total population simulation; (**b**) Water resources per capita simulationa; (**c**) Simulation of domestic water consumption; (**d**) Agricultural water consumption simulation; (**e**) Waste water discharge simulation; (**f**) Total water consumption simulation.

As can be seen from Figure 4, under the five scenarios, the total population (Figure 4a), domestic water consumption (Figure 4c), agricultural water consumption (Figure 4d), total water consumption (Figure 4f), and the total amount of sewage discharge (Figure 4e) all slowly increase, while the per capita water resources decrease (Figure 4b). The specific data are presented in Table 9. The status continuation mode and development continuation mode ensure stable economic development. Under the status quo continuation model and the development continuation model, the annual average per capita water resources decrease by 13.88 m^3 and 25.75 m^3, and the annual growth rate decreases by 0.004% and 0.98%, respectively. Under the conservation continuation mode, the per capita water resources basically remain in a stable state, indicating that the pressure on the water resources is the lowest, but this mode limits economic development. In contrast, the two comprehensive modes are superior in that the per capita water resources change slowly while ensuring stable economic development and slowing the increase in the total water consumption, which improves the water resources utilization in the short term. This shows that the balance of the per capita water resources can be guaranteed in the long term in the future through measures such as improving water use efficiency, reducing sewage discharge, and improving sewage treatment and utilization.

Table 9. Annual growth and annual growth rate.

	Comprehensive Mode II		Comprehensive Mode I		Development Continuation Mode		Conservation Continuation Mode		Status Continuation Mode	
	Annual Increment	Annual Growth rate	Annual Increment	Annual Growth Rate	Annual Increment	Annual Growth Rate	Annual Increment	Annual Growth Rate	Annual Increment	Annual Growth Rate
Total population (Ten thousand people)	0.296	0.17%	0.296	0.18%	0.970	0.53%	0.375	0.20%	0.463	0.30%
Per capita water resources (m^3)	1.441	0.06%	1.441	0.06%	−25.750	−0.98%	1.584	1.50%	−13.880	4.70%
Domestic water consumption (hundred million m^3)	0.001	0.21%	0.001	0.24%	0.009	1.34%	0.013	0.10%	0.004	0.60%
Agricultural water consumption (hundred million m^3)	0.050	0.10%	0.046	0.09%	0.147	0.28%	0.042	0.10%	0.089	0.20%
Total amount of sewage discharge (hundred million m^3)	0.125	4.46%	0.108	4.45%	0.279	6.65%	0.093	4.20%	0.159	5.10%
Total water consumption (hundred million m^3)	0.060	0.11%	0.053	0.10%	0.184	0.34%	0.042	0.10%	0.117	0.20%

3.5. Analysis of the Variation Trends of the Bearing Capacity of Each Subsystem and the Collaborative Bearing Capacity under the Different Modes

The three subsystems of Ulan Suhai Lake (the water resources, water environment, and water ecology) and the large, complex system of the synergy of the three were simulated under the different scenarios, and the results were analyzed (Figures 5 and 6).

As is shown in Figure 5a, under the five modes, the state and level of the water resources carrying capacity are general, and the simulation results of the water resources carrying capacity are as follows: conservation continuation mode > comprehensive mode I > comprehensive mode II > status continuation mode > development continuation mode. The carrying capacity of the water resources subsystem is generally weak [40] and in a fragile and generally critical state [38]. It decreases under the development continuation mode and increases under the conservation continuation mode and the two comprehensive modes, and the growth is most obvious during 2021–2040. Under the status continuation mode, the slow growth of the population and gross domestic product (GDP) causes the water resources carrying capacity to increase more slowly. If the current situation continues, the water shortage will increase further after 2035, which is not conducive to the development of Bayannur City. If regulatory measures are adopted, the carrying capacity of the water resources in 2035 (2045) will be 0.597 (0.598) under the status continuation mode, while the relative ratios of the carrying capacity of the water resources in 2035 (2045) under the development continuation mode, conservation continuation mode, comprehensive mode I, and comprehensive mode II will be −14.4% (−17.2%), +29.5% (+34.4%), +26.8% (+31.75), and +21% (+25.8%). This demonstrates that the adoption of water conservation and water protection measures while ensuring economic development can alleviate the pressure on the water resources caused by economic and population development, and the comprehensive mode can largely reduce the pressure on the water resources subsystem. The conservation continuation mode takes more into account the protection of the water resources, so the water carrying capacity value increases significantly, but the GDP decreases by 3.5%, which inhibits the economic development of the region. The development continuation mode considers slowing down the growth rate of the GDP in 20355; that is, under the comprehensive mode I, as opposed to the status continuation mode, the growth rates of the primary and secondary industries are both reduced by 20%, and the growth rate of the tertiary industries reaches 55%. The effective utilization coefficient of agricultural irrigation will increase to 0.70, and the rate of industrial water use will decrease by 20% to improve the utilization rate of the water resources, which will more effectively relieve the pressure on the water resources subsystem [41], improve the per capita water resources, and protect the water resources while ensuring economic development.

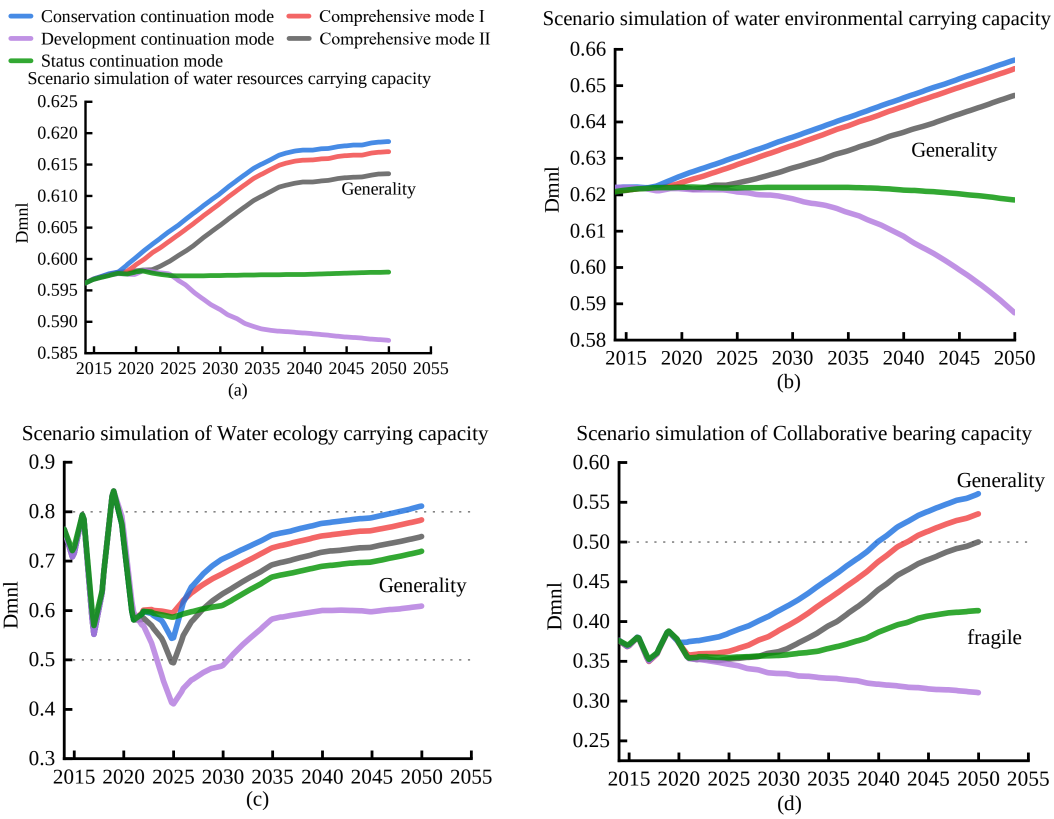

Figure 5. Simulations of bearing capacity under different scenarios. (**a**) Scenario simulation of water resources carrying capacity; (**b**) Scenario simulation of water environmental carrying capacity; (**c**) Scenario simulation of Water ecology carrying capacity; (**d**) Scenario simulation of Collaborative bearing capacity. Analysis of variations in carrying capacity of water resources subsystem.

a. Analysis of variations in the carrying capacity of the water environment subsystem

As can be seen from Figure 5b, under the status continuation mode, the increases in the population and economic development increase the demand for water resources in all aspects, leading to increased pollution of the water environment and affecting the water ecology. The water environment carrying capacity initially exhibits a constant trend and then decreases [42], and is mainly affected by the total amount of water resources and other factors [43]. The carrying capacity of the water environment decreases under both the status continuation mode and development continuation mode, but it decreases faster under the development continuation mode. Under the other three modes, it increases and remains average over time. Compared with the water environment carrying capacity value of 0.610 (0.621) under the status continuation mode in 2035 (2045), the water environment carrying capacity values in 2035 (2045) under the development continuation mode, conservation continuation mode, comprehensive mode I, and comprehensive mode II are −11.2% (−33.6%), +30.9% (+51.0%), +27.3% (+47.2), and +16.2% (+35.3%). Under the status continuation mode, the wastewater treatment rate increases to 95%, the domestic wastewater discharge coefficient decreases by 20%, and the industrial wastewater discharge coefficient decreases by 50%. The COD and NH_3-N emission concentrations of the industrial, agricultural, and domestic water decrease by 50%, 30%, and 10%, and the growth rates of the primary, secondary, and tertiary industries all increase to 65%. The effluent standard of the wastewater plant is increased to Class III or IV type water standards, to support the development of water-saving agriculture, and other measures are taken to protect the water environment. Thus, all three modes can alleviate the water environment pollution, the pressure on the water environment subsystem is correspondingly reduced. However, the conservation continuation mode limits local development. synergistic economic and environmental development is ensured while the water environment is effectively protected, so comprehensive mode I performed best.

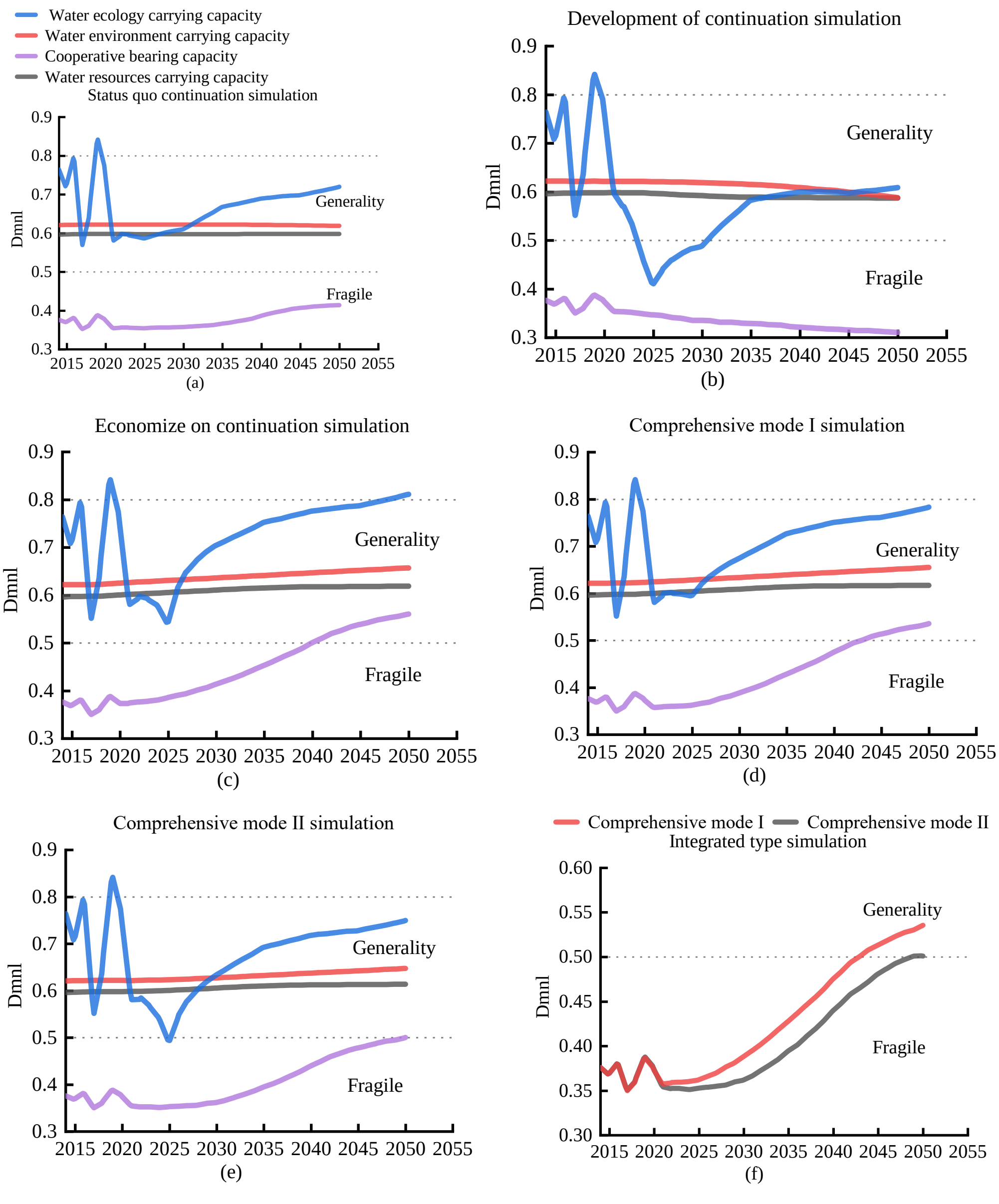

Figure 6. Simulation of bearing capacity of each system under the different scenarios. (**a**) Status quo continuation simulation; (**b**) Development of continuation simulation; (**c**) Economize on continuation simulation; (**d**) Comprehensive mode I simulation; (**e**) Comprehensive mode II simulation; (**f**) Integrated type simulation.

b. Analysis of variations in the carrying capacity of the water ecological subsystem

Figure 5c shows that the water ecological carrying capacity value is 0.6673 in 2035 under the status continuation mode, and it exhibits a gradual upward trend [44] and has a good carrying capacity [45]. However, with the growth of the population and GDP, the change in the water ecological carrying capacity is not obvious, which means that the water ecological subsystem is less influenced by the population and GDP. It is most strongly influenced by the eutrophication index, biodiversity index, and wetland area. If regulation measures are taken, the water ecological carrying capacity of 0.667 (0.698) in 2035 (2045) will be less changed under the development continuation mode and conservation continuation mode than under the status continuation mode, −12.7% and +15.7%, respectively. Under the comprehensive mode, measures such as keeping the population growth rate constant, reducing the total nitrogen and total phosphorus concentrations, chlorophyll concentration, and submerged plant cover in the lake area and increasing the biodiversity index and wetland area put the least pressure on the aquatic ecosystem and protect the aquatic ecology while allowing economic development.

Based on the analysis of the change trends of the bearing capacities of the three subsystems, the collaborative bearing capacity simulation (Figure 5d) results are as follows: conservation continuation mode > comprehensive mode I > comprehensive mode II > status continuation mode > development continuation mode. Under the five modes, considering the economic and population growth alone, the collaborative carrying capacity will face greater pressure, and the carrying capacity will be low and in a fragile state. If the conservation continuation mode is adopted alone, the respective carrying capacity values of the water resources, water environment, and water ecology will improve, the carrying status will improve, and the water resources gap will improve, but local economic development will be limited. In contrast, the status continuation mode, the development continuation mode, and comprehensive mode II result in a long-term fragile state. The conservation continuation mode and the comprehensive mode I have bearing capacity values of greater than 0.5 in 2043, the bearing status changes from fragile to general, and the bearing capacity level increases to general, which effectively improves the collaborative bearing capacity. It was found that the collaborative bearing capacity is more comprehensive and systematic than the single carrying capacity. By setting and comparing the different modes, comprehensive model I was selected, which can effectively improve the carrying efficiency of Ulan Suhai Lake.

As is shown in Figure 6, the simulations under the five modes from 2021 to 2050 show that the water resources carrying capacity, water environment carrying capacity, water ecology carrying capacity, and collaborative bearing capacity are higher under the conservation continuation mode, comprehensive mode I, and comprehensive mode II than under the other two modes, and the changes in the water resources carrying capacity and water environment carrying capacity of Ulan Suhai Lake are small, while the changes in the water ecological carrying capacity are significant. The collaborative bearing capacity of Ulan Suhai Lake does not change significantly under the status continuation mode (Figure 6a) and remains in a fragile state for a long time. Under the development continuation mode (Figure 6b), economic development is accelerated. However, the lake's carrying capacity gradually weakens, its carrying status changes from fragile to collapse, and its carrying level is extremely poor. Its collaborative bearing capacity gradually increases under the conservation continuation mode (Figure 6c), and in 2040 its bearing status changes from fragile to average, while its bearing level changes from poor to average. Its state increases under the two comprehensive modes, but changes slowly under comprehensive mode II (Figure 6e)and remains in a fragile state until 2049. Under comprehensive mode I (Figure 6d), the lake's bearing capacity value is greater than 0.5 after 2043, its bearing status changes from fragile to average, and its bearing level increases from poor to average. In comparison, under the conservation continuation mode, the lake's collaborative bearing capacity increases, but in terms of the local development strategy, this mode is not suitable for improving the lake's carrying capacity. Under the development continuation mode, the lake's collaborative bearing capacity decreases, which is not conducive to the protection of the water resources, water environment, and water ecology. Comprehensive mode I is more conducive than other modes to improving the lake's carrying capacity value, and is thus the optimal solution.

4. Conclusions

A dynamic model of the collaborative bearing capacity of the water resources–water environment–water ecology system of Ulan Suhai Lake was established, and the dynamics and regulation of the carrying capacity were predicted using the model. The main conclusions are as follows.

(1) The current collaborative bearing capacity level of Ulan Suhai Lake is poor and the bearing capacity is fragile, but it exhibits a slow growth trend, indicating that the future development prospect of Ulan Suhai Lake's bearing capacity is good. The poor carrying capacity of Ulan Suhai Lake is mainly influenced by the decrease in the water resources carrying capacity. Therefore, we can start from the perspective of the water resources carrying capacity, establish water conservation awareness, cultivate water-saving habits, build rainwater storage facilities, and vigorously promote sprinkler irrigation, drip irrigation, low-pressure pipe irrigation, and other measures to reduce farmland water use and improve the carrying capacity of the water resources.

(2) We can improve the carrying capacity of Ulan Suhai Lake by adopting comprehensive mode I—for example, increasing the wastewater treatment rate to 95%, improving the water resource utilization and increasing the effective utilization coefficient of the farmland irrigation. In addition, the domestic sewage discharge coefficient and industrial sewage discharge coefficient should be appropriately decreased to improve the carrying capacity of Ulan Suhai Lake; in other words, more water conservation management efforts should be made regarding urban, rural, and industrial water use.

(3) The water quality of Ulan Suhai Lake is mainly reduced by the inorganic fertilizers and pesticides in the water draining from the farmland, the discharge of urban and rural domestic sewage and industrial wastewater, the lack of ecological water pay, and the lakewater pollutants exceeding the standard levels and accumulating in the lake. These issues can be resolved using the following measures. First, the use of organic fertilizers and bio-pesticides and the accurate scientific usage of drugs should be promoted, and the utilization rate of chemical fertilizers and pesticides should be improved. Second, the sewage treatment plant should be upgraded, and the collection and recycling of wastewater should be conducted to achieve the discharge of zero sewage into the water supply. Third, timely dredging of the lake and reed harvesting should be conducted to increase the ecological water pay and improve the self-purification ability of the lake.

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Conflicts of Interest: The authors declare that they have no conflicts of interest.

Appendix A

Table A1. Normalized data values.

Index	2014	2015	2016	2017	2018	2019	2020
A1	0.41234	0.41182	0.41169	0.41168	0.24119	0.24121	0.24116
A2	2.04116	2.04118	2.04118	2.04118	2.04108	2.04109	2.04108
A3	0.39024	0.39251	0.39325	0.39329	0.04117	0.20412	0.20412
A4	0.41288	0.41235	0.41220	0.41219	−0.41243	−0.41268	−0.41206
A5	−0.41291	−0.41224	−0.41195	−0.41195	0.41242	0.41268	0.41206
A6	−0.41278	−0.41225	−0.41210	−0.41208	0.41242	0.41268	0.41206
B1	2.02682	2.03834	2.03983	2.03970	2.04099	2.04073	2.03641
B2	0.46498	0.43432	0.42641	0.42768	0.24992	0.24090	0.24142
B3	0.46765	0.43574	0.42744	0.42902	0.20840	0.40672	0.39450
B4	0.46084	0.43232	0.42525	0.42587	0.27331	0.40689	0.39369
B5	0.46525	0.43481	0.42698	0.42694	−0.48390	−0.40905	−0.41887
B6	0.16810	0.30116	0.33375	0.33019	0.55708	0.40960	0.41989
C1	−0.75424	−0.75114	−0.74790	−0.68595	−0.74092	−0.70042	−0.70400
C2	−0.77830	−0.77646	−0.77636	−0.71408	−0.76554	−0.72930	−0.73189
C3	1.48041	1.50460	1.46579	1.67570	1.53448	1.42466	1.49553
C4	−0.58837	−0.54480	−0.61561	−0.15678	−0.49095	−0.63355	−0.51868
C5	−0.53625	−0.52180	−0.55713	−0.43245	−0.51897	−0.52823	−0.47317

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