Pol. J. Environ. Stud. Vol. 32, No. 3 (2023), 2893-2907
DOI: *10.15244/pjoes/161326* ONLINE PUBLICATION DATE: 2023-04-03

Original Research

Assessment and Simulation of Water Environment Carrying Capacity in a River Basin Using System Dynamics Model

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Received: 14 November 2022
Accepted: 16 February 2023

Abstract

Due to intensive human activities, water environment systems in China have severely deteriorated, particularly in villages and towns. How agricultural and complex point sources contribute to this deterioration remains unknown. We developed a system dynamics prediction and regulation model to assess the water environment carrying capacity (WECC) of the Tongyang River Basin. Four development scenarios were proposed for the analyses: status quo, socioeconomic restrictions, sustainable use of water resources, and sustainable development of the water environment. In the status quo simulation, the overall water demand surpasses the capacity threshold after 2027, and the water resource deficit approaches 60 million m^3 by 2035. Moreover, pollution parameters like chemical oxygen demand, ammonia nitrogen, total phosphorus, and total nitrogen (TN) show a significant rise after 2030. TN is the primary factor limiting water carrying capacity in the Tongyang River Basin. Under different scenarios, the concentrations of pollutants decrease, and then increase. Under comprehensive management, the WECC index values are predicted to be 31% lower in 2035 than those of 2020, indicating that there is room to improve the most crucial WECC index. Our findings can provide theoretical basis for rural development and water environment protection in Tongyang River Basin.

Keywords: water environment carrying capacity, system dynamics model, Tongyang River Basin, water environment conservation, prediction and regulation model

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Introduction

With rapid economic growth and the acceleration of urbanization, the deterioration of the water environment has become a severe global problem [1, 2]. Problems such as water quality deterioration, eutrophication, severe devastation of aquatic ecosystems, and water resource depletion are serious issues in China, and require immediate attention [3]. The water environment systems in China are seriously degraded due to intensive anthropogenic activities, especially in villages and towns with small-scale water supply systems [4]. The process by which rural non-point and complex point sources contribute to the deterioration of the water environment remains unclear. Therefore, it is necessary to study the water environment carrying capacity (WECC) to coordinate the relationships among rural populations, agricultural growth, and water environment conservation [5]. It is also urgent to assess the maximum population and socio-economic scale that can be supported by rural water environment capacity [6].

Thus, the quantitative measurement of WECC and optimal regulation of watershed systems have become important research topics [7]. Researchers have conducted extensive studies and innovations based on traditional research methods and WECC [8-10]. Previous studies primarily focused on the establishment of a water environment model [11] and studying the balance between supply and demand of water resources [12], dynamic balance and threshold of water environment capacity, and population [13], as well as the relationship between various factors of carrying capacity at different spatial scales including country [14], region, city [15], and watershed [16]. Previous research methods included principal component analysis [17, 18], fuzzy comprehensive evaluation [19], grey correlation analysis, artificial neural network [20, 21] and multi-objective decision-making technique [22], which is the rational and scientific selection of multiple contradictory goals. Each evaluation method has its advantages and disadvantages [23]. These methodologies rely on static assessment, neglecting the dynamic changes in the water environment carrying capacity, and cannot determine a causal relationship between factors [16]. The system dynamics (SD) model can simulate the complex nonlinear dynamic relationship among multiple factors and make dynamic predictions under different strategies [24, 25].

Although many researchers have established SD models at country, city, and river basin scales [26], the research elements of the socioeconomic subsystem are relatively simple and primarily concentrated in the city; thus, they fail to design the process mechanisms of rural development and agricultural growth and lack the combination of population, economy, and other factors [27]. Most studies emphasize the importance of water resources and ignore the limitation of water environment to assess the basin carrying capacity [28, 29]. Additionally, other studies investigating the impact of rural agricultural pollution on the water environment [30] could not reflect the mechanism of change in the water environment due to rural activities and agricultural growth. Therefore, it is necessary to analyze the interaction of water resources and the water environment in rural areas [31]. Moreover, the bearing capacity of the water environment is influenced by several factors, including the complex feedback relationship, a large number of data overlap, and the primary and secondary influences on each other that change with time [32]; therefore, an SD model that systematically analyzes the causal and feedback messages between all elements in a countryside must be introduced. Furthermore, the traditional assessment of the WECC cannot explain the values of different periods or regions under different development modes and economic levels, and it is difficult to reflect the changing trend and regional differences with time [33].

The water quality standard is determined as the upper limit and threshold of WECC, which is the core premise of the WECC theory [34]. From the three dimensions of "structure, scale, and network," the economic and population scale that the water environment capacity can support is predicted [35]. Furthermore, we considered chemical oxygen demand (COD), ammonia nitrogen (NH_3-N), total phosphorus (TP), and total nitrogen (TN) as the pollution factors in the index system [36]. The water pollution system in the SD model is helpful to compensate for the water quality constraints neglected while evaluating the WECC.

Most studies emphasize the importance of water resources and ignore the limitation of water environment to assess the basin carrying capacity.

Using Tongyang River Basin as the study area, the subsystems of agriculture, population, society, economy, water resources, and water pollution were established, and the concentrations of COD, NH_3-N, TP, and TN were incorporated into the water pollution system. The SD evaluation model of WECC was constructed, and the results were analyzed and verified; further, the simulation results of the WECC under different scenarios were analyzed. Through the sensitivity of the constraint index, the key factors affecting the WECC were determined. Our findings can provide targeted optimization and control schemes for water environment governance and the sustainable development of villages and towns in the Tongyang River Basin.

Experimental

Materials and Methods

Overview of The Study Area

The Tongyang River is located on the north bank of Chaohu Lake, one of the five largest freshwater lakes in China. The total area of the Tongyang River Basin is 91.5 km^2, including 88.2 and 3.3 km^2 of hilly and polder areas, respectively. The Tongyang River Basin encompasses 2 townships and 14 administrative villages of Tongyang town and Feidong County (Fig. 1). In 2020, the basin had a total population of 62 411, which was primarily engaged in agriculture. It was one of the most important commodity grain producing bases in China. The agricultural output value of the basin was 1785.8228 million yuan, and the industrial added value was 376.3606 million yuan.

In the study area, 35% of the residual chemical fertilizers and pesticides stayed in and around the farming/agricultural areas, and 65% entered the water bodies in runoff. Many of these residual chemical fertilizers and pesticides entered the Tongyang River and Chaohu Lake through runoff [37]. Industrial wastewater and untreated domestic sewage were released directly into the water body. The COD, NH_3-N, TP, and TN discharges were found to be 125.83, 11.75, 2.63, and 25.04 t/a, respectively. The discharge of wastewater was growing annually, resulting in a steady decline in water quality. Particularly, TN had exceeded the class III water quality target over the past three years and reached class V water quality in May, June, October, and December. The significantly reduced environmental quality of the Tongyang River had severely hampered the sustainable growth of the rural agricultural sector in the Tongyang River Basin [38].

System Dynamics Model

System dynamics is an analytical theory and method for studying complex time-varying systems. It is based on the feedback control theory and uses computer simulations to examine the changing trends of system state under the interaction and effects of elements [33]. It is suitable for the quantitative study of complex time-varying systems [39]. This method can be utilized to (1) define the modeling purpose and delimit the system boundary, (2) determine the feedback mechanism and analyze the system structure, (3) construct a causal relationship, establish a system model, and test/modify parameters according to the simulation, and (4) apply and optimize a decision experiment. Various simulation results are obtained by adjusting and controlling the parameters, and the schemes are compared and analyzed [40]. In this study, the dynamic simulation model of rural WECC is established using Vensim-PLE software [41]. Based on this, the dynamic simulation and prediction of water environment quality and carrying capacity are conducted (Fig. 2).

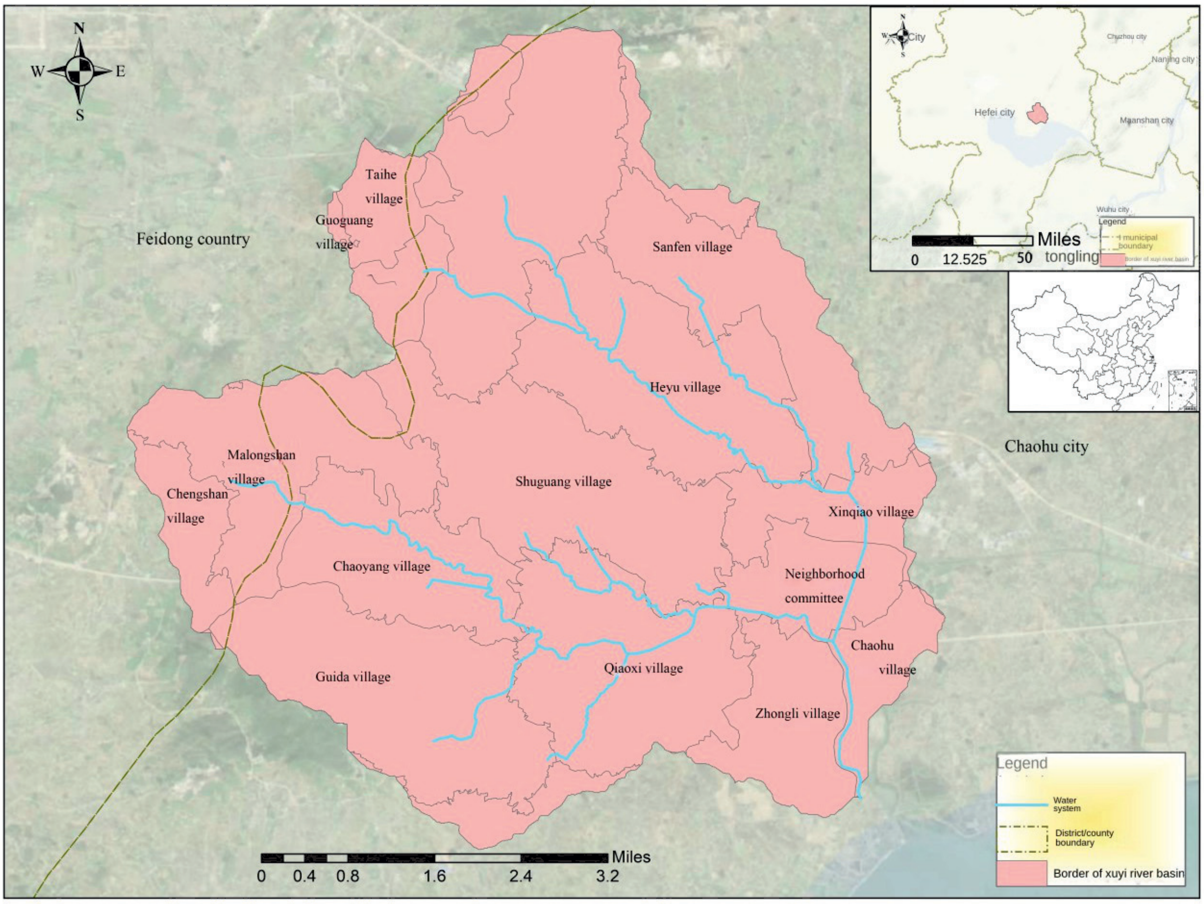

Fig. 1. Overview of the location of the Tongyang River Basin.

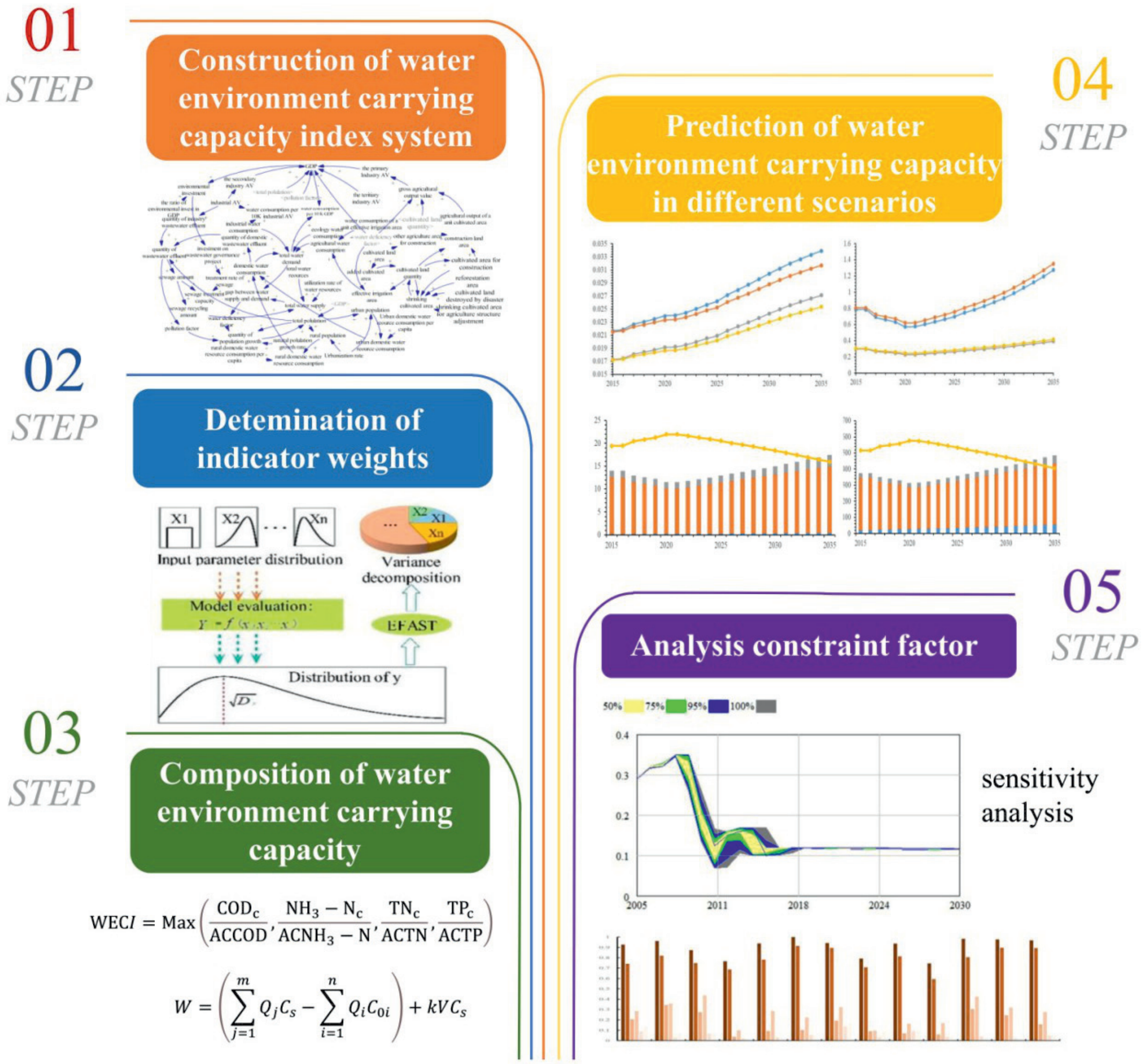

Fig. 2. Flow chart of water environmental carrying capacity (WECC) simulation.

Calculation of Water Environmental Carrying Capacity

The WECC is a comprehensive characterization of a drainage basin's sewage and pollution. Based on the barrel principle, the representative COD, NH_3-N, TN, and TP indicators are selected to calculate the comprehensive WECC index reflected by each indicator. The maximum value is used as the quantitative standard to evaluate whether the WECC of the basin is overloaded. The equation to calculate WECC is as follows:

$$WECI = Max\left(\frac{COD_c}{ACCOD}, \frac{NH_3 - N_c}{ACNH_3 - N}, \frac{TN_c}{ACTN}, \frac{TP_c}{ACTP}\right)$$

where *WECI* is the water environment carrying capacity index, *CODc* is the concentration of COD, *ACCOD* is the allowable concentration of COD, NH_3-Nc is the concentration of NH_3-N, and $ACNH_3$-N is the allowable concentration of NH_3-N within the water environment capacity. *TNc* is the total concentration of nitrogen in the river, *TPc* is the total concentration of phosphorus in the river, and *ACTP* is the allowable concentration of TP within the water environment capacity. Concentrations are measured in t/a.

When WECI = 1, the WECC and pressure are in equilibrium; at WECI<1, the water environment still has some capacity; and at WECI>1, the water environment of the basin is overloaded.

The equation of the one-dimensional steady-state model of water environment capacity is given as follows:

$$W = \left(\sum_{j=1}^{m} Q_j C_s - \sum_{i=1}^{n} Q_i C_{0i}\right) + kVC_s$$

where W is the water environment capacity, Q_i is the discharge of the *ith* river into the lake, Q_j is the discharge of the *jth* outlet river, C_{0i} is the average concentration of pollutants in the *ith* river, C_s is the target concentration of pollutants, V is the total volume of water resources, and k is the self-purification coefficient of pollutants. The self-purification coefficient of 0.2 (d-1) recommended by the State Environmental Protection Administration is adopted.

Data Sources

The data required for the study of WECC mainly include socioeconomic and meteorological hydrological factors. The primary data are from the Hefei City Statistical Yearbook, Chaohu City Statistical Yearbook, Hefei City Water Resources Bulletin, Tongyang River Basin's Agricultural Annual Report, Water Quality and Quantity Data of Sewage Treatment Plant, and meteorological data from 2015 to 2020. The parameter setting of the model prediction year mainly refers to the data of the Chaohu urban master plan (2017–2035) and the "14th five-year plan" water conservancy development plan of Chaohu City. Remote sensing and geospatial data come from Geospatial Data Cloud（http://www.gscloud.cn/） and Resource and Environmental Science Data Center（http://www.resdc.cn/）.

Establishment of SD Model to Determine the Water Environment Carrying Capacity of the Tongyang River

Model Boundary

The simulation period of SD model for the Tongyang River Basin was 2015-2035. The real data from 2015 to 2020 was used for model validation, and 2021-2035 was the prediction period. The base year was 2015, and the model step size was one year.

System Modeling Index and Feedback Relationship

The WECC system consists of four subsystems: social, economic, water resources, and water environment [42]. The entire system contains 144 influencing factors. These four subsystems are interrelated and form causal feedback relationships.

1. Social Subsystem

The social subsystem predicts future changes in urban and rural populations based on the development trend of urbanization rate, population age structure, birth rate, mortality rate, and immigration rate, as well as the trend of water consumption and sewage discharge caused by population change [43]. As point source pollution, urban sewage is discharged to sewage treatment plants and then into rivers, whereas rural sewage is dumped directly into rivers as non-point source pollution.

2. Economic Subsystem

The economic subsystem mainly simulates the situation of the primary, secondary, and tertiary industries in the Tongyang River Basin. The fundamental concept is to model the relationship between production elements, such as capital and production circumstances of primary industries, and economic growth by developing a production function [44]. Changes in industrial output value and advancements in production technology will result in a shift in water consumption, sewage discharge and treatment capacity.

3. Water Resources Subsystem

In the water resources subsystem, the total water supply is comprised of surface water resources, groundwater resources, and the Chaohu Lake water diversion [45]. The total water demand includes domestic, agricultural, and industrial water demand. Residential domestic water demand is categorized as rural and urban domestic. Agricultural water demand is divided into irrigation for crops and the aquaculture industry [46].

4. Water Environment Subsystem

By simulating the inflow of COD, NH_3-N, TN, and TP into the Tongyang River Basin, the water environment subsystem constructs an environmental capacity function, which can reflect the water environment status of the entire Tongyang River Basin area. In this subsystem, the amount of sewage produced is comprised of rural and urban domestic sewage, industrial sewage, and agricultural runoff pollution [47, 48]. The urban domestic and industrial sewage enters the river as point source pollution, after being processed at a sewage treatment plant and is discharged at the 1A level standard. In contrast, the rural domestic sewage and agricultural runoff pollution are non-point source pollution and flow directly into the river. The primary variable parameters and equations involved in the model are summarized in Table 1.

The regulation mechanism of the carrying capacity of COD in WECC is shown in Fig. 3. In terms of the lives of residents, COD emissions can be adjusted through the birth policy, optimizing the step water price, increasing the sewage pipe network coverage area, and improving sewage treatment technologies while regulating the carrying capacity of COD. The following is the overall regulatory and control path (Fig. 3): the number of rural populations→water quota of rural population→sewage discharge coefficient of rural population→COD discharge of rural domestic sewage→COD treatment capacity of rural domestic sewage→total inflow of COD into the river→water environment carrying capacity index, through which the regulation of COD carrying capacity is completed. According to the above regulation mechanism, other variables such as industrial production and agricultural development can also be regulated. The mechanisms of NH_3-N, TN, and TP are similar.

The causal feedback loop diagram is formulated based on the analysis of the interaction among the influencing factors of the internal mechanism of the system through the correlation analysis of each

Table 1. Primary equations of system dynamics model for the water environment carrying capacity in Tongyang River Basin.

Serial number	Modular subsystem	Primary equations
1	Social subsystem	Total population = population growth – population decrease
		Population growth = (birth rate + immigration rate) × total population
		Population reduction = (mortality rate + emigration rate) × total population
		Urban population = total population × urbanization rate
		Rural population = total population – urban population
2	Economic subsystem	Gross domestic product = added value of primary industry + added value of secondary industry + added value of tertiary industry
		Added value of primary output = INTEG (agricultural development × reduction index of added value of primary production, 56603. 2)
		Agricultural development = added value of agriculture + added value of livestock and poultry
		Agricultural added value = agricultural added value per unit cultivated area × cultivated area
		Added value of livestock and poultry = output value per unit weight × livestock and poultry production
3	Water resource subsystem	Water supply = total water resources × water resources development intensity + Chaohu Lake water diversion
		Total water demand = agricultural water demand + industrial water demand + tertiary industry water demand + total domestic water demand
4	Water environment subsystem	Industrial wastewater discharge = industrial wastewater discharge coefficient × industrial water consumption
		Domestic sewage discharge = domestic sewage discharge coefficient × domestic water consumption
		Total COD emission = Industrial COD emission + domestic COD emission + farmland runoff COD emission
		Total amount of COD entering the lake = total amount of COD discharge - total amount of COD reduction
		Total COD reduction = COD wastewater treatment plant reduction + COD river ecological reduction

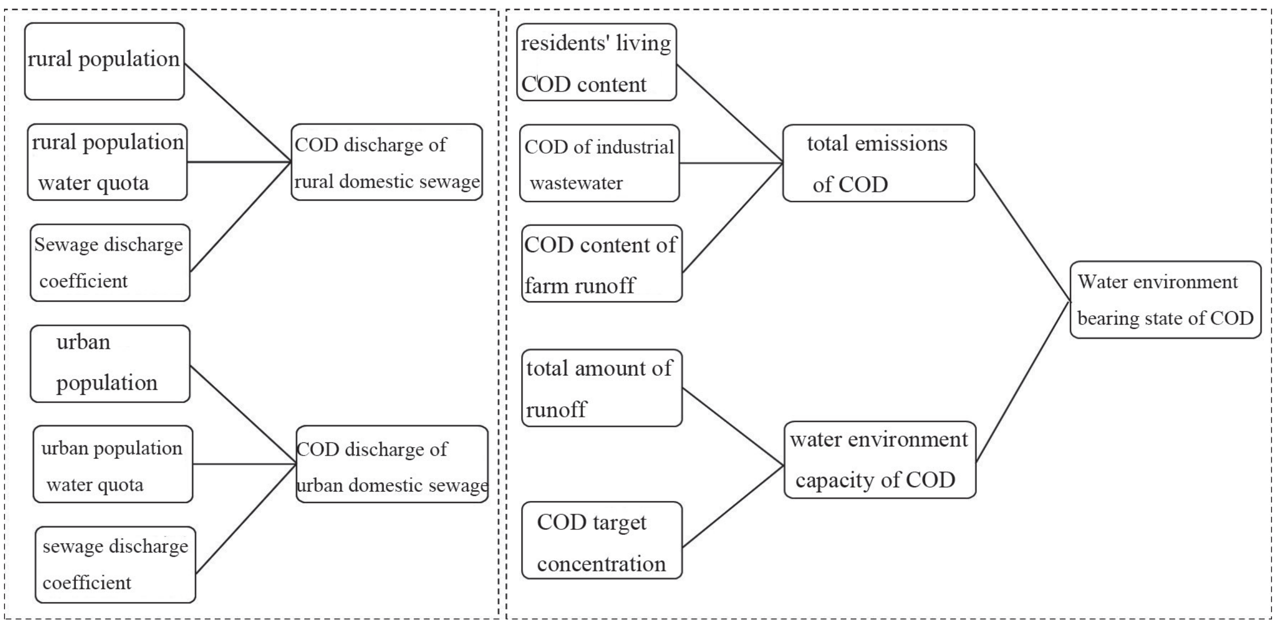

Fig. 3. Regulation mechanism of chemical oxygen demand (COD) carrying capacity.

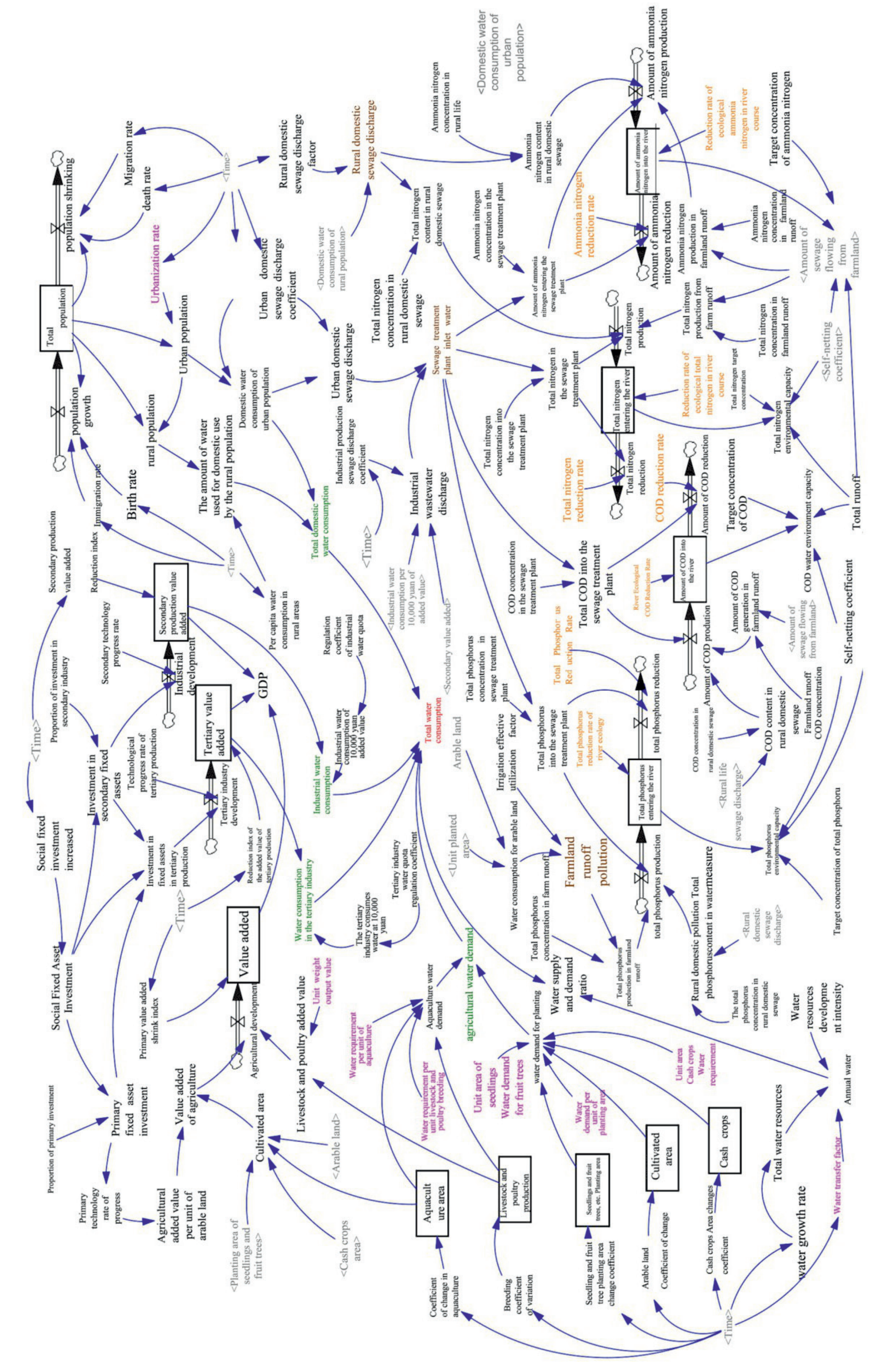

Fig. 4. Flow diagram of system dynamics model of water environment carrying capacity in the Tongyang River Basin.

subsystem and the feedback relationship analysis of each element [49]. The SD model of the WECC of the Tongyang River Basin is established using Vensim software (Fig. 4).

Model Validation

The model is examined based on two aspects: historical and sensitivity tests [50]. The relative error analysis shows that the relative errors between the simulated and actual values of the variables are all within 10%. The simulation findings fit the actual data well and can be used to predict the development trend of the system. Table 2a) and b) summarize the historical test of the model. The sensitivity test is performed for the parameters that have a significant impact on the operating outcomes of the model, as shown in Table 3. Except for the sensitivity of NH_3-N reduction rate,

Table 2a) Model fit results of the primary indicators of water environment carrying capacity from 2015 to 2020.

Time	Total population (10000 yuan)			Industrial added value (10000 yuan)			Cultivated area (Mu)		
	Historical actual value	Analog value	Relative error	Historical actual value	Analog value	Relative error	Historical actual value	Analog value	Relative error
2015	60235	60235	0. 0000%	30947. 81	30947. 8	0. 00%	148388	150135	1. 18%
2016	60705	60707. 2	0. 0036%	32253. 8	32053. 8	-0. 62%	149673	153878. 1	2. 81%
2017	61215	61216	0. 0016%	33890. 2	33383. 5	-1. 50%	161349	164075	1. 69%
2018	61777	61778. 1	0. 0018%	35637. 86	35225. 3	-1. 16%	154549	162592. 6	5. 20%
2019	62230	62232. 1	0. 0034%	36789. 36	36447. 3	-0. 93%	152539	160844. 9	5. 45%
2020	62411	62413. 8	0. 0045%	37636. 06	37166. 2	-1. 25%	143144	154443. 5	7. 89%

Table 2b) Model fit results of the primary indicators of water environment carrying capacity from 2015 to 2020.

Time	NH_3-N			TP			TN		
	Historical actual value	Analog value	Relative error	Historical actual value	Analog value	Relative error	Historical actual value	Analog value	Relative error
2015	11. 712	10. 730	-8. 39%	2. 698	2. 492	-7. 65%	24. 169	22. 079	-8. 65%
2016	12. 023	11. 119	-7. 52%	2. 755	2. 582	-6. 25%	23. 837	22. 879	-4. 02%
2017	12. 582	12. 857	2. 18%	2. 867	2. 986	4. 16%	25. 442	26. 456	3. 98%
2018	13. 413	13. 754	2. 54%	3. 498	3. 194	-8. 69%	26. 169	28. 302	8. 15%
2019	13. 858	14. 585	5. 24%	3. 555	3. 387	-4. 71%	28. 778	30. 011	4. 29%
2020	14. 839	15. 667	5. 58%	3. 867	3. 639	-5. 90%	30. 022	32. 240	7. 39%

Table 3. Sensitivity analysis of the key variable system.

Variable	Variable	Increased average sensitivity by 10%	Decreased sensitivity by 10%
Total population	Birth rate	2. 57%	2. 57%
Rural population	Urbanization rate	2. 11%	2. 11%
GDP	Growth rate of social fixed investment	0. 27%	0. 26%
Cultivated land area	Coefficient of change of cultivated land area	1. 65%	1. 83%
Water demand of planting industry	Water requirement per unit planting area	8. 31%	8. 02%
Total water consumption	Industrial water regulation coefficient	0. 31%	0. 32%
Annual water supply	Growth rate of water resources	0. 39%	0. 39%
Inflow of sewage treatment plant	Discharge coefficient of industrial wastewater	7. 32%	7. 32%
Ammonia nitrogen inflow into river	Ammonia nitrogen reduction rate	10. 21%	10. 22%
Ammonia nitrogen capacity	Self-purification coefficient	5. 64%	4. 39%

which is greater than 10%, the sensitivities of the other associated parameters are within 10%, indicating that the model is stable and applicable. The results suggest that the established SD model can accurately and reliably simulate the WECC.

Results and Discussion

Scenario Design

This study introduces the concept of elasticity into the setting of scenario parameters to improve the accuracy of the model simulation results and proposes four scenarios: current situation continuity (maintaining the existing situation), socioeconomic constraints, resource and environment protection, and comprehensive coordination [15]. The current situation continuity scenario simulates the historical trend of each parameter; the socioeconomic constraint scenario controls the scale and speed of social and economic development (the population growth rate, development scale of agriculture, and the service industry, among others) to improve the WECC. The scenario for resource and environmental protection focuses on the efficient utilization and protection of resources and the environment. The comprehensive coordination scenario considers the balance of urban construction demand and resource and environment supply. Table 4 shows four possibilities based on the key indicators of WECC. Three primary governance scenarios and six secondary governance scenarios with fourteen linked variables were set up. Using the current situation as a reference, the control parameters for simulation were adjusted within a 20% change range.

Simulation Results of Water Demand under Different Scenarios

The simulation results of the total water demand for production and living, under the four scenarios, are shown in Fig. 5. Fig. 5a) demonstrates that in the current situation continuity scenario, the total demand for water resources in the Tongyang River Basin will surpass the red line after 2027, and the water shortage will continue to expand. By 2035, the water shortage will be approximately 60 million m^3. By this time, the water demand of the Tongyang River Basin will reach 124 million m^3, which is approximately twice the average annual water supply of the Tongyang River Basin. If development is conducted according to the current situation continuity scenario, the water resources in the Tongyang River Basin will be seriously overloaded in the future. Our results are the same as those in most literatures. Most studies show that there will be water shortage in different degrees in the future [51]. The total

Table 4. Scenario design scheme of water environment carrying capacity of the Tongyang River Basin.

First level scenario	Secondary scenario	Regulatory parameters	Regulation path
Socio economic constraint scenario	Social development constraints	Population growth rate (‰)	Based on the current value, it is reduced by 20%, and the other variables adopt historical value.
		Urbanization rate (%)	
	Economic development constraints	Growth rate of social fixed investment (%)	Same as above
		Growth rate of rice planting area (%)	
		Growth rate of forestry, animal husbandry, and fishery (%)	
Resource and environmental protection scenario	Reduce water use	Change rate of domestic water quota (%)	Same as above
		Change rate of net irrigation quota of rice (%)	
		Change rate of water quota of 10 000-yuan industrial added value (%)	
	Reduce source pollutant emissions	Variation rate of the discharge coefficient of domestic sewage (%)	Same as above
		Change rate of industrial wastewater discharge coefficient (%)	
	Increase sewage treatment	Change rate of irrigation water utilization coefficient (%)	Based on the current value, it increases by 20% (the upper limit of growth approaches 1), and other variables adopt historical values.
		Reuse rate of industrial water (%)	
		Reduction rate of wastewater treatment plant (%)	
		Reduction rate of ecological purification project (%)	
Integrated and coordinated scenario	Comprehensive control	—	Combined with the parameter changes in the first two scenarios

water consumption under the four scenarios shows an upward trend, whereas the other scenarios have a water-saving effect compared with that in the current situation continuity scenario, and the water-saving effect is more evident with increasing time. The water demand under the comprehensive coordination scenario is the lowest. The total water demand will be 53 million m^3 by 2035, which is 1.3 times lower than that of the current situation continuity scenario. Moreover, the growth rate of water demand in this scenario is the slowest, indicating that the comprehensive and coordinated development model has the best water-saving effect. The water volume of the basin is an important factor determining the upper limit and threshold of WECC rebound potential, which is consistent with Zhou's research results [52].

Fig. 5b) depicts the simulation results for agricultural water demand. The findings reveal that agricultural water consumption is far more than domestic and industrial water consumption. The water demand for agricultural resources and environmental protection is modest. According to the socioeconomic constraint scenario, the agricultural water demand in 2035 will be 88 million m^3. In contrast, the agricultural water demand under the resource and environmental protection scenario will be 62 million m^3, indicating that the water-saving effect of reducing per-hectare irrigation water consumption and enhancing the utilization efficiency of irrigation water will be more pronounced in the Tongyang River Basin [53]. According to the simulation results of the four scenarios, the agricultural water demand is the lowest under the comprehensive coordination scenario, and the water demand will be 42 million m^3 by 2035.

The simulation results of domestic water demand are shown in Fig. 5c). The results show that the domestic water demand for resource and environment protection is low. By 2035, the domestic water demand under the current situation continuity, socioeconomic constraints, resource and environment protection, and comprehensive coordination scenarios will be 3.4, 3.2, 2.7, and 2.5 million m^3, respectively. The water demand shows the following trend: comprehensive coordination <resources and environmental protection<socio-economic constraints<status quo continuation. The results show that the water-saving effect is the best under a comprehensive and coordinated situation. The water-saving effect of reducing the per capita water quota is more significant than reducing population growth and urbanization rates.

The simulation results of industrial water demand are shown in Fig. 5d). Under the four scenarios, the industrial water demand will continue to increase. By 2035, the industrial water demand under the current situation continuity, socioeconomic constraints, resource

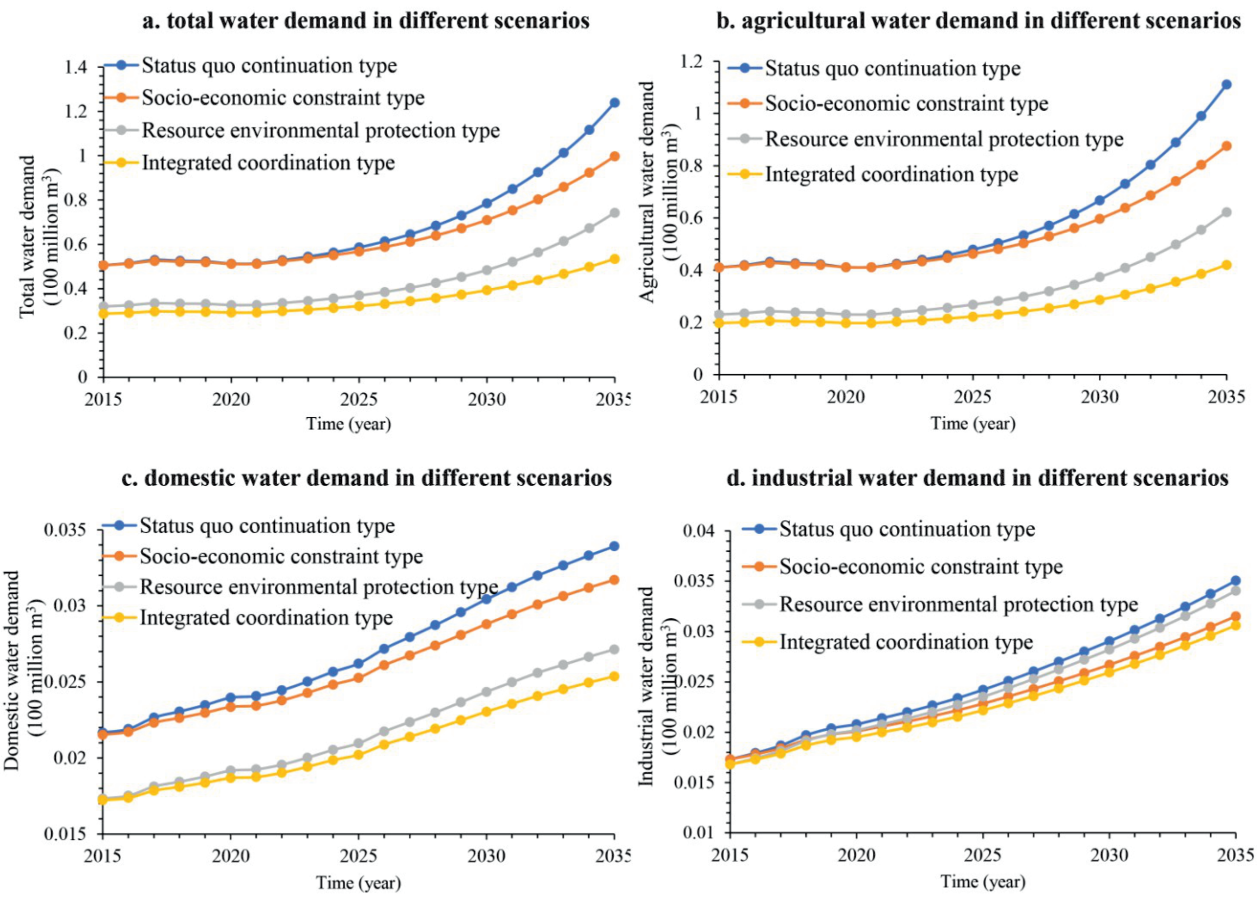

Fig. 5. Simulation results of production and domestic water demand under different scenarios.

and environmental protection, and comprehensive coordination scenarios will be 5.91, 5.85, 5.89, and 5.83 million m^3, respectively. The impact of the four development modes on total water consumption is insignificant.

Simulation Results of Water Environmental Pollution Emission Under Different Scenarios

The total amount of pollutants into the river under different scenarios is shown in Table 5. If the Tongyang River Basin is developed according to the current situation, under the class III water quality target, the basin will be overloaded with pollutants for an extended period after 2030. Rural domestic sewage discharge is the main pollution source of the Tongyang River Basin, and the total amount of pollutants discharged in the basin is affected by the rural population.

Due to the change in rural population, COD, NH_3-N, TN, and TP emissions decrease, then increase. It is characterized by resources and environmental protection <comprehensive coordination <current situation continuity <socioeconomic constraints. By 2035, the amount of COD, NH_3-N, and TP pollutants entering the river will be 225.771, 8.843, and 2.810 t/a, respectively, which is approximately half that in the current situation continuity scenario (485.987, 17.432, and 5.564 t/a, respectively), indicating the reduction

Table 5. Simulation results of the amount of pollutants entering the river under the different scenarios from 2015–2035.

Index parameters	Level year	Status quo continuation type	Economic restraint type	Resources and environment protection	Comprehensive coordination type
COD inflow (t/a)	2015	375.112	380.720	184.188	187.288
	2020	314.888	329.644	149.741	158.387
	2030	417.615	430.550	195.340	204.416
	2035	485.987	496.579	225.771	234.541
Ammonia nitrogen inflow into the river (t/a)	2015	13.993	14.222	7.164	7.283
	2020	11.474	12.105	5.841	6.174
	2030	15.009	15.642	7.610	7.952
	2035	17.432	18.003	8.843	9.153
Total phosphorus inflow (t/a)	2015	4.368	4.435	2.285	2.323
	2020	3.628	3.812	1.860	1.967
	2030	4.780	4.952	2.423	2.534
	2035	5.564	5.709	2.810	2.913
Total nitrogen inflow into the river (t/a)	2015	32.197	32.413	18.381	18.518
	2020	28.302	28.581	15.045	15.389
	2030	36.138	35.414	18.342	18.286
	2035	43.125	41.510	21.685	21.239
Total nitrogen inflow into rivers in rural areas	2015	21.271	21.671	13.206	13.455
	2020	15.719	16.750	9.588	10.217
	2030	18.781	19.910	11.193	11.865
	2035	20.994	22.309	12.477	13.259
Total nitrogen inflow from point source	2015	7.190	7.005	2.589	2.477
	2020	9.173	8.407	3.139	2.844
	2030	13.244	11.590	4.418	3.821
	2035	16.542	14.199	5.505	4.667
Total nitrogen inflow from farmland runoff	2015	3.737	3.737	2.586	2.586
	2020	3.410	3.424	2.318	2.328
	2030	4.112	3.914	2.732	2.600
	2035	5.590	5.002	3.703	3.313

of COD, NH_3-N, and TP pollutants in the Tongyang River Basin. The effect of implementing the scenario scheme of resource and environment protection is highly significant. Under the current situation continuity scenario, the TN inflow into the river will be 43.125 t/a by 2035. The TN inflow under the resource and environmental protection and comprehensive coordination scenarios will be 21.685 and 21.239 t/a, respectively, which will be reduced by 0.99 and 1.03 times compared with that in the current situation continuity scenario.

Regarding the structure of total nitrogen inflow, the total nitrogen inflow from point sources and farmland runoff has decreased under economic constraints and natural resource conservation regulations. It has been manifested as a comprehensive coordination type <natural resource conservation type <economic constraint type <status quo continuation type. The results show that for point source pollution, reducing pollution source emissions is more effective than limiting economic development to reduce the amount of pollutants entering the river. The policy of reducing the discharge of pollution sources includes reducing the domestic water quota of urban residents, the water quota of industrial added value, the discharge coefficient of residential and industrial sewage, and improving the treatment rate of sewage treatment plants. This is consistent with Hu's research results [54]. For farmland runoff pollution, reducing the net irrigation quota of rice and increasing the utilization coefficient of irrigation water is more effective in reducing the amount of pollutants entering the river. The results are well consistent with the findings by Zhang [5]. From observing the TN entering the river under various scenarios, it is found that the connection rate and sewage treatment rate of rural domestic sewage pipes play a decisive role in the amount of domestic sewage discharged into the river. Rural domestic sewage discharge pollutants account for a relatively large proportion, which is the same as Sun's research results [55]. The follow-up water environment treatment of the river basin should focus on expanding the coverage area of the sewage pipe network, increasing the sewage collection and treatment rates [56].

Results of the Water Environmental Carrying Capacity Index Under Different Scenarios

Fig. 6 shows the predicted results of the WECC of COD, NH_3-N, TN, and TP under different scenarios. The WECC index values of COD, NH_3-N, TN, and TP first decreased, then increased under the current situation continuity scenario. By 2035, the WECC index values of NH_3-N, COD, TP, and TN are estimated to be 1.09, 1.20, 1.27, and 1.54, respectively. The WECC index values of TN are constantly higher than those of the other three pollutants, and TN is the primary limiting factor of WECC in the Tongyang River Basin.

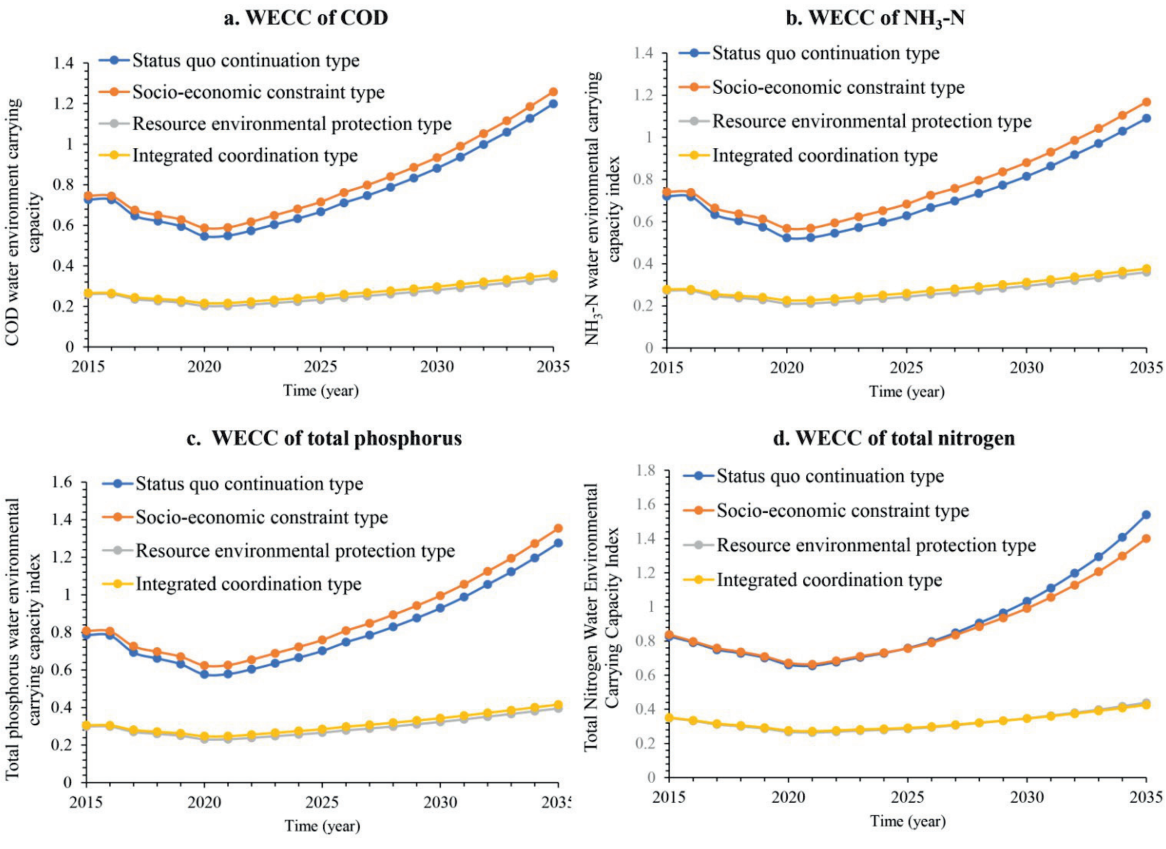

Fig. 6. Simulation results of water environment carrying capacity in the Tongyang River Basin under different scenarios.

This is because the reduction rates of COD, NH_3-N, and TP sewage treatment plants are more than 85%, whereas the reduction rate of TN in sewage treatment plants is 65. 71%, and the amount of point source TN into the river is relatively high.

In terms of COD, NH_3-N, and TP, the WECC indices show the following trend: resource and environmental protection <comprehensive coordination <current situation continuity <socioeconomic constraints. By 2035, under the current situation continuity, socioeconomic constraints, resource environment protection, and comprehensive coordination scenarios, the carrying capacity index values of COD are predicted to be 1.20, 1.26, 0.34, and 0.35 respectively. The NH_3-N index values are estimated to be 1.09, 1.17, 0.36, and 0.38, respectively. The bearing capacity index values of TP are predicted to be 1.27, 1.35, 0.39, and 0.42, respectively. The socioeconomic constraints scenario has a larger WECC index value than that of the current situation continuity scenario, and the water environment in both scenarios is in an overloaded state. It suggests that the establishment of a socioeconomic scenario scheme cannot increase the WECC for COD, NH_3-N, and TP but rather decrease it. Under the resource and environment protection and comprehensive coordination scenarios, the WECC of COD, NH_3-N, and TP is <0.5, indicating that the two scenarios have significant effects on the improvement of the WECC. Moreover, according to the scenario of resource development and environmental protection, COD, NH_3-N, and TP have the highest environmental carrying capacity in water.

By 2035, the carrying capacity indices of TN under the current situation continuity, socioeconomic constraints, resource and environment protection, and comprehensive coordination scenarios are predicted to be 1.54, 1.40, 0.44, and 0.43, respectively. The comprehensive coordination scenario has the greatest improvement over the TN WECC, but there is little difference compared to the resource and environment protection scenario. The TN WECC index value is still the largest compared with that of other pollutants, indicating that under the various scenarios, TN is still the primary limiting factor for the future development of the WECC of the Tongyang River Basin.

In the current situation continuity and socioeconomic constraints scenarios the carrying capacity of the water environment will be exceeded in 2032 and 2033, respectively, indicating a condition of continual overload. Protection of resources and comprehensive coordination can enhance the carrying capacity of the water environment. By 2035, the WECC index values will not exceed 1. Under this scenario, the WECC index in 2035 will be 31% lower than that in 2020. Socioeconomic development constraints will increase the discharge of contaminants from rural areas into the basin and will not improve the carrying capacity of the water environment [57-59].

Conclusions

The Tongyang River Basin was chosen as the study area. By combining the WECC assessment model with the system dynamics model, four distinct development scenarios were established. Compared with previous studies, the main innovation of this study is the consideration of water environment feedback. The existing research mainly formulated the objective of optimizing water resources management to optimize the strategy, but seldom considered the feedback relationship between the water environment objectives and subsystems. Assess the threshold of population, agriculture and socio-economic scale that the water environment can sustain. The main conclusions are as follows:

In the current continuity scenario, parameters of COD, NH_3-N, TP, and TN are anticipated to overload for an extended period after 2030. We found that rural domestic sewage discharge is the main pollution source in the Tongyang River Basin. Under the four scenarios, the pollutant emissions of COD, NH_3-N, TP, and TN first decreased, then increased. Under the resource and environment protection scenario, the reduction of COD, NH_3-N, and TP pollutants was the most significant, with inflow amounts of 225.771, 8.843, and 2.810 t/a, respectively, which were approximately one-fold lower than those of the current situation continuity scenario.

Under the current situation continuity scenario, the WECC indices of COD, NH_3-N, TP, and TN first decreased, then increased. All pollutants are predicted to be overloaded in 2035, and TN will be the primary limiting factor of the WECC of the Tongyang River Basin. In the comprehensive and coordinated situation, the WECC index values will decrease by 31% in 2035 compared with that in 2020, indicating there is still water environment capacity, and the improvement of the WECC index is the most significant.

Our study has some limitations: During SD modeling, some factors and relationships between subsystems are simplified or not considered, including the impact of climate change, water price change, interaction between social economy and water environment. Some data are difficult to collect, such as wastewater discharge, which is limited when SD establishes the model. Because the statistical quality of data obtained by different departments is different, it is difficult to ensure the fairness and accuracy of parameter design. In addition, the uncertainty of population policy, water conservation policy, pollution control policy and water diversion policy may affect the prediction results. In future studies, the model establishment, parameter selection, and scenario design should be further improved for more robust outcomes. We will also consider the dynamic evaluation of WECC.

Acknowledgments

This work was supported by the National Natural Science Foundation of China [grant numbers 42101318]; National Key R&D Program of China [grant number 2018YFD1100101]; and the Science and Technology Service Network Initiative of the Chinese Academy of Sciences (grant number KFJ-STS-ZDTP-011).

Author Contributions

Yazhu Wang: Conceptualization, Methodology, Project administration, Writing-original, Validation, Formal analysis, Supervision. Jurong Wang: Resources, Data curation, Investigation, Writing - original draft, Software, Writing - Review & Editing, Validation. Xuejun Duan: Conceptualization, Formal analysis, Funding acquisition. Lingqing Wang: Visualization, Methodology, Validation, Writing - Review & Editing. All authors read the manuscript and approved the submission.

Conflict of Interest

The authors declare no conflict of interest.

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