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Prediction of water resource carrying status based on the 'three red lines' water resource management policy in the coastal area of Jiangsu Province, China

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ABSTRACT

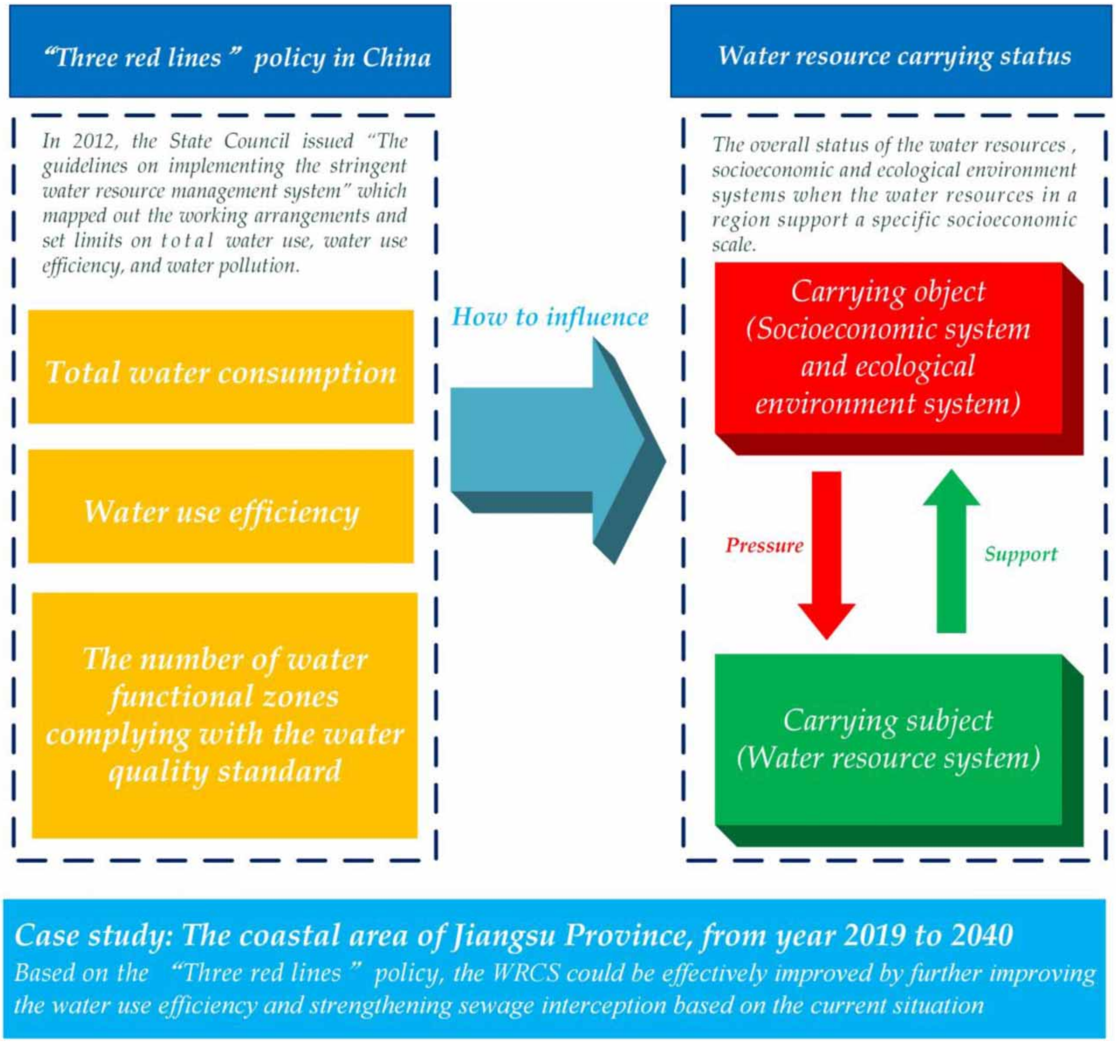
Recently, the Chinese government has issued various policies to regulate water resource management. The 'three red lines' policy is one of the most important. To quantify the influence of the 'three red lines' policy on water resource carrying status (WRCS), analyze the shortcomings of the current water resource management and provide support for adjusting the direction of water resource management, we constructed a system dynamics model that considered 'red line' constraint feedback and simulated changes in WRCS characterization indicators from the period 2019 to 2040 in coastal cities of Jiangsu Province. The WRCS in Nantong city from 2019 to 2035 was medium and that from 2036 to 2040 was poor; that in Yancheng city from 2019 to 2037 was medium and that from 2038 to 2040 was poor; that in Lianyungang city from 2019 to 2036 was medium and that from 2037 to 2040 was poor. We then constructed three schemes with strategies to improve the WRCS. Compared with the initial scheme, Scheme I, involving further enhanced water resource utilization efficiency and reduced discharge of pollutants, improved the WRCS. Based on Scheme III, the economic scale can be expanded by increasing economic development at an appropriate speed, while the WRCS remains almost consistent with the initial scheme.

Key words: Coordinated development index, Development strategy, System dynamics model, 'Three red lines' policy, Water resource carrying status

HIGHLIGHTS

- We explored the influence of the 'three red lines' policy on the water resource carrying status in Jiangsu Province.
- We constructed a system dynamics model that considered 'red line' constraint feedback.
- The WRCS changes from 2019 to 2040 based on the existing planning were simulated.
- The economic scale can expand by maintaining appropriate strategies while the WRCS remains nearly constant.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The water cycle is the link connecting the Earth's geosphere–biosphere–atmosphere system and is one of the core effectors of natural environment change (Yang *et al.*, 2021a). The water resource cycling process has changed significantly owing to the interference of human activities and change in natural conditions (Zhang *et al.*, 2019a). In certain areas, this has caused severe problems, such as the continuous decrease in precipitation, the imbalance between water resource supply and demand, and water environment pollution, which have contributed to the destruction of natural ecosystems (Wang & Yang, 2016; Chen *et al.*, 2021; Hao *et al.*, 2022). Water-related problems have gradually become key factors restricting sustainable socioeconomic development (Vorosmarty *et al.*, 2010; Ni *et al.*, 2012). As the most populous country on earth, China faces an uneven spatial distribution of water resources, evident interannual differences in precipitation, and scarce water resources per capita (Qin *et al.*, 2020). Since the implementation of the reformation and opening-up policy (Xie, 2020), the scale of China's economy has expanded by more than 200 times. Residents' living standards have improved significantly, but owing to limited natural water resources and unreasonable development and utilization, a series of water-related issues, such as cyanobacteria outbreaks, wetland area reduction, and river interruption, frequently occur (Zhang *et al.*, 2019b; Cai *et al.*, 2021). To alleviate the gap between the supply and demand of water resources and preserve water environments and their ecology, the Chinese government emphasized the urgency of water resource management (He *et al.*, 2020). The State Council issued 'opinions on the implementation of the strictest water resource management system,' requiring the establishment of 'three red lines' for water resource management by setting limits on water use, water use efficiency, and water pollution. The policy includes a red line for water resource utilization (the total water consumption must be less than the specified value), a red line for controlling water use efficiency (including two indicators: irrigation efficiency and water use per 10^4 yuan of industrial added value), and a red line for restricting pollution absorption in water functional areas (water functional zones must comply with the specified water quality standard) (Wu *et al.*, 2021). In addition, the State Council stipulated that the rigid restriction of the water resource carrying capacity (WRCC) must be strengthened, and the total consumption and use efficiency of water resources must be controlled. However, few scholars systematically quantified or predicted the impact of these policies on regional water resources and economic development, which is important for the adjustment of future water resource utilization and protection strategies.

Since the concept of WRCC was put forward, scholars have widely studied and discussed it, and its connotations have received a certain consensus (Mei *et al.*, 2010). First, an analysis of the WRCC must be conducted within the framework of sustainable development, and any strategy of WRCC promotion that will cause ecological environment deterioration is unfeasible (Naimi Ait-Aoudia & Berezowska-Azzag, 2016; Li & Chen, 2021). Second, the WRCC is characterized by different categories of indicators, and according to the different connotations of these indicators, the WRCC is further divided into the water resource carrying status (WRCS) and the ultimate water resource carrying capacity (UWRCC) (Yang *et al.*, 2021a, 2021b). The WRCS represents the overall status of the water resources, as well as socioeconomic and ecological environment systems, when the water resources in a region support a specific socioeconomic scale (Yang *et al.*, 2021b). The overall status is determined by many factors, such as water resource utilization, socioeconomic development status, and the region's ecological health. The WRCS is obtained using multi-index evaluation methods, and the most common evaluation methods include comparative analysis (Chapagain *et al.*, 2022), fuzzy mathematics (Wang *et al.*, 2021a), and cloud models (Wu *et al.*, 2020), among others. The UWRCC represents the largest socioeconomic scale (population or gross domestic product) over which water resources can support a region (an administrative area or a basin) under specific economic and technological conditions under which a favorable aquatic ecosystem can be maintained (Dong *et al.*, 2021; Khorsandi *et al.*, 2022). The UWRCC is usually calculated using a multi-objective programming model (Dou *et al.*, 2015; Dong *et al.*, 2021). Although the UWRCC offers the upper limit of population size and the economic scale that the water resources can support in a region, which are critical values for regional development strategy formulation, the calculation of the UWRCC is exceptionally complex, and it is not widely used in practical management. In contrast, the WRCS offers the advantage of simple calculations, making it convenient for various applications. Moreover, the WRCS can be used to analyze the causes of WRCC overloading and guide the formulation of improvement strategies using the disorder factor diagnosis method.

Many water resource, economy, and ecology indicators are involved in WRCS evaluation. As these indicators are easily affected by government policies, it is difficult to use traditional numerical analysis methods to predict future changes. Therefore, scholars primarily focused on analyzing the historical changes and spatial differences in the WRCS. The main achievements include the evaluation framework and the evaluation method. Among them, Wang *et al.* (2021b) propose an evaluation framework based on a 'driving force–water resources situation and consumption–water resources pressure–water environmental situation–response–management' system. This system was used to analyze the WRCC of the Dianchi Lake Basin from 2005 to 2015. Zhao *et al.* (2021) established a geographically and temporally weighted regression model. The model was applied to investigate the spatiotemporal heterogeneity of the factors affecting the WRCC of the Beijing–Tianjin–Hebei urban agglomeration. According to the 'National Technical Outline of Water Resource Carrying Capacity Monitoring and Early Warning' in China, Fang *et al.* (2019) describe a novel WRCC evaluation process that combines the binary index and reduction index evaluation methods and analyzes the causes of WRCC overloading in the Taihu Lake Basin. In WRCC prediction, considering that the WRCC is affected by the interaction of various elements of the regional 'water resources–social economy–ecological environment' system, scholars often use system dynamics (SD) models to quantitatively analyze the relationships between elements and their changes over time (Wang *et al.*, 2019; Keyhanpour *et al.*, 2021). Using this method, the WRCCs of Guangzhou city (2021–2030) (Wang *et al.*, 2022), Xi'an city (2015–2020) (Yang *et al.*, 2019), and Kunming city (2010–2020) (Zhao *et al.*, 2012) were predicted.

The above WRCS prediction achievements mainly considered the relationship between water resource-related systems, rarely accounting for the influence of management policies on development strategies in the SD modeling process. To address this issue, this study selected the coastal area of Jiangsu Province as the study area, and an SD model was constructed to describe the evolution of the regional 'water resources–social economy–ecological environment' system under the 'three red lines' policy constraint. Compared to SD models in previous studies, a feedback module was included in the SD model to describe the mutual feedback relationship between water resource management targets and development strategies. In addition, the influence of policies on the WRCS under different development strategies in the future was predicted.

2. METHODS

2.1. Study area and data

2.1.1. Introduction of the study area

The coastal area of Jiangsu Province is an important part of the Yangtze River Delta. This area has unique geographical advantages and a well-developed social economy. As shown in Figure 1, the coastal areas of Jiangsu include Nantong city, Yancheng city, and Lianyungang city, covering a land area of 32,500 km^2. In 2018, the precipitation in coastal Jiangsu Province was 1,024.8 mm, 3.04% more than the long-term average precipitation (994.5 mm, 1965–2018). The region's GDP in 2018 was 1,668.58 billion yuan, and its industrial structure was adjusted to 7.8:45.5:46.7. The resident population in this area is 19.03 million, and the urbanization rate is 0.65, with a per capita GDP of 87,700 yuan. While the social and economic development of coastal Jiangsu Province has made progress, resource and environmental constraints are increasing. Insufficient water supply and water environmental quality deterioration are especially troubling. Coastal Jiangsu Province is located in plain river network areas, and the local water resource regulation and storage capacity are poor. The area relies on the south-to-north water diversion project to provide a stable water supply. In terms of water consumption, agricultural water use accounts for more than 70% of the total water consumption. The water consumption pattern is uneven, the water consumption efficiency is relatively low, and the allocation of water resources requires optimization. The non-point source pollution caused by large-scale agricultural planting and the point source pollution caused by high-density centralized chemical industrial parks have noticeable adverse effects on the water quality of the rivers and lakes, and the environmental water quality must be urgently improved.

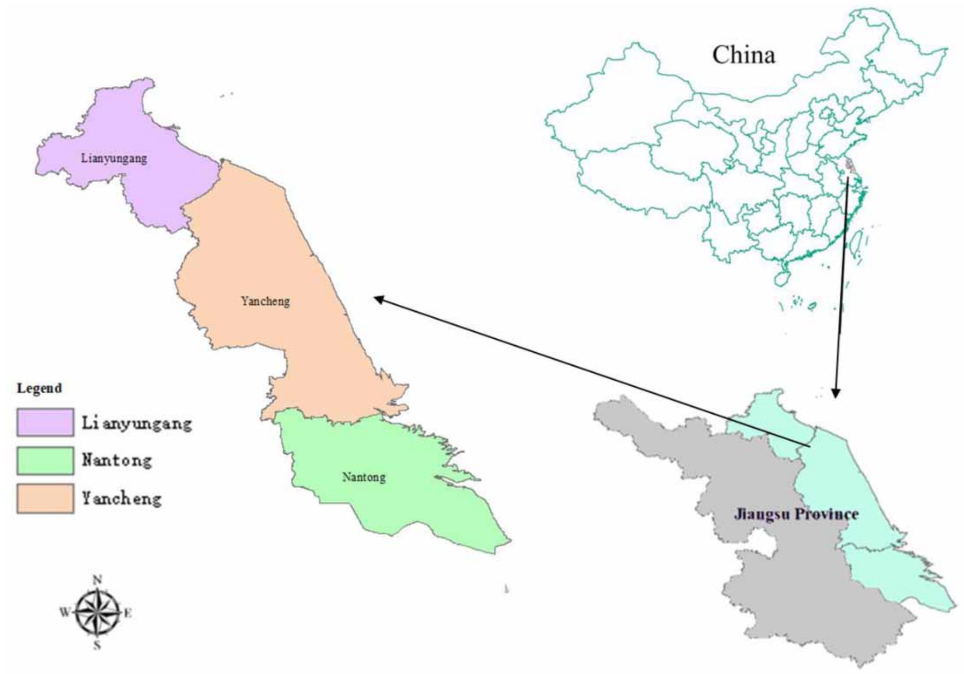


Fig. 1 | Location of the study area.

2.1.2. Data

2.1.2.1. The 'three red lines' policy in the study area. In 2012, the State Council issued 'The guidelines on implementing the stringent water resource management system,' which mapped out the working arrangements. These guidelines identified the main objectives and put forward the measures to be taken, the tasks to be completed, and the accountability procedures to be put in place to ensure rational development, water use, and protection, as well as sustainable economic and social development (Global Water Partnership, 2015). To ensure the targets are achieved, the measures below will be implemented: (1) Leadership will be strengthened to monitor performance, specify targets, and set up working systems. (2) Legislative systems will be refined to regulate water conservation. (3) Supervision and management will be strengthened among key water users. (4) Key pilot and demonstration projects will be implemented, including recycling industrial water, introducing and rehabilitating water-saving technologies, and publicizing water-saving devices in cities. (5) The public will be educated, so that water saving becomes a cultural norm.

As shown in Table 1, according to the requirements of the State Council, Jiangsu Province has set specific assessment indicators for the 'three red lines' policy in its three coastal cities.

2.1.2.2. Data source. The data used in this paper were primarily sourced from bulletins and yearbooks prepared by the government. The data include historical water use and water quality data from the Water Resources Bulletin (http://slj.yancheng.gov.cn/col/col1471/index.html; http://slj.lyg.gov.cn/lygsslj/szygb/szygb.html; http://slj.nantong.gov.cn/ntslj/) and historical population, urbanization rate, GDP scale, and industrial structure data from the Statistical Yearbook and the National Economic Development Statistics Bulletin

Table 1 | Assessment indicators of the 'three red lines' policy in the study area.

City	Upper limit of total water use (10^8 m^3)		Annual decline of water consumption per 10^4 yuan of GDP		Upper limit of COD discharge (10^4 t)		Upper limit of AN discharge (10^4 t)	
	2020	2030	2020	2030	2020	2030	2020	2030
Nantong	45	46.45	10%	10%	10.48	9.94	0.81	0.56
Yancheng	56	57.24	10%	10%	11.05	8.09	1.23	0.93
Lianyungang	28	29.43	10%	10%	7.97	6.36	0.82	0.66

GDP, gross domestic product; COD, chemical oxygen demand; AN, ammonia nitrogen.

(http://tjj.nantong.gov.cn/ntstj/tjgb/tjgb.html; http://tjj.yancheng.gov.cn/col/col1773/index.html; http://tjj.lyg.gov.cn/tjxxw/tjsj/tjsj.html), among other sources.

2.2. Study framework

This study is divided into six sections (Figure 2). In Section 2.1, we explain the 'three red lines' policy in the context of China's water resource management and report the assessment indicators of the policy in the study area. Then, a WRCS evaluation method and the SD model incorporating the policy are proposed. The SD model is used to predict evaluation indicators for the WRCS. Then, based on the 'three red lines' policy, the WRCS is predicted (Section 3.2). In the final section, the impact of water resource limitations and 'three red lines' policy

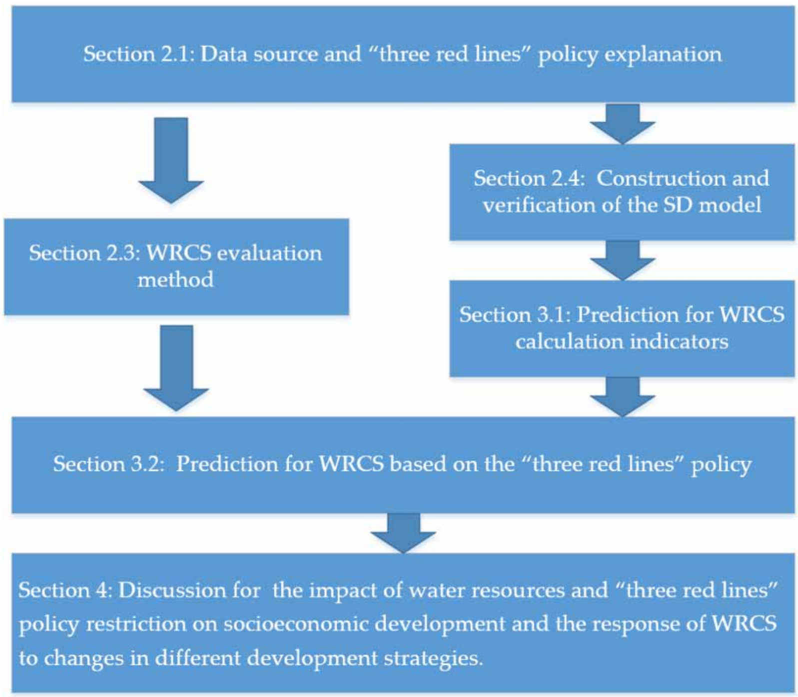


Fig. 2 | Study framework (WRCS, water resource carrying status; SD, system dynamics).

restrictions on socioeconomic development, obstacle factor diagnosis of WRCS deterioration, and the response of the WRCS to changes in different development strategies are discussed.

2.3. WRCS classification

To reflect the interaction between water resource carrying subjects (the water resource system) and water resource carrying objects (the socioeconomic and ecological environment systems), a coordinated development index (CDI) was selected as the WRCS measurement indicator in this study. The CDI was calculated using a multi-indicator method. The analysis steps of WRCS classification are shown in Figure 3.

2.3.1. Calculation indicators for the CDI

Combined with previous WRCS research and the requirements of the 'three red lines' policy in the study area, several indicators were preliminarily selected to characterize the water resource carrying subject and object. As shown in Table 2, nine indicators were chosen using principal component analysis. Three were used to characterize the water resource carrying subject and six to characterize the water resource carrying object.

2.3.2. Calculating the CDI

2.3.2.1. Indicator normalization. To remove the influence of different dimensions of each indicator, the indicators were normalized as follows:

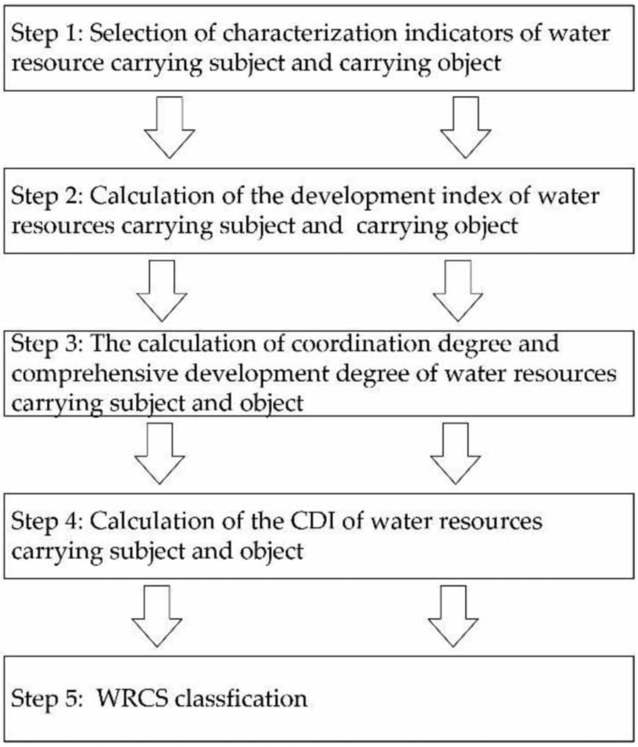


Fig. 3 | Analysis steps of WRCS classification. CDI, coordinated development index.

Table 2 | Indicators of CDI calculation.

Criterion layer A	Criterion layer B	Indicator layer	Indicator explanation	Unit
Carrying subject	Water resources	Ratio of water use to control value	Reflects the total water consumption control status	–
		Ratio of COD discharge to control value	Reflects the COD emission control status	–
		Ratio of AN discharge to control value	Reflects the AN emission control status	–
Carrying object	Socioeconomic conditions	Water use per 10,000 yuan of GDP	Reflects the water use efficiency	$m^3/10^4$ yuan
		COD released into the river per 10,000 yuan of GDP	Reflects the level of pollution interception	$t/10^4$ yuan
		AN released into the river per 10,000 yuan of GDP	Reflects the level of pollution interception	$t/10^4$ yuan
		Per capita GDP	Reflects the economic level	10^4 yuan/ person
	Ecological environment	Environmental water use rate	Reflects the intensity of eco-environmental protection	–
		Per capita public green area	Reflects the living environment of residents	m^3/person

GDP, gross domestic product; COD, chemical oxygen demand; AN, ammonia nitrogen.

(1) Positive indicators

$$x_i = \frac{x_i^* - x_{min}}{x_{max} - x_{min}} \tag{1}$$

(2) Negative indicators

$$x_i = \frac{x_{max} - x_i^*}{x_{max} - x_{min}} \tag{2}$$

where x_i^* $(i = 1, 2, \ldots, n)$ is the value of indicator i, x_{max} is the maximum indicator value, and x_{min} is the minimum indicator value.

2.3.2.2. Determination of weights. To avoid disadvantages related to subjective weighting lacking a theoretical basis while objective weighting cannot fully reflect the actual situation, a comprehensive weighting method based on cooperative game theory was used to determine the weights of each indicator (Shan *et al.*, 2020, 2021).

2.3.2.3. Calculating the CDI.

$$f(x) = \sum_{t_1=1}^{m_1} w_{t_1} x_{t_1} \tag{3}$$

$$g(y) = \sum_{t_2=1}^{m_2} w_{t_2} y_{t_2} \tag{4}$$

where $f(x)$ and $g(y)$ are the development indices of the carrying subject and object, respectively.

The value of the CDI is calculated as follows:

$$C = (1 - C_{fg}^2)^K \tag{5}$$

$$C_{fg} = \sqrt{1 - \frac{f(x)g(y)}{\left(\frac{f(x)+g(y)}{2}\right)^2}} \tag{6}$$

$$D = \sqrt{CT} \tag{7}$$

$$T = af(x) + \beta g(y) \tag{8}$$

where C is the coordination index between the carrying subject and the carrying object, C_{fg} is the deviation coefficient, K is the adjustment coefficient (2 in this study), D is the CDI, T is the system comprehensive index, and a and β are the weight coefficients (0.7 and 0.3, respectively).

2.3.3. WRCS classification standard

The WRCS classification standard was formulated based on the historical conditions of the study area, existing policies, technical standards, and related research results (Fang *et al.*, 2019), and the WRCS was divided into three grades: good (CDI value $>$0.87), medium (CDI value between 0.74 and 0.87), and poor (CDI value $<$0.74).

2.3.4. Obstacle factor diagnosis of WRCS deterioration

To provide a basis for the formulation of WRCS regulation, it is first necessary to identify the obstacle factors, which is a two-step process. First, the deviation degree S_i of each indicator value x_i from the ideal point is calculated, as shown in the following equation:

$$S_i = 1 - x_i \tag{9}$$

Then, the obstacle degree of each indicator is calculated according to the following equation:

$$P_i = \frac{S_i T_i}{\sum_i^I S_i T_i} \tag{10}$$

where I is the total number of indicators, T_i is the weight of indicator i, and P_i is the obstacle degree.

2.4. Construction of the SD model of regional water resource–socioeconomic–ecological environment system

SD is a discipline that quantitatively studies complex nonlinear, high-order, and multi-feedback systems based on system theory and by means of computer simulation technology (Wang *et al.*, 2022). The core of SD is to quantitatively describe the special relationship between different variables and their feedback mechanisms (Wen *et al.*, 2022). The WRCS results from the interactions between the carrying subject and the carrying object, involving the complex regional 'water resources–social economy–ecological environment' system. For the SD model to better reflect the internal structure and the interaction of the large-scale regional system, the system was subdivided into several subsystems, namely, population, economy, water resources, and water environment. Combined with the 'three red lines' constraints, the causal relationships between the key elements of each subsystem were analyzed.

2.4.1. Population subsystem

The most important element in the population subsystem is the total regional population, which is affected by migration, birth, and death rates, as well as other variables. In addition, different urbanization rates cause the urban and rural population numbers to change over time.

2.4.2. Economic subsystem

The economic subsystem includes agriculture, secondary industry, and tertiary industry. The output value of each industry is affected by the output value of the stock in the previous period and the growth rate in the present period. Economic growth may cause more water resource consumption and pollutant discharge (Sun *et al.*, 2022). When the water resource supply and demand are out of balance, and the water environment is polluted, the rate of economic growth is restricted.

2.4.3. Water resource subsystem

The water resource subsystem is the basis of the benign development of the population, the economy, and the water environment subsystems. Simultaneously, the above subsystems can restrain the benign development of the water resource subsystem. Population increases, economic scale expansion, and the improvement of eco-environmental requirements all lead to an increase in water demand, eventually leading to contradictions between the supply and demand of water resources. Specifically, in the SD model, domestic, industrial, and ecological/environmental water use are calculated separately. Domestic water use includes rural domestic and urban domestic water use, and industrial water use is divided into agricultural, secondary industrial, and tertiary industrial water use. Ecological/environmental water use includes water used for urban green areas, road flushing, and the artificial recharge of rivers and lakes. The ratio of water use to the control value is also calculated in the SD model. According to the policy, if water use exceeds the red line for water resource utilization, it will be required to reduce water use in the future, which may harm social and economic development.

2.4.4. Water environment subsystem

The water quality has a direct impact on the living standards of residents and water resource conditions. The main pollutants considered in the SD model are chemical oxygen demand (COD) and ammonia nitrogen (AN). The emission sources of pollutants are divided into domestic, agricultural, secondary industrial, and tertiary industrial. The total amount of pollutants discharged into the river is the sum of the pollutants from these different pollution sources. Specifically, the non-point pollution in the SD model includes rural domestic, secondary industrial, and tertiary industrial sources; the point pollution includes centrally treated agricultural sources. In addition, the ratio of pollutant discharge to the control value is calculated from the actual amount of pollutant discharged into the river and the control value presented in the 'three red lines' policy. This indicator reflects the effect of residents and the economy on the environment, and it impacts the rate of economic growth in the next calculation period.

There are complex relationships among the regional 'water resources–social economy–ecological environment' system variables in the SD model. Figure 4 presents a flow graph of the model to describe the causality between the variables more clearly. The first module simulates the water supply, the second module simulates the amount of pollutants released into the river, and the third module simulates the dynamic feedback of economic growth on the ratio of water use to the control value and the ratio of pollutant discharge to the control value. The SD model contains many variables and calculation equations, which are listed separately for each subsystem (population, economy, water resources and water environment) in the supplementary file.

3. RESULTS

3.1. Simulation results of the SD model

According to the requirements of socioeconomic development planning, water resource planning, and the 'three red lines' policy in the study area, the parameter values of the initial scheme were determined, and the key indicators from 2019 to 2040 were dynamically simulated using the SD model. The simulation results of the key indicators are shown in Figure 5.

From 2019 to 2040, as the birth rate exceeded the death rate, the population of coastal Jiangsu province continued to increase, from 7.35 to 7.80 million in Nantong city, from 7.76 to 7.92 million in Yancheng city, and increasing most significantly from 4.75 to 5.47 million in Lianyungang city. Economic development and industrial structure adjustment promoted the expansion of the GDP scale; Nantong increased from 867.6 to 1,815.8 billion yuan, Yancheng from 604.9 to 1,572 billion yuan, and Lianyungang city expanded the most, from 291.9 to 842 billion yuan. Although the water use efficiency of the three coastal cities improved, it was affected by the continuous growth of the population and GDP, and the total water use still showed an increasing future trend. Water use in Nantong will increase from 4.15 to 5.23 billion m^3, that in Yancheng will increase from 5.45 to 6.27 billion m^3, and that in Lianyungang is expected to grow from 2.53 to 3.75 billion m^3. Compared with the continuous increase in water consumption, the measures of sewage interception and discharge limitation in the three cities have achieved better results; the COD and AN emission of the three coastal cities show a fluctuating future trend. For 2040, the COD emission estimates of the three cities were 82,700, 109,900, and 86,100 t, respectively, and the AN emission estimates were 12,000, 12,100, and 0.75,000 t, respectively.

3.2. Changes in the CDI and the WRCS in the future

Combined with the simulation results of the SD model, the development of the carrying subject and the carrying object, comprehensive value, coordination value, and the CDI from 2019 to 2040 were calculated (Figure 6). From 2019 to 2040, due to the pressure of the increasing population and socioeconomic development, regional water consumption continued to increase, even exceeding the control value of total water consumption, causing a downward trend in the development index of the carrying subject of the three coastal cities. On the contrary, the development index of the carrying object in the three cities increased with the improvement in water saving, pollution interception, and residents' economic status. These opposite trends stabilized the comprehensive development value and the marked decrease of the coordination value over time, resulting in the downward trend of CDI in the three coastal cities. From the perspective of space, given that the control values of the three red lines differ in each city, although the water consumption and the amount of pollution discharged into the river in Lianyungang city are expected to be the least by 2040, the development index of the carrying subject of this city remains the worst among the three cities. In addition, due to the decrease of the development

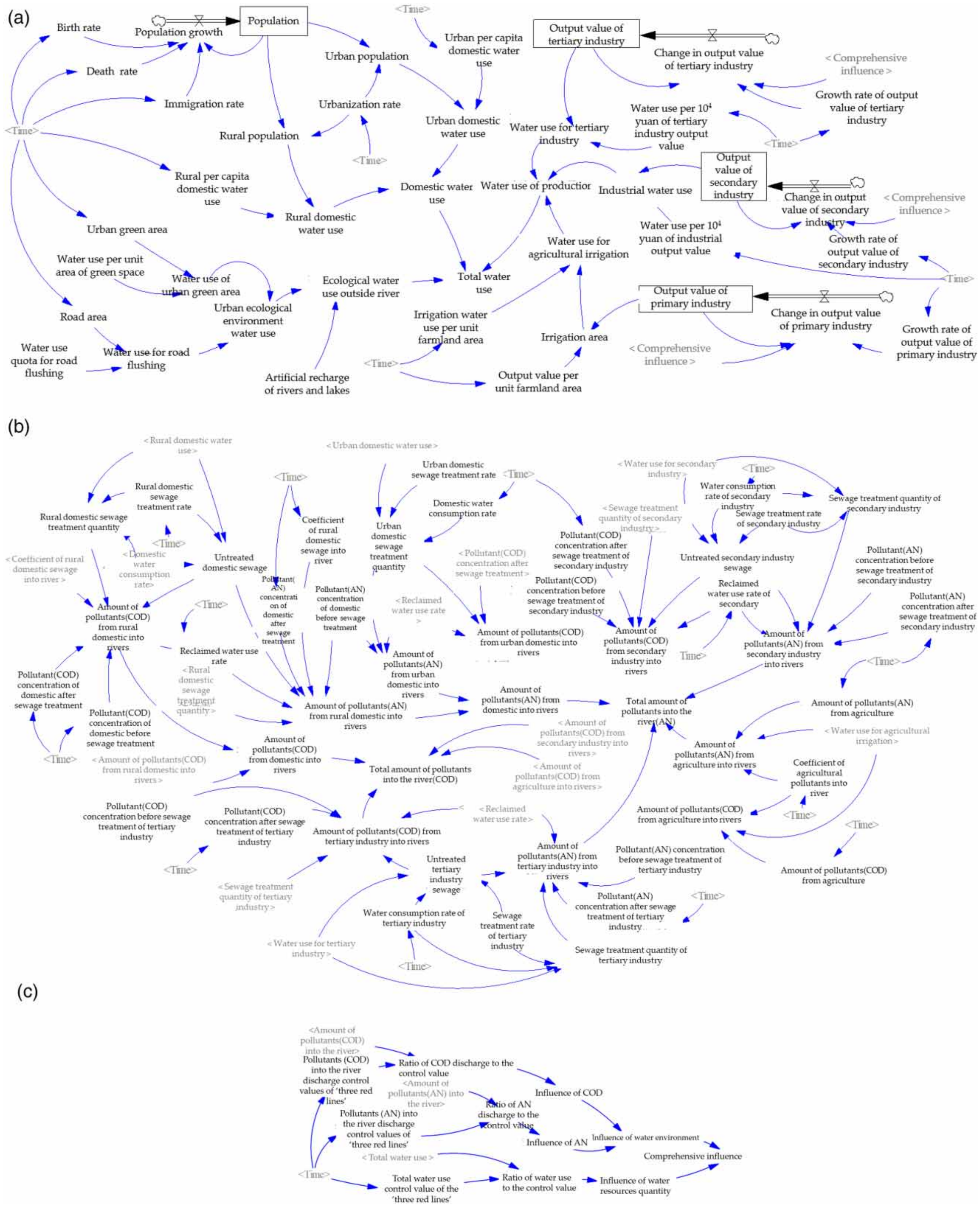


Fig. 4 | SD model of water resource–social economy–ecological environment system considering 'three red lines' policy. (a) Water supply and water use module. (b) Pollutant discharge module. (c) 'Three red lines' feedback modules.

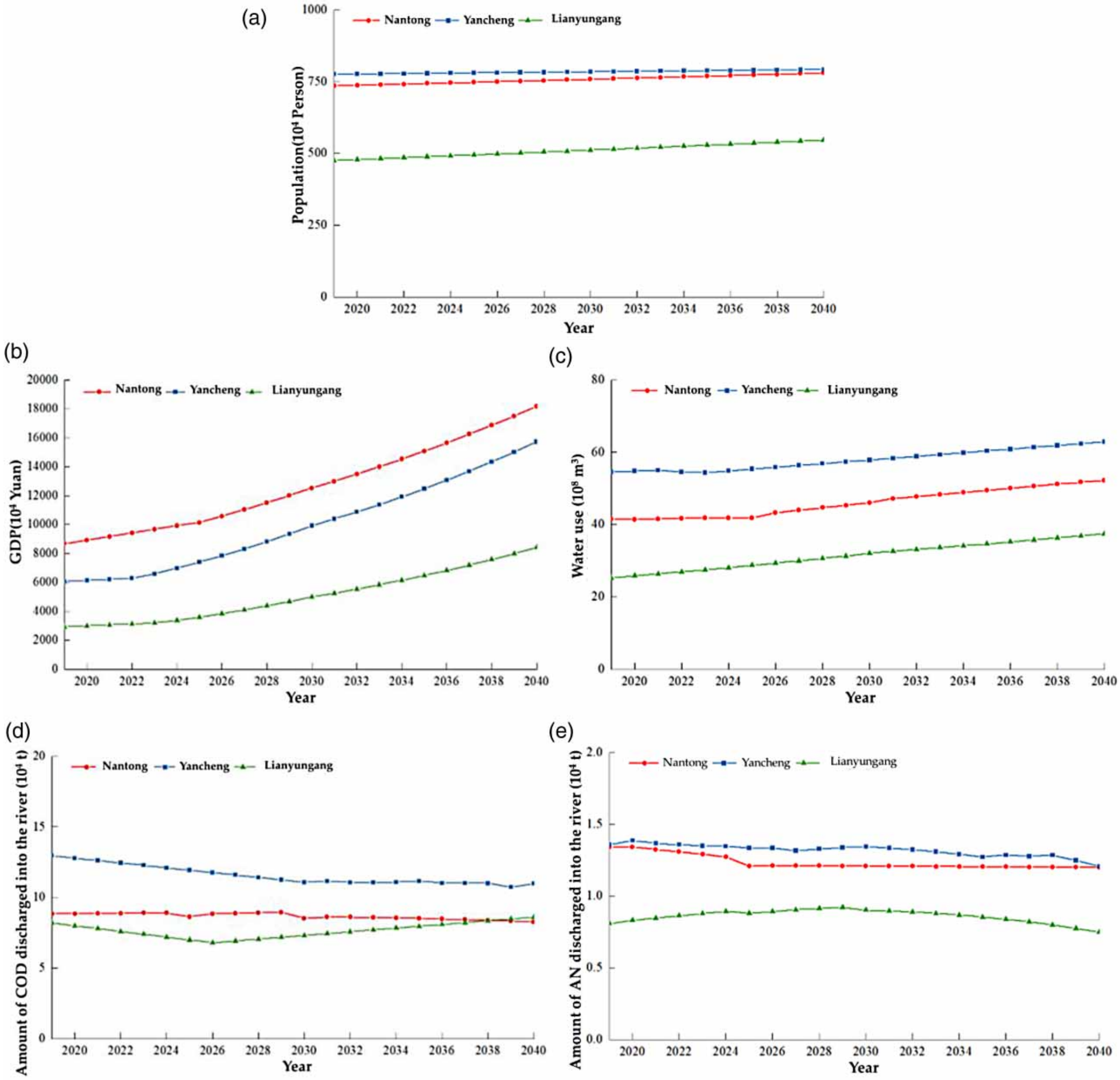


Fig. 5 | Simulation results of the system dynamics model in the Jiangsu coastal area from 2019 to 2040. GDP, gross domestic product; COD, chemical oxygen demand; AN, ammonia nitrogen. (a) Population, (b) GDP, (c) water use, (d) amount of COD discharged into the river, and (e) amount of AN discharged into the river.

index of the carrying subject and the rapid growth of the development index of the carrying object, by 2040, the development of the carrying subject and the carrying object in Nantong will be asynchronous, leading to the worst CDI value for Nantong among the three cities. This prediction anticipates that water resource protection and economic growth must be simultaneously considered when formulating development strategies; otherwise, development may be uncoordinated.

According to the CDI value calculated, the estimated WRCS in Nantong city from 2019 to 2035 was medium and that from 2035 to 2040 was poor. Similarly, the estimated WRCS in Yancheng city from 2019 to 2037 was

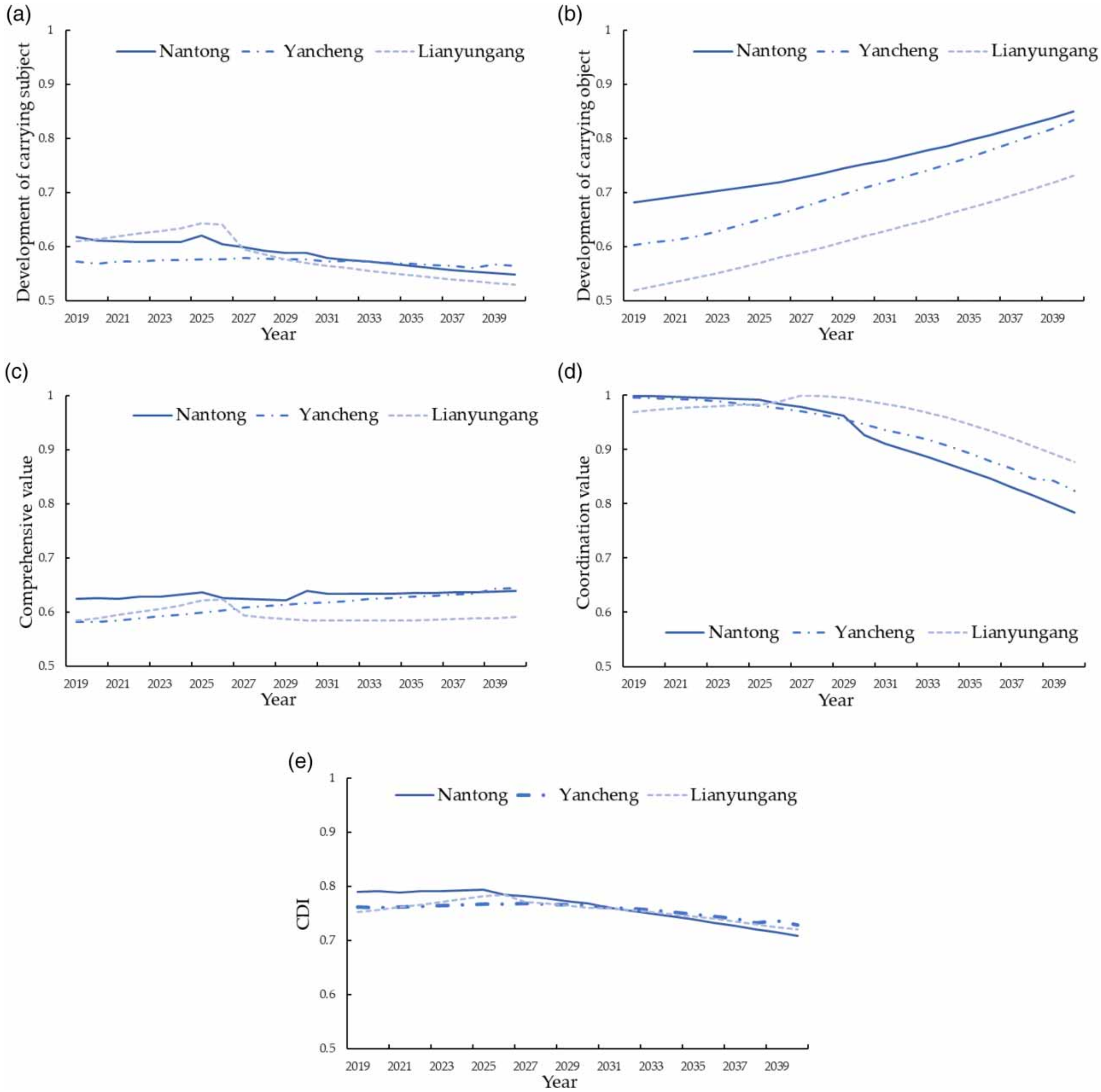


Fig. 6 | Calculated CDI and WRCS from 2019 to 2040. (a) Development of carrying subject, (b) development of carrying object, (c) comprehensive value, (d) coordination value, and (e) CDI.

medium and that from 2038 to 2040 was poor, and that in Lianyungang city from 2019 to 2036 was medium and that from 2037 to 2040 was poor.

3.3. Obstacle factor of WRCS

According to the formulas (9) and (10), the obstacle degrees of each indicator of the water resource carrying subject and object in the three coastal cities were calculated, and the results are shown in Table 3. Although the obstacle degree values of each indicator differ, the main obstacle factors are similar. For the water resource carrying subject, limited by the red line for water resource utilization and the increase in water consumption, the ratio

Table 3 | Obstacle factor diagnosis results.

Year	Area	Carrying subject or object	Primary obstacle factor	Obstacle degree	Secondary obstacle factor	Obstacle degree
2020	Nantong	Subject	Ratio of AN discharge to control value	0.53	Ratio of water use to control value	0.31
		Object	Per capita GDP	0.39	Per capita public green area	0.29
	Yancheng	Subject	Ratio of COD discharge to control value	0.4	Ratio of water use to control value	0.34
		Object	Per capita GDP	0.41	Per capita public green area	0.26
	Lianyungang	Subject	Ratio of water use to control value	0.47	Ratio of COD discharge to control value	0.21
		Object	Per capita GDP	0.38	Per capita public green area	0.28
2025	Nantong	Subject	Ratio of AN discharge to control value	0.47	Ratio of water use to control value	0.37
		Object	Per capita GDP	0.38	Per capita public green area	0.31
	Yancheng	Subject	Ratio of water use to control value	0.39	Ratio of COD discharge to control value	0.37
		Object	Per capita GDP	0.42	Per capita public green area	0.26
	Lianyungang	Subject	Ratio of water use to control value	0.48	Ratio of COD discharge to control value	0.27
		Object	Per capita GDP	0.39	Per capita public green area	0.31
2030	Nantong	Subject	Ratio of AN discharge to control value	0.43	Ratio of water use to control value	0.43
		Object	Per capita public green area	0.36	Per capita GDP	0.33
	Yancheng	Subject	Ratio of water use to control value	0.43	Ratio of COD discharge to control value	0.33
		Object	Per capita GDP	0.42	Per capita public green area	0.26
	Lianyungang	Subject	Ratio of water use to control value	0.49	Ratio of COD discharge to control value	0.29
		Object	Per capita public green area	0.35	Per capita GDP	0.38
2035	Nantong	Subject	Ratio of water use to control value	0.46	Ratio of AN discharge to control value	0.41
		Object	Per capita public green area	0.44	Per capita GDP	0.25
	Yancheng	Subject	Ratio of water use to control value	0.46	Ratio of AN discharge to control value	0.33
		Object	Per capita GDP	0.37	Per capita public green area	0.24
	Lianyungang	Subject	Ratio of water use to control value	0.53	Ratio of AN discharge to control value	0.28
		Object	Per capita public green area	0.4	Per capita GDP	0.33

GDP, gross domestic product; COD, chemical oxygen demand; AN, ammonia nitrogen.

of water use to the control value of each city is the obstacle factor, and the obstacle degree shows an upward trend. In 2035, the predicted value for Nantong, Yancheng, and Lianyungang will be 0.46, 0.46, and 0.53, respectively. Another major obstacle factor in Nantong city is the ratio of AN discharge to the control value, and that of COD is important in Lianyungang and Yancheng. For the water resource carrying object, the obstacle degree of each city is higher in per capita GDP and per capita green space areas. Over the years, the economic level of the three cities has been significantly improved and the obstacle degree of the per capita GDP decreased, while the obstacle degree of the per capita green space area presented an upward trend. Specifically, in 2020, the obstacle degree of per capita GDP of Nantong, Yancheng, and Lianyungang was 0.39, 0.41, and 0.38, respectively, while it is expected to decrease to 0.25, 0.37, and 0.33, respectively, in 2035.

4. DISCUSSION

4.1. The influence of the 'three red lines' policy on the WRCS

The WRCS calculation indicators selected in this study and the subsequent SD model were closely related to the 'three red lines' policy. In accordance with the requirements of the 'three red lines' policy, the water conservancy bureau of each city (Nantong, Yancheng, Lianyungang) issued planning documents for the future and formulated relevant strategies for water resource regulation and protection. Moreover, management objectives, such as water use efficiency and pollution discharge coefficients, were also defined. These indicators were set as the parameters of the SD model to predict changes in the 'water resources–socio-economic–ecological environment' system under the influence of the policy. According to the calculation results, the CDI values of the three coastal cities in Jiangsu Province first experience a rising trend, followed by a decreasing one, showing that, from the perspective of the 'three red lines' policy, the WRCS first improves and then deteriorates. This is because, although the efficiency indicators improve in the future, the expansion of the population and GDP cause the total water use and the total amount of pollutants in the river to show a first decreasing and then increasing trend, gradually exceeding the 'three red lines' control values for total water use and pollutant discharge in the later periods. In terms of the water resource carrying subject and carrying object, owing to the improvement of the economic level, water use efficiency, and degree of water resource protection compared with the current situation, the development index value of the water resource carrying object continues to rise. Conversely, the fluctuation of total water consumption and sewage discharge results in a downward trend in the development index of the carrying subject. The maximum development index of the carrying subject in Nantong was 0.620 in 2025, 0.579 in Yancheng in 2027, and 0.640 in Lianyungang in 2026, which is consistent with the occurrence time of the CDI value in each city. Compared with 2019, the 2040 development index values of the three coastal cities decreased by 0.07, 0.008, and 0.080, respectively, and the development index values of the carrying objects increased by 0.167, 0.230, and 0.212, respectively. In conclusion, to continuously improve WRCS, it could be necessary to introduce further regulatory measures for water use and water environmental protection based on existing policies.

4.2. Response of WRCS to changes in different development strategies

4.2.1. Scheme setting

Although water saving and pollution interception measures were accounted for in the initial calculation scheme, the expansion of the economic scale will lead to an increase in total water consumption and sewage discharge in the future, especially after 2025, resulting in the decline of the development index of the carrying object. Three groups of development strategies were constructed to assess such a situation, with reference to the obstacle factor diagnosis results. These strategies use different measures from the point of industrial structure adjustment onwards, further improving the water use efficiency.

(1) *Scheme I*: Based on the initial calculation scheme, this scheme considers further improving water resource development and utilization efficiency, reducing the discharge of pollutants and increasing green areas to protect regional water resources and the environment. The relevant parameters in the SD were adjusted. Compared with the initial calculation scheme, the parameter values of the average irrigation water use, industrial 10,000-yuan-added-value water use, and tertiary industrial 10,000-yuan-added-value water use decreased

by 10%. The rural domestic sewage treatment rate increased to 100% after 2025, and the coefficient of agricultural planting pollutants released into the river was reduced by 50%.

(2) *Scheme II*: By adjusting the development speed of different industries, this scheme can improve the economic level of residents in coastal Jiangsu while adjusting the industrial structure and improving the comprehensive water use efficiency. Specifically, compared to the parameters in the initial calculation scheme, the growth rate of the added value of the secondary and tertiary industries increases by 20%.

(3) *Scheme III*: This scheme includes the measures in Schemes I and II together.

4.2.2. Scheme simulation

Using the SD model, simulation results of each scheme were obtained. In Scheme I, the inhibition effect on economic growth was alleviated due to the improvement of water use efficiency and pollution intervention parameters. Compared with the initial scheme, the economic growth rate slightly increased. By 2040, the estimated GDP of the three coastal cities was 1,906.5, 1,600.6, and 884.2 billion yuan in Nantong, Yancheng, and Lianyungang, respectively. The growth rate of total water use dwindled year by year. By 2040, the total water use of the three coastal cities was 4.94, 5.68, and 3.34 billion m^3, respectively, which is similar to the total water use control value. In addition, the emissions of COD and AN decreased significantly after 2025. In Scheme II, compared with the initial scheme, the economic scale expanded significantly. By 2040, the estimated GDP of the three coastal cities was 1,979.1, 1,713.4, and 917.8 billion yuan, respectively. With the expansion of the economic scale, the total water use and the total sewage discharge increased significantly. By 2040, the total amount of water use in the three coastal cities was 5.41, 6.31, and 3.88 billion m^3, respectively, which is 1.16, 1.37, and 1.31 times the total water use control value. The total COD discharge was 8.56, 11.31, and 8.91 t, respectively, which is 0.87, 1.41, and 1.40 times the COD control value, respectively. The total AN emissions were 1.24, 1.25, and 0.78 t, respectively, which is 2.21, 1.35, and 1.18 times the AN control value, respectively. In Scheme III, the parameter changes in Schemes I and II were considered simultaneously. The improvement in the water use efficiency and pollution intercession level reduces the restraining effect of the ratio of water use to the control value and the ratios of pollutant discharge to the control values. Superimposed with high GDP growth, the economic scale of the three coastal cities expanded to a greater extent. By 2040, the GDP of the three coastal cities was 2,015.5, 1,744.5, and 934.7 billion yuan, respectively. The values for total water use, COD discharge, and AN discharge were intermediate between those for Schemes I and II. The total water use was 5.22, 6.28, and 3.74 billion m^3, respectively, all exceeding the control value. The COD emissions were 7.34, 9.75, and 8.60 t, respectively, and the AN emissions were 1.06, 1.07, and 0.75 million t, respectively.

4.2.3. Analysis of the effect of each scheme

The ratio of the CDI value of each regulation scheme to the initial scheme was calculated, and the results are shown in Figure 7. If the ratio is larger than 1, it indicates that the regulation scheme has achieved positive effects; otherwise, it indicates that the regulation scheme has caused negative effects. For Scheme I, the coastal areas shall optimize agricultural irrigation modes, accelerate industrial transformation, strengthen the use of water-saving appliances, the collection and treatment of rural sewage, and control pesticides and fertilizers, to achieve the goal of improving water use efficiency and reducing pollutants entering rivers. Regarding the benefits, the ratio of the CDI value of each city in each year was larger than 1, and the ratio increased gradually every year overall, indicating that this scheme could effectively improve the WRCS in coastal Jiangsu. These improvements might grow in parallel to the expansion of the economic scale. By adjusting the growth rate of different industries, the regional economic structure is expected to develop toward reduced water consumption and pollution. However, due to the excessive socioeconomic aggregates, the ratio of the CDI value of each city in Scheme II was less

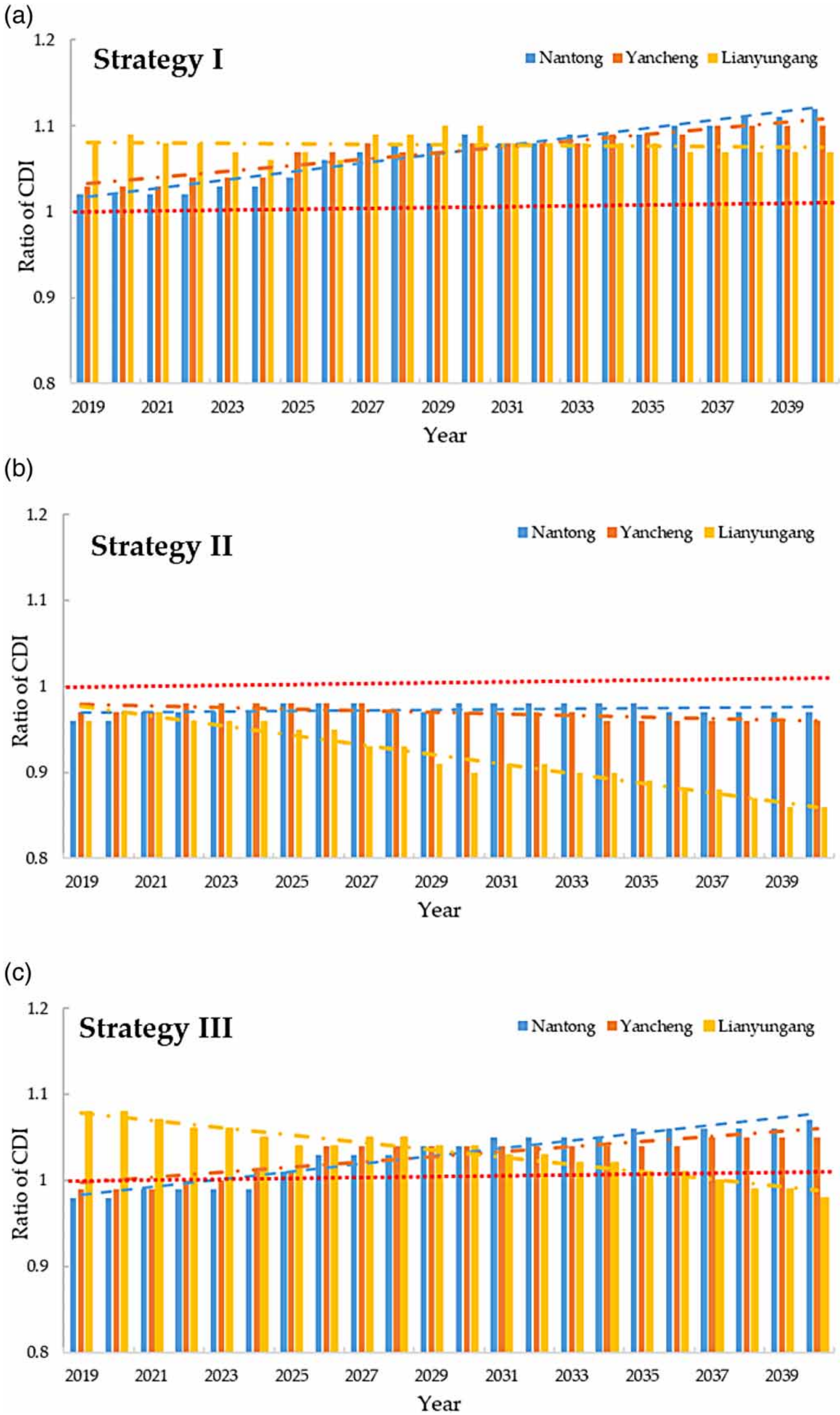


Fig. 7 | CDI comparison of each regulation scheme. (a) Scheme I, (b) Scheme II, and (c) Scheme III.

than 1, and the ratio decreased gradually over the years, indicating that strategies in Scheme II might improve the economic level of coastal Jiangsu. However, this scenario also poses a higher water resource demand and pollution load, which are not conducive to WRCS improvement. Nevertheless, the negative impact of economic expansion became increasingly prominent over time, rendering Scheme II unfeasible. Scheme III was constructed by combining the measures in Scheme I and II to analyze whether WRCC can be maintained while improving economic growth. From the simulation results of Scheme III, differences were noted in the CDI changes of the coastal Jiangsu cities. The early ratio of Nantong city and Yancheng city was less than 1; however, the ratios of the two cities exceeded 1 in 2025 and 2022, respectively, showing a gradually increasing trend. For Lianyungang city, the early ratio was greater than 1 and gradually decreased over the years to 0.98 in 2040. This scheme could effectively improve the economic development speed in coastal Jiangsu areas on the premise that the WRCS is essentially consistent with the initial scheme.

5. CONCLUSIONS

To accurately simulate the evolution of the regional 'water resources–socio-economic–ecological environment' system under the influence of the 'three red lines' policy, an SD model considering the 'red line' constraint feedback was constructed in this study. The SD was divided into the water supply and consumption module, the water environment module, and the 'red line' feedback module, which realizes the simulation of social and economic development, water use, pollutant discharge, and the dynamic feedback of economic growth on the ratio of water use to the control value and the ratio of pollutant discharge to the control value. Using the SD model, the characterization indicators of the water resource carrying subject and carrying object were predicted. The CDI between the carrying subject and carrying object from 2019 to 2040 was calculated, and the WRCS classified. According to existing policies and planning, from 2019 to 2040, the CDI value of the three coastal cities experienced an evolution, first rising and then falling. The WRCS in Nantong city from 2019 to 2035 was medium and that from 2035–2040 was poor. The WRCS in Yancheng city from 2019 to 2037 was medium and that from 2038 to 2040 was poor. The WRCS in Lianyungang city from 2019 to 2036 was medium and that from 2037 to 2040 was poor. Three regulation schemes were constructed to improve the WRCS in the future, considering the diagnostic results of the WRCS obstacle factors. The results show that the WRCS could be effectively improved by further improving the water use efficiency and strengthening sewage interception based on the current situation; continuing to improve the regional economic development speed will lead to increases in water resource demand and pollutant discharge, which will adversely impact the WRCS. If the above strategies are combined, and the intensity of each measure is properly controlled, the population and GDP that can be carried by the regional water resources can be further improved, while maintaining the WRCS at the current level.

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DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Cai, Y., Liang, J., Zhang, P., Wang, Q., Wu, Y., Ding, Y., Wang, H., Fu, C. & Sun, J. (2021). Review on strategies of close-to-natural wetland restoration and a brief case plan for a typical wetland in northern China. *Chemosphere 285*, 131534. https://doi.org/10.1016/j.chemosphere.2021.131534.

Chapagain, K., Aboelnga, H. T., Babel, M. S., Ribbe, L., Shinde, V. R., Sharma, D. & Dang, N. M. (2022). Urban water security: a comparative assessment and policy analysis of five cities in diverse developing countries of Asia. *Environmental Development 43*, 100713. https://doi.org/10.1016/j.envdev.2022.100713.

Chen, J., Yao, Y., Wang, G., Zhong, X., Yang, T. & Sun, W. (2021). Decreased precipitation frequency altered abundance, but not community structure, of soil nematodes in degraded grasslands. *Ecological Indicators 131*, 108184. https://doi.org/10.1016/j.ecolind.2021.108184.

Dong, Z. C., Yang, G., Feng, S. N., Ma, J. Y. & Li, B. (2021). Analysis of the ultimate water resources carrying capacity in Yancheng, China. *Water Supply 21*(6), 3099–3113. doi:10.2166/ws.2021.102.

Dou, M., Ma, J., Li, G. & Zuo, Q. (2015). Measurement and assessment of water resources carrying capacity in Henan Province, China. *Water Science and Engineering 8*(2), 102–113. https://doi.org/10.1016/j.wse.2015.04.007.

Fang, H., Gan, S. & Xue, C. (2019). Evaluation of regional water resources carrying capacity based on binary index method and reduction index method. *Water Science and Engineering 12*(4), 263–273. https://doi.org/10.1016/j.wse.2019.12.008.

Global Water Partnership (2015). *China's Water Resources Management Challenge: The 'Three Red Lines'. Technical Focus Paper*. Elanders, Sweden.

Hao, R., Huang, G., Liu, L., Li, Y., Li, J. & Zhai, M. (2022). Sustainable conjunctive water management model for alleviating water shortage. *Journal of Environmental Management 304*, 114243. https://doi.org/10.1016/j.jenvman.2021.114243.

He, C., Harden, C. P. & Liu, Y. (2020). Comparison of water resources management between China and the United States. *Geography and Sustainability 1*(2), 98–108. https://doi.org/10.1016/j.geosus.2020.04.002.

Keyhanpour, M. J., Musavi Jahromi, S. H. & Ebrahimi, H. (2021). System dynamics model of sustainable water resources management using the Nexus Water-Food-Energy approach. *Ain Shams Engineering Journal 12*(2), 1267–1281. https://doi.org/10.1016/j.asej.2020.07.029.

Khorsandi, M., Homayouni, S. & van Oel, P. (2022). The edge of the petri dish for a nation: water resources carrying capacity assessment for Iran. *Science of the Total Environment 817*, 153038. https://doi.org/10.1016/j.scitotenv.2022.153038.

Li, Y. & Chen, Y. (2021). Variable precondition S-type cloud algorithm: theory and application on water resources carrying capacity assessment. *Ecological Indicators 121*, 107209. https://doi.org/10.1016/j.ecolind.2020.107209.

Mei, H., Liu, Y., Du, H. & Yang, X. (2010). Advances in study on water resources carrying capacity in China. *Procedia Environmental Sciences 2*, 1894–1903. https://doi.org/10.1016/j.proenv.2010.10.201.

Naimi Ait-Aoudia, M. & Berezowska-Azzag, E. (2016). Water resources carrying capacity assessment: the case of Algeria's capital city. *Habitat International 58*, 51–58. https://doi.org/10.1016/j.habitatint.2016.09.006.

Ni, X., Wu, Y., Wu, J., Lu, J. & Wilson, P. C. (2012). Scenario analysis for sustainable development of Chongming Island: water resources sustainability. *Science of the Total Environment 439*, 129–135. https://doi.org/10.1016/j.scitotenv.2012.09.031.

Qin, J., Ding, Y., Zhao, Q., Wang, S. & Chang, Y. (2020). Assessments on surface water resources and their vulnerability and adaptability in China. *Advances in Climate Change Research 11*(4), 381–391. https://doi.org/10.1016/j.accre.2020.11.002.

Shan, C. J., Yang, J. H., Dong, Z. C., Huang, D. J. & Wang, H. (2020). Study on river health assessment weight calculation. *Polish Journal of Environmental Studies 29*(2), 1839–1848. doi:10.15244/pjoes/110041.

Shan, C. J., Dong, Z., Lu, D. B., Xu, C. D., Wang, H., Ling, Z. & Liu, Q. (2021). Study on river health assessment based on a fuzzy matter-element extension model. *Ecological Indicators 127*. doi:10.1016/j.ecolind.2021.107742.

Sun, X., Zhu, B., Zhang, S., Zeng, H., Li, K., Wang, B., Dong, Z. & Zhou, C. (2022). New indices system for quantifying the nexus between economic-social development, natural resources consumption, and environmental pollution in China during 1978–2018. *Science of the Total Environment 804*, 150180. https://doi.org/10.1016/j.scitotenv.2021.150180.

Vorosmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A., Liermann, C. R. & Davies, P. M. (2010). Global threats to human water security and river biodiversity. *Nature 467*(7315), 555–561. doi:10.1038/nature09440.

Wang, Q. & Yang, Z. (2016). Industrial water pollution, water environment treatment, and health risks in China. *Environmental Pollution 218*, 358–365. https://doi.org/10.1016/j.envpol.2016.07.011.

Wang, K., Davies, E. G. R. & Liu, J. (2019). Integrated water resources management and modeling: a case study of Bow river basin, Canada. *Journal of Cleaner Production 240*, 118242. https://doi.org/10.1016/j.jclepro.2019.118242.

Wang, G., Xiao, C., Qi, Z., Meng, F. & Liang, X. (2021a). Development tendency analysis for the water resource carrying capacity based on system dynamics model and the improved fuzzy comprehensive evaluation method in the Changchun city, China. *Ecological Indicators 122*, 107232. https://doi.org/10.1016/j.ecolind.2020.107232.

Wang, J., Mu, X., Chen, S., Liu, W., Wang, Z. & Dong, Z. (2021b). Dynamic evaluation of water resources carrying capacity of the Dianchi Lake Basin in 2005–2015, based on DSPERM framework model and simulated annealing-projection pursuit model. *Regional Sustainability 2*(2), 189–201. https://doi.org/10.1016/j.regsus.2021.06.003.

Wang, X., Liu, L., Zhang, S. & Gao, C. (2022). Dynamic simulation and comprehensive evaluation of the water resources carrying capacity in Guangzhou city, China. *Ecological Indicators 135*, 108528. https://doi.org/10.1016/j.ecolind.2021.108528.

Wen, C., Dong, W., Zhang, Q., He, N. & Li, T. (2022). A system dynamics model to simulate the water-energy-food nexus of resource-based regions: a case study in Daqing City, China. *Science of the Total Environment 806*, 150497. https://doi.org/10.1016/j.scitotenv.2021.150497.

Wu, C., Zhou, L., Jin, J., Ning, S., Zhang, Z. & Bai, L. (2020). Regional water resource carrying capacity evaluation based on multi-dimensional precondition cloud and risk matrix coupling model. *Science of the Total Environment 710*, 136324. https://doi.org/10.1016/j.scitotenv.2019.136324.

Wu, B., Zeng, H., Zhu, W., Yan, N. & Ma, Z. (2021). Enhancing China's Three Red Lines strategy with water consumption limitations. *Science Bulletin 66*(20), 2057–2060. https://doi.org/10.1016/j.scib.2021.06.012.

Xie, Z. (2020). China's historical evolution of environmental protection along with the forty years' reform and opening-up. *Environmental Science and Ecotechnology 1*, 100001. https://doi.org/10.1016/j.ese.2019.100001.

Yang, Z., Song, J., Cheng, D., Xia, J., Li, Q. & Ahamad, M. I. (2019). Comprehensive evaluation and scenario simulation for the water resources carrying capacity in Xi'an city, China. *Journal of Environmental Management 230*, 221–233. https://doi.org/10.1016/j.jenvman.2018.09.085.

Yang, D., Yang, Y. & Xia, J. (2021a). Hydrological cycle and water resources in a changing world: a review. *Geography and Sustainability 2*(2), 115–122. https://doi.org/10.1016/j.geosus.2021.05.003.

Yang, G., Dong, Z., Feng, S., Li, B., Sun, Y. & Chen, M. (2021b). Early warning of water resource carrying status in Nanjing City based on coordinated development index. *Journal of Cleaner Production 284*, 124696. https://doi.org/10.1016/j.jclepro.2020.124696.

Zhang, X., Dong, Q., Costa, V. & Wang, X. (2019a). A hierarchical Bayesian model for decomposing the impacts of human activities and climate change on water resources in China. *Science of the Total Environment 665*, 836–847. https://doi.org/10.1016/j.scitotenv.2019.02.189.

Zhang, R., Qi, F., Liu, C., Zhang, Y., Wang, Y., Song, Z., Kumirska, J. & Sun, D. (2019b). Cyanobacteria derived taste and odor characteristics in various lakes in China: Songhua Lake, Chaohu Lake and Taihu Lake. *Ecotoxicology and Environmental Safety 181*, 499–507. https://doi.org/10.1016/j.ecoenv.2019.06.046.

Zhao, X., Rao, H., Yi, Q., He, C. & Yang, H. (2012). Scenarios simulation on carrying capacity of water resources in Kunming City. *Procedia Earth and Planetary Science 5*, 107–112. https://doi.org/10.1016/j.proeps.2012.01.018.

Zhao, Y., Wang, Y. & Wang, Y. (2021). Comprehensive evaluation and influencing factors of urban agglomeration water resources carrying capacity. *Journal of Cleaner Production 288*, 125097. https://doi.org/10.1016/j.jclepro.2020.125097.

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