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Research on the urban water resources carrying capacity by using system dynamics simulation

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ABSTRACT

The relationship between water resources and social economy has become a restricting factor for sustainable development of cities around the world. Linhai City in eastern China has the fastest economic growing and population boom. The system dynamics model of water resources carrying capacity was established to analyze the interaction between society, economy and water resources of Linhai city. Six different modes of water resources utilization were designed. Taking total population, gross domestic product, industrial output value, tertiary industry output value, water consumption, water supply and sewage discharge as the measurement indexes, the research predicted the development status of water resources carrying capacity of Linhai City from 2015 to 2030 under different development modes. Through the simulation results, it is found that the water-saving measures can reduce the gap between water supply and demand only in the short term. In the long run, the adjustment of industrial structure can improve the water resources carrying capacity and simultaneously promote the economy. In addition, increase the water income sources as well as strengthen sewage treatment are also necessary to balance the water supply and demand.

Key words: development mode, Linhai City, social economy, system dynamics model, water resources carrying capacity, water resources utilization

HIGHLIGHTS

- Establishment of the water resources carry a capacity prediction model based on the system dynamics model.
- Sensitive variables selection for a coupled system of society, economy, water resources and environment.
- Optimization of development modes and water resource utilization for the study area.

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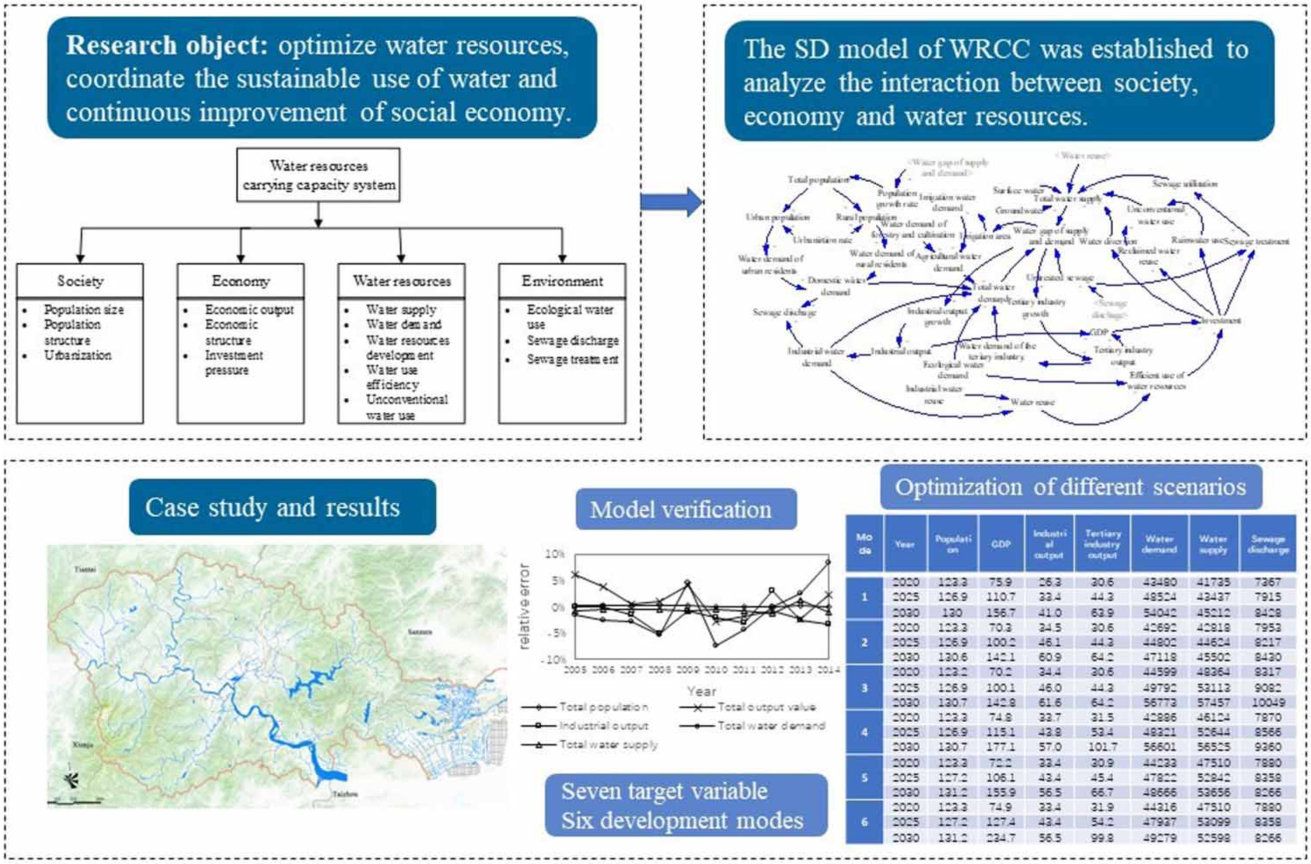
GRAPHICAL ABSTRACT



INTRODUCTION

Most of the Chinese cities face the problem of water resources shortage at present (Cai *et al.* 2017). There is a long-term contradiction of supply and demand between the quantity and quality of water resources and the social and economic development (Jia *et al.* 2018). Social and economic development should be within the scope of security according to the analysis of regional status-quo water resource conditions and regional development requirements (Ren *et al.* 2016). Therefore, the limit threshold assessment for water resources utilization and decision-making of the improvement measures are essential parts in the formulation of the urban sustainable development plan (Tian & Sun 2018). The analysis of water resources carrying capacity is one important research content (Wu *et al.* 2018; Zhang *et al.* 2019). The urgent task we face is to explore the best development mode of water resources so that it can maximize the benefits to the social economy and population while ensuring the healthy ecological environment. Only by having a systematic understanding of water resources carrying capacity can we achieve sustainable urban development.

Water resources carrying capacity is part of the theory of sustainable development (Giwa & Dindi 2017). Along with the advance of the research on the complicated system of water resources, the research on the water resource carrying capacities of different fields has become more and more active accordingly (Li *et al.* 2018). Water resource carrying capacity should be an important indicator in urban water resources management research (Rijsberman & Van de Ven 2000; Zuo *et al.* 2021). Tang *et al.* (2022) proposed that the pollution control of the water system should be reinforced against the contradiction of water supply and demand, and 20 years of water pollution control was evaluated. The comprehensive frameworks were built for evaluating the carrying capacity of cities, and decisive factors were selected including water supply capacity and sewage treatment capacity (Kyushik *et al.* 2005; Wang *et al.* 2022a). In order to study the carrying capacity of Florida Keys Basin, URS Company in the USA built the analysis model of carrying capacity consisting of society and economy,

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infrastructures, water, ocean and land. Simulations of the socioeconomic and ecological systems were conducted from an overall perspective (Clarke 2002; Hong *et al.* 2022).

The complex coupling system of socioeconomic-ecological water resources has been studied a lot at present. System dynamics is not only proficient in analyzing the internal relations among non-linear complicated systems, but also capable of simulating multiple scenes and targets. There are many applications in the studies of water resource systems. As pointed out by Davies & Simonovic (2011), most water resources models explicitly focused on water systems, while socioeconomic and environmental changes were used as external drivers. The utilization of the system dynamics-based water resources model was paying attention to non-linear feedback processes through the dynamic expressions of subsystems after interconnection (Liu *et al.* 2022; Wang *et al.* 2022b). Yang *et al.* (2015) built a composite system of social economy and water by taking Tieling City as an example, and selected population, gross domestic product (GDP) and per-capita GDP as thresholds representing water resources carrying capacity. Rehan *et al.* (2013) explored the solution to the contradiction between water supply and social economic development from the perspective of reclaimed water and water conservation. Sahin *et al.* (2015) conducted a system dynamics simulation of the future water supply and demand of Queensland, Australia, and predicted the degree of water safety under long-term planning. Davies & Simonovic (2011) incorporated factors of the hydrological cycle, water supply and demand, wastewater treatment and reuse and water quality into the model. Pluchinotta *et al.* (2021) applied the system dynamics model to analyze sustainable urban growth and water resource management and to explore the effects of different policies and future scenarios. Zhao *et al.* (2012) established the system dynamics water resources carrying capacity model including aspects of water resources, society, economy and eco-environment for Kunming city. The multi-objective planning was used to optimize industrial water use and to improve water use efficiency, pollutant reduction and sewage recycling. By building a model of system dynamics, Yang *et al.* (2019) studied the impacts of agricultural water consumption on the water resources carrying capacity in Xi'an. Jeong & Adamowski (2016) used system dynamics in the river basin to develop and validate the socio-hydrological model, so as to connect the deterministic conceptual hydrological model and the social development model including population, land use, economy, technology and policies.

Based on the concept of regional sustainable development, this research constructed water resources carrying capacity system dynamics model. This model consists of four subsystems: society, economy, water supply and demand and water environment. the four subsystems are closely related and interdependent. Water resources and the social economy are in a dynamic process of change in the process of development. They interact with each other and are also mutually restricted. Therefore, using the system dynamics method to build a composite system can reflect its complex internal relationship and make a more reasonable and reliable quantitative description for a water-socioeconomic composite system.

The model is applied to Linhai City, China, which has an increasingly serious water shortage. The spatial difference between the water supply and demand is very prominent in the area. The relationship between urban development and water resources in Linhai City was discussed. The feedback effects of water resources carrying capacity under various subsystems were investigated. The impacts of different water resource utilization modes on the urban water resource carrying capacity were explored. The objective of model and scenario analysis is to optimize the supply and demand of water resources, coordinate the sustainable use of water and continuous improvement of the social economy and guarantee water environment and water ecological health. The research could provide a reliable basis for scientific decision-making in water resources management and contribute to the sustainable development strategies of the environment and economy for Linhai City.

STUDY AREA

Topography and hydrometeorology

Located at the center of the coastal area of Zhejiang Province, Linhai City enjoys a crucial economic position on the southern side of the Yangtze River Economic Circle. Linhai City is situated to the north of Taizhou City, the east of Xianju County, the south of Tiantai County and Sanmen County and the west of the East Sea (see Figure 1). The city is embraced by mountains on three sides and by the sea on one side. Linhai City lies between NL 28°40′ ~ 29°04′ and EL 120°49′ ~ 121°41′. The east-west maximum transverse distance of the city is 85 km and the north-south maximum longitudinal distance is 44 km. Linhai has a land area of 2,203 km^2, 68.4% of which is mountains and hills, 25.1% of which is plain and 6.5% of which is water area.

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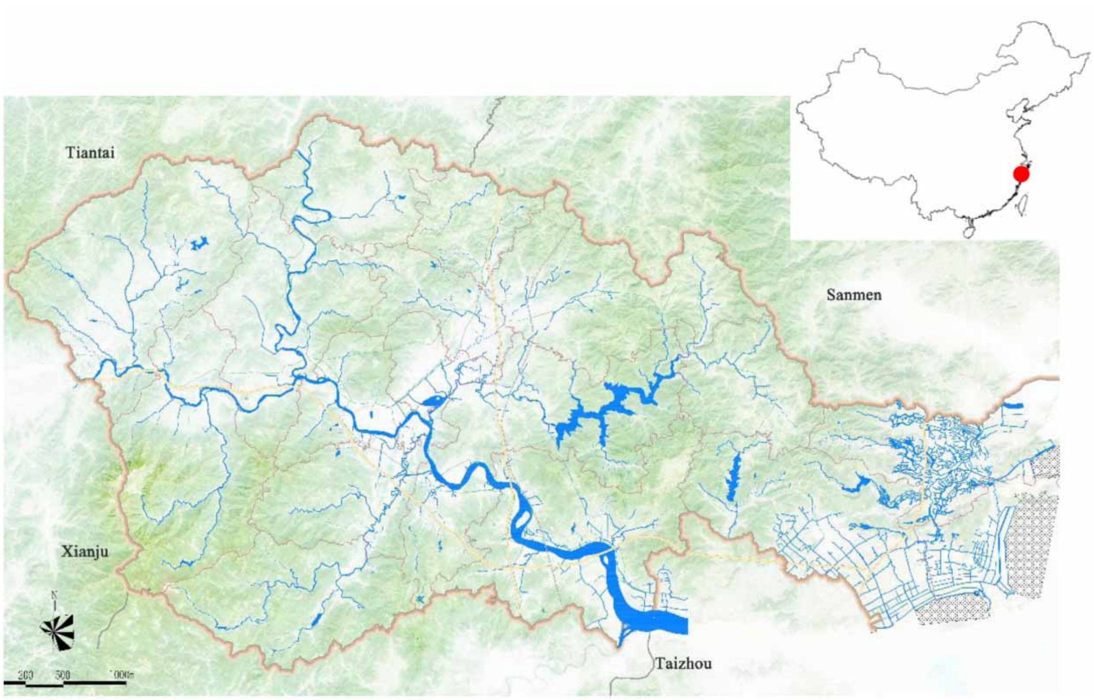

Figure 1 | The location and river system in Linhai City.

The landform of Linhai is mostly corrosion and accumulated. Hills and mountains account for more than 2/3, with diverse types. From the southwest to the northeast, the gradation of the terrain is high, most of which is a hilly and mountainous landform, where a lot of brooks and streams originate. The center of the city is a river valley plain located between Tiantai Mountain and Kuocang Mountain. The eastern region of the city is a coastal plain resulting from the alluviation of the Lingjiang River and the siltation of sea waves, with fertile soil, as an important grain and crop production area of the city.

Linhai is controlled mostly by a subtropical monsoon climate, with four distinct seasons and plentiful rainfall, and frequent typhoon movement in the turn of the summer and autumn. Linhai has an annual average temperature of 17°C, an average wind speed of 2.2 m/s, average annual surface evaporation of 1,007.2 mm, average annual rainfall of 1,685.5 mm and 140–180 rainy days. The maximum annual rainfall of Linhai is 2,378.5 mm (in 1990) and the minimum annual rainfall is 1,123.6 mm (in 1967). The rainfall is unevenly distributed both spatially and temporally in Linhai. The rainfall in the west is more than the rainfall in the east of Linhai. The rainfall in hilly and mountainous areas is more than that in the plain areas. The rainfall in the Plum Rain Season in May and June and the rainfall in the Typhoon Period in August and September account for more than 60% of the total annual rainfall.

Data sources

The data used in the paper are from the Statistical Yearbook of Linhai City, the water resources bulletin of Linhai City, the statistical bulletin of national economic and social development of Linhai City and the environmental quality bulletin of Linhai City.

The water resources utilization in Linhai City

The water resources utilization of Linhai City is mainly composed of five parts: domestic water demand, agricultural water demand, industrial water demand, tertiary industry water demand and ecological water requirement. Among these, ecological water requirement refers to off-river ecological water demand. The ecological water demand in the river is not taken into account in the calculation because the annual runoff can fully satisfy the requirement according to the analysis of 30-year data. The changing trend of the proportion of different types of water consumption from 2004 to 2015 is shown in Figure 2.

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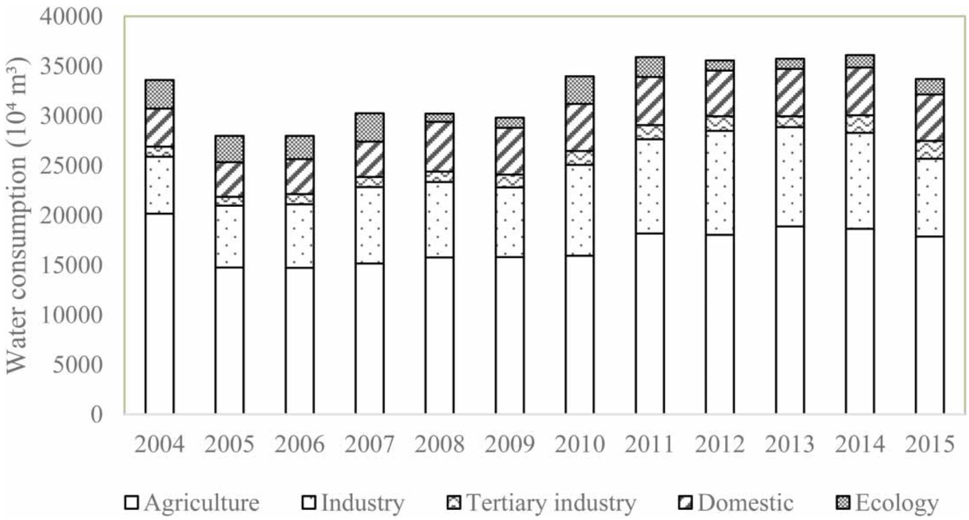

Figure 2 | The change of water consumption of Linhai City from 2004 to 2015.

As shown in Figure 2, the total water consumption of Linhai appears an overall trend of growth. According to the historical record, agricultural water consumption accounts for over 52.2% of the total water consumption on average. The agricultural water consumption mainly includes the water consumption of forestry, animal husbandry, fishery and irrigation; of which irrigation water accounts for an average of 85% and forestry, animal husbandry and fishery account for 15%. The industrial water consumption is subject to the values of the industrial output, the water demand per 10,000 RMB of industrial output and the reuse of water. Although the overall trend is increasing, the growth rate slows down, as shown in Figure 2. The average percentage of industrial water consumption in total water consumption is 24.7%, reaching the highest in 2012 (29.4%) and then declining, accounting for 23.2% in 2015.

The sewage discharge sources include domestic sewage and industrial sewage. Therein, domestic sewage accounts for a relatively large percentage and shows a rising trend; and industrial sewage maintains a stable discharge percentage at around 16%. The sewage discharge of Linhai city from 2004 to 2015 is shown in Figure 3.

The amount of water resources in Linhai City is relatively abundant, but the degree of water resource development is not high, merely 20%. Moreover, subject to topography, the west of Linhai has sufficient water supply due to reservoir water accumulation. The eastern plain area of Linhai has a large gap in water supply and demand despite its developed economy

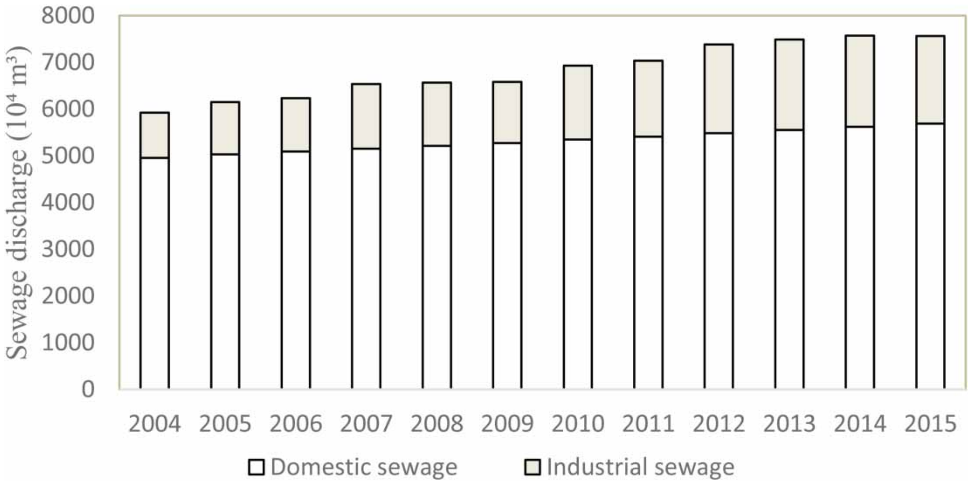

Figure 3 | The change of sewage discharge of Linhai City from 2004 to 2015.

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and high potential of expansion. Subject to the year-by-year increase in sewage discharge, the water environment is deteriorating in some areas of Linhai, and the water supply quality is threatened, which intensifies the shortage of water resources in the future.

MATERIALS AND METHODS

The concept model of water resources carrying capacity in Linhai City

The water resources carrying capacity in this research is defined as the development states of the population, economy and society that can be supported by local water resources. According to the above requirements, the subsystems of the water resources carrying capacity system are the social subsystem, economic subsystem, water resources subsystem and environmental subsystem. Figure 4 shows the composition and influencing factors.

The framework of water resources carrying capacity system dynamics of Linhai

Model boundaries

The water resources carrying capacity model of Linhai City covered the aspects of society, population, economy, agriculture, industry and ecology. The spatial boundary of the model was determined to be the administrative area of Linhai City with a total area of 2,203 km^2. The time boundary was from 2004 to 2030. In order to ensure the accuracy of the prediction, 2004–2014 was used as the historical period to build and validate the model, with the benchmark year being 2004. 2015–2030 was the forecast period of the model, and 2015 was the benchmark year. The simulation time step was 1 year.

The generalization of the system structure

Based on the analysis of each subsystem and their correlation, the causal relationship diagram of the dynamic model of water resources carrying capacity of Linhai was drawn using Vensim software, referring to Figure 5. The casual diagram generalized the logical relations of the system. On the one hand, along with the population growth and economic speed-up of Linhai City, a change would occur to the gap between water supply and demand. Moreover, the amount of water resources could affect the development of the regional society, economy and ecology.

Transmission mechanism of the model

According to the positive and negative feedback actions among various variables in the system, with the water supply and demand gap as a target parameter, the loop feedback of the water supply and demand gap is analyzed to reflect the feedback processes of the water resources carrying capacity system in Linhai City. The following analysis is made:

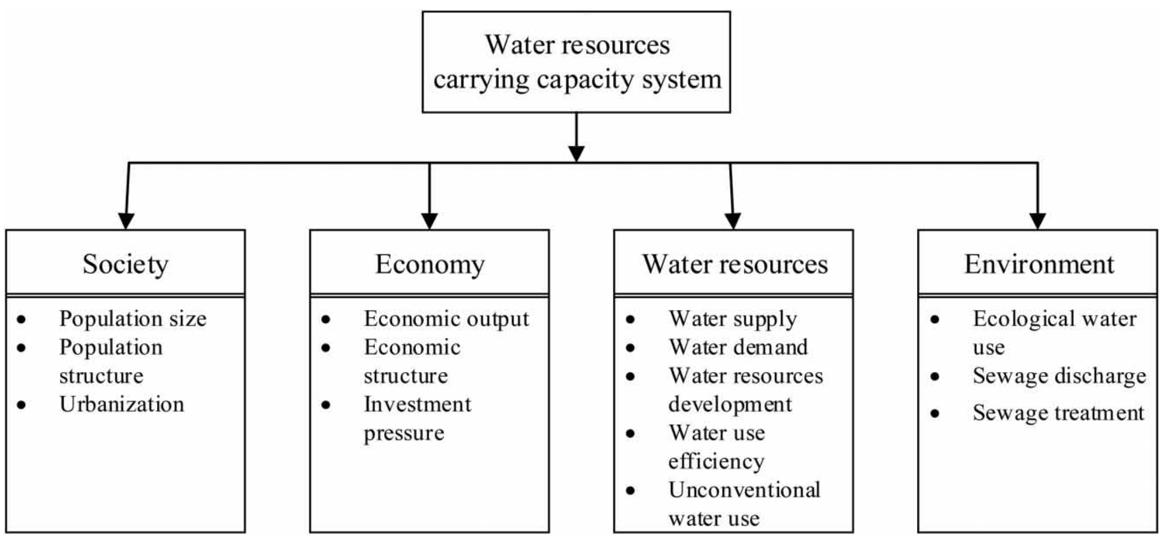

Figure 4 | The constitution of the water resource carrying capacity system.

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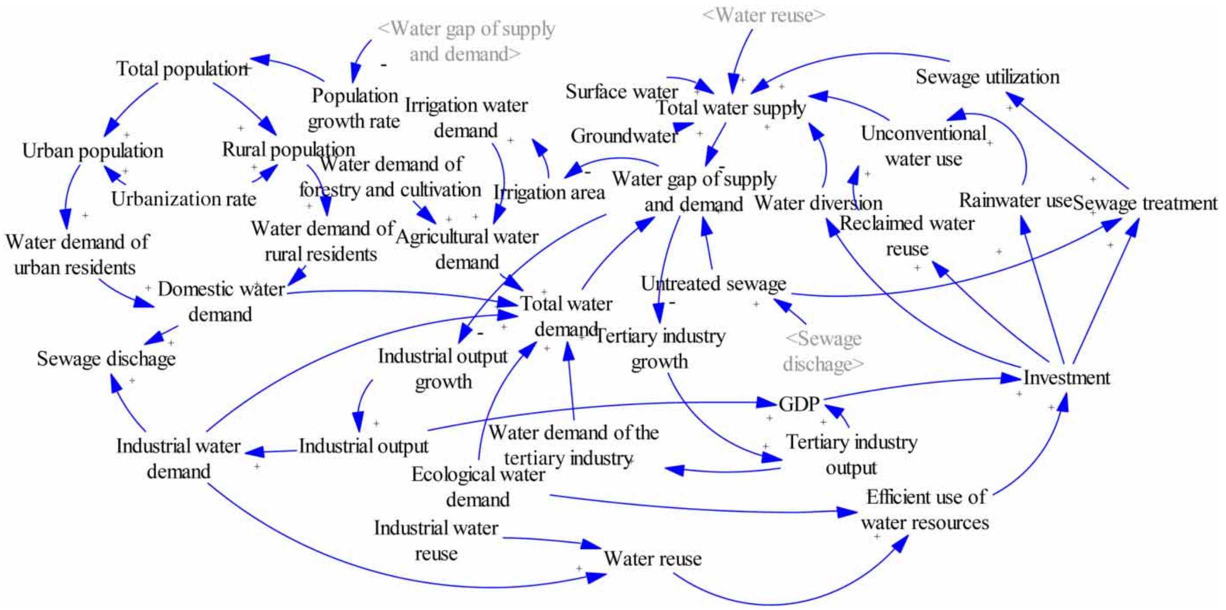

Figure 5 | The causal relationship diagram of water resource carrying capacity in Linhai City.

Expansion of the water supply and demand gap → Decline of irrigation area → Decline of agricultural and production water use → Decline of total water demand → Decline of the water supply and demand gap;

Expansion of the water supply and demand gap → Decline of the industrial output growth → Decline of the industrial output → Decline of GDP → Decline of investment → Decline of investment in water diversion → Decline of water supply → Expansion of the water supply and demand gap;

Expansion of the water supply and demand gap → Decline of the industrial output growth → Decline of the industrial output → Decline of GDP → Decline of investment → Decline of investment in reclaimed water reuse → Decline of water supply → Expansion of the water supply and demand gap;

Expansion of the water supply and demand gap → Decline of the industrial output growth → Decline of the industrial output → Decline of GDP → Decline of investment → Decline of investment in rainwater use → Decline of water supply → Expansion of the water supply and demand gap;

Expansion of the water supply and demand gap → Decline of the industrial output growth → Decline of the industrial output → Decline of GDP → Decline of investment → Decline of investment in sewage treatment → Increase of untreated sewage → Decline of water supply → Expansion of the water supply and demand gap;

Expansion of the water supply and demand gap → Decline of the tertiary industry growth → Decline of the tertiary industry output → Decline of GDP → Decline of investment → Decline of investment in reclaimed water reuse → Decline of water supply → Expansion of the water supply and demand gap;

Expansion of the water supply and demand gap → Decline of the tertiary industry growth → Decline of the tertiary industry output → Decline of GDP → Decline of investment → Decline of investment in rainwater use → Decline of water supply → Expansion of the water supply and demand gap;

Expansion of the water supply and demand gap → Decline of the tertiary industry growth → Decline of the tertiary industry output → Decline of GDP → Decline of investment → Decline of investment in sewage treatment → Increase of untreated sewage → Decline of water supply → Expansion of the water supply and demand gap;

Expansion of the water supply and demand gap → Decline of the industrial output growth → Decline of the industrial output → Decline of the industrial water demand → Decline of total water demand → Decline of the water supply and demand gap;

Expansion of the water supply and demand gap → Decline of the tertiary industry growth → Decline of the tertiary industry output → Decline of the tertiary industry water demand → Decline of total water demand → Decline of the water supply and demand gap;

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Expansion of the water supply and demand gap → Decline of the population growth → Slowdown of the domestic water demand growth → Slowdown of the total water demand increase → Slowdown of growth trend of the water supply and demand gap.

Parameter sets of system dynamics model

Parameters were classified as rate variable (R), level variable (L) and state variable (A). This model involved 7 rate variables, 7 level variables and 54 state variables as shown in Table 1.

Water shortage impact 1 represented the feedback of the water supply and demand gap to the population. Water shortage impact 2 represented the influence of the water supply and demand gap on irrigation water use. Water shortage impact 3 and 4 represented the limitation of the water supply and demand gap on tertiary industry growth and industrial output growth, respectively. Water shortage impact 5 represented the negative feedback of the water resource unbalance to the growth rate of GDP. Parameters of investment 1, investment 2 and investment 3 represented the impact on the economy when the water resource development is reinforced. The higher the GDP is, the larger the investment can be provided, which has a positive significance to the improvement of water resources utilization.

Parameter prediction of the social economic subsystems

In the social subsystem, it mainly needs to predict the population and urbanization rate. According to the historical data of Linhai City, the population expansion trend was extrapolated. The equation under the linear fitting is as follows.

$$P = 0.783 \times (T - 2003) + 110.605 \tag{1}$$

where P is the total population, T stands for the year and the linear fitting coefficient R^2 is 0.993.

The urbanization rate has an upper limit with confined population growth, which can be described by the block model. According to the relevant planning of Linhai City, the urban population will not exceed 1.4 million by 2030, the total population will not exceed 1.6 million and the upper limit of urbanization rate is set as 0.85. The SPSS software was used to logistically fit the urbanization rate as in the following equation.

$$R = 1/(1.179 + 2.011 \times 0.901^{T-2003}) \tag{2}$$

where R is the urbanization rate, T is the year and the fitting coefficient R^2 is 0.992.

In the economic subsystem, the industrial structure determines the water consumption structure. From 2004 to 2010, Linhai experienced a period of rapid economic growth. The average growth speed of the industry and the tertiary industry was 15.07 and 13.57%, respectively. After 2010, the growth of the industry and the tertiary industry slowed down, maintaining a relatively stable growth at an average rate of 6.5 and 8.4%. The logistic model in SPSS regressive analysis was used to predict the output value of the agriculture, industry and tertiary industry from 2015 to 2030.

The regression equation of the agricultural output can be expressed as:

$$A = 1/(0.000625 + 0.732 \times 0.904^{T-2003}) \tag{3}$$

The regression equation of the industrial output can be expressed as:

$$I = 1/(0.000979 + 0.012 \times 0.895^{T-2003}) \tag{4}$$

The regression equation of the tertiary industry output can be expressed as:

$$S = 1/(0.000588 + 0.020 \times 0.871^{T-2003}) \tag{5}$$

where A, I and S are output values of the agriculture, industry and tertiary industry. The fitting correlation coefficients are 0.970, 0.912 and 0.993, representing a high correlation. In terms of the developing trend, the output value of the tertiary industry has the highest growth speed. The ratio of the output value of the three industries eventually reaches

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Table 1 | Parameter sets of model subsystems of water resources carrying capacity in Linhai City

	Category	Variable	Unit	Category	Variable	Unit
Subsystem of society	L	Population	10^4 p	R	Population growth	10^4 p/y
	A	Urban domestic water demand	10^4 m^3	A	Rural daily water demand per capita	m^3/(p•d)
	A	Urban population	10^4 p	A	Rural domestic water demand	10^4 m^3
	A	Rural population	10^4 p	A	Total domestic water demand	10^4 m^3
	A	Urbanization rate	/	A	Domestic sewage discharge coefficient	/
	A	Population growth rate	/	A	Water shortage impact 1	10^4 p
	A	Urban daily water demand per capita	m^3/(p•d)	A	Domestic sewage discharge	10^4 m^3
Subsystem of economy	L	Industrial output	100 million RMB	A	Irrigation water quota 1	m^3/mu
	R	Industrial value added growth	100 million RMB	A	Water shortage impact 2	Mu
	A	Industrial value added growth rate	/	A	Irrigation water quota 2	m^3/mu
	A	Water demand per 10,000 RMB of industrial output	m^3/10^4 RMB	A	Irrigation water demand	10^4 m^3
	A	Industrial water demand	10^4 m^3	A	Forestry and cultivation water demand	10^4 m^3
	A	Industrial water reuse factor	/	A	Agricultural water demand	10^4 m^3
	A	Industrial water reuse	10^4 m^3	A	Production water demand	10^4 m^3
	A	Water shortage impact 4	100 million RMB	A	Industrial sewage discharge coefficient	/
	L	Tertiary industry output	100 million RMB	L	GDP	100 million RMB
	R	The growth of the added value of the tertiary industry	100 million RMB	R	GDP growth	100 million RMB
	A	The growth rate of the added value of the tertiary industry	/	A	GDP growth rate	/
	A	Water demand per 10,000 RMB of tertiary industry output	m^3/10^4 RMB	A	Water demand per 10,000 RMB GDP	m^3/10^4 RMB
	A	Tertiary industry water demand	10^4 m^3	A	Water shortage impact 5	100 million RMB
	A	Water shortage impact 3	100 million RMB	A	The percentage of investment in GDP	/
	L	Irrigation area	10^4 mu	A	Investment	100 million RMB
	R	Irrigation area growth	10^4 mu	A	Investment 1	100 million RMB
	A	Investment 2	100 million RMB	A	Investment 3	100 million RMB
Subsystem of water resources	A	Total water supply	10^4 m^3	A	Water supply of storage project	10^4 m^3
	A	Rain utilization	10^4 m^3	A	Water supply of water diversion project	10^4 m^3
	L	Reclaimed water	10^4 m^3	A	Groundwater supply	10^4 m^3
	A	Surface water supply	10^4 m^3	A	Sewage utilization	10^4 m^3
	R	Annual increase of reclaimed water	10^4 m^3	A	Water supply and demand gap	10^4 m^3
Subsystem of environment	A	off-stream ecological water requirement	10^4 m^3	A	inner-stream ecological water requirement	10^4 m^3
	A	Percentage of reclaimed water in ecological water	/	A	reclaimed water in ecological water	10^4 m^3

(*Continued.*)

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Table 1 | Continued

Category	Variable	Unit	Category	Variable	Unit
L	Annual sewage treatment	10^4 m^3	A	Sewage treatment rate	/
A	Domestic sewage discharge	10^4 m^3	R	The increment of annual sewage treatment	10^4 m^3
A	Industrial sewage discharge	10^4 m^3	A	Total sewage discharge	10^4 m^3

3.1:10.6:15.6, which agrees with the law that the tertiary industry will be gradually increasing in the process of urban development.

Model verification

The model passed the Vensim unit dimension test and the structure test. The logic is clear, and no error or useless variable emerges. Historical data sets were used to simulate the historical processes of variables, and the simulated values were compared with observations to calculate the error and verify the model. This study used the historical data from 2004 to 2014 for model validation, and selected five major output variables (total population, total output value, industrial output, total water demand and total water supply) for verification. As inferred from Figure 6, the relative error is controlled within an acceptable range of 10%, and the simulations are reliable and accurate.

RESULTS AND DISCUSSION

Development mode design

The selection of target variables

When designing development modes, only some variables were selected to represent different types of input conditions and form development modes of different emphases. In the social subsystem, the urban and the rural per-capita daily domestic water demands were selected as target variables to characterize the structure change of urban and rural water consumption and the degree of water saving. In the economic subsystem, indicators of tertiary industry growth, industrial output growth, water demand per 10,000 RMB industrial output and the industrial water reuse coefficient were selected. Among them, the growth rates of the tertiary industry and industry affect the water demand of tertiary industry and industry and directly influence economic structure. In addition, the irrigation water quota was selected to represent the regional water conservation

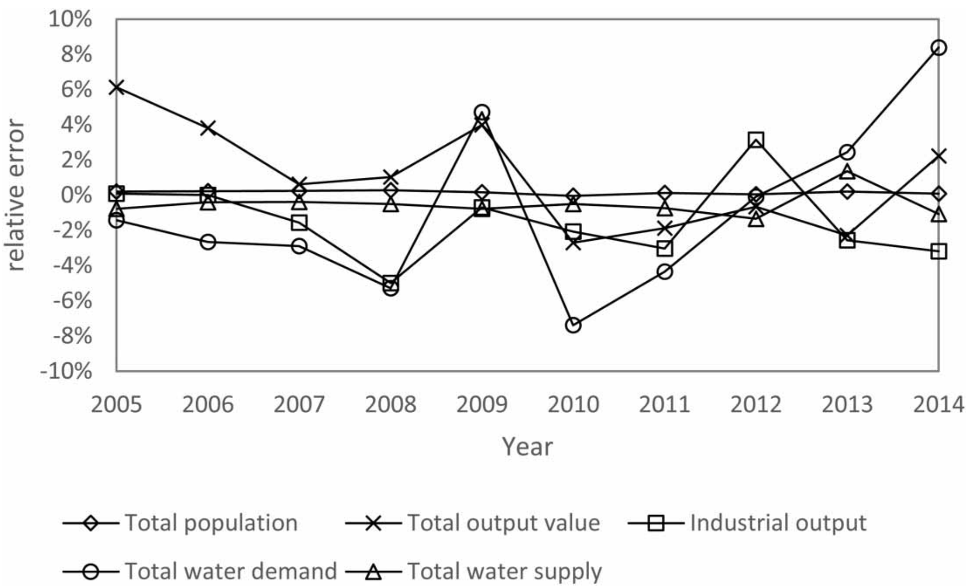

Figure 6 | Simulation errors of system dynamics model.

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measures. In the water resources subsystem, the water supply of the storage projects, the water supply of the water diversion projects and the rainwater usage were selected to reflect measures of a comprehensive water supply system. In the environment subsystem, the increment of annual sewage treatment and reclaimed water reuse rate was selected as target variables.

The design of six development modes

Based on the current condition, the development modes of Linhai City were designed from five perspectives as water saving, water supply increasing, acceleration of tertiary industry development, the promotion of the comprehensive water supply system and multiple measures to coordinate the development of social and economic and water resources subsystems. The simulation time used 2015 as the base year, and 2020, 2025 and 2030 as the level years. The water resources carrying capacity of Linhai City under various development modes were simulated from 2016 to 2030.

Mode 1: Extending the current condition. In mode 1, the constant parameters remained unchanged. The growth of population and the tertiary industry was calculated with Equations (1) and (2).

Mode 2: Water saving. The water saving was conducted in industrial, domestic and agricultural water demand. The irrigation water quota will decrease by 10% in 2016 and maintain this value until 2030. According to regional requirements, the water demand per 10,000 RMB industry output would reach 45 m^3 in 2020, 35 m^3 in 2025 and 27 m^3 in 2030. The industrial water reuse rate will reach 0.65 by 2030. Domestic water demand of urban and rural residents will decline by 5% in 2016.

Mode 3: Increasing water supply. Mode 3 emphasized target variables of water resource development. The water supply of the water storage and extraction projects will increase by 10% in 2020 compared with 2015 and by 5% in 2025 compared with 2020. The water demand per 10,000 RMB industry will reach 39 m^3 by 2030. The industrial water reuse rate will reach 0.75 in 2020 and 0.85 in 2025 and maintain this level until 2030.

Mode 4: Developing the tertiary industry plus water supply and water-saving measures. As the economic expansion accompanied by water demand increases, it is necessary to supplement water supply and conservation measures in mode 4. The output growth rate of the tertiary industry will reach 10% in 2020, 13% by 2025 and 15% by 2030. The irrigation water quota and daily urban and rural domestic water demand per capita will decline by 5%. The water demand per 10,000 RMB industry will reach 39 m^3 by 2030. The industrial water reuse rate will reach 0.65 by 2020, and 0.75 by 2025 and maintain this level until 2030. The water supply of water storage and extraction projects will increase by 5% in 2020 over 2015 and by 10% in 2025 over 2020.

Mode 5: Comprehensive water supply system enhancement. The available water resources will be enhanced from aspects of water supply, water saving and unconventional water utilization. The irrigation water quota and daily urban and rural domestic water demand per capita will decline by 5%. The water demand per 10,000 RMB industry will reach 45 m^3 by 2020, 39 m^3 by 2025 and 27 m^3 by 2030. The industrial water reuse rate will reach 0.65 by 2020, 0.75 by 2025 and 0.85 by 2030. The usage of rainwater and reclaimed water will grow 10% by 2020 over 2015 and 5% by 2020 over 2025. The water supply of the water storage and extraction projects will increase by 10% in 2025 over 2015, and be maintained until 2030.

Mode 6: Integrated development. Considering the coordination among economic adjustment, water resources utilization and water environment of Linhai City, on the basis of mode 5, the output growth rate of the tertiary industry will reach 10% in 2020, 13% by 2025 and be maintained, meanwhile the irrigation water quota and daily urban and rural domestic water demand per capita will decline by 5%.

Discussions of simulation results

The constructed water resources system dynamics model was used to simulate the development trend of water resources carrying capacity of Linhai City from 2015 to 2030.

Simulation results of mode 1

As shown in Figures 7(a) and 8(a), the economy of Linhai still keeps steady growth with mode 1, and the GDP will reach 130.8 billion RMB in 2030, two times that in 2015. Industrial water demand grows rapidly before 2022. After that, due to the negative impact of the water shortage on the industrial output value, the growth of industrial water demand becomes slower. Along with the water demand increasing, sewage discharge rises every year and will reach 85.56 million m^3 in 2025 and 90.28 million m^3 in 2030. In contrast, the current sewage treatment capacity maintains at 62.39 m^3/year, which could not satisfy the ever-increasing sewage discharge.

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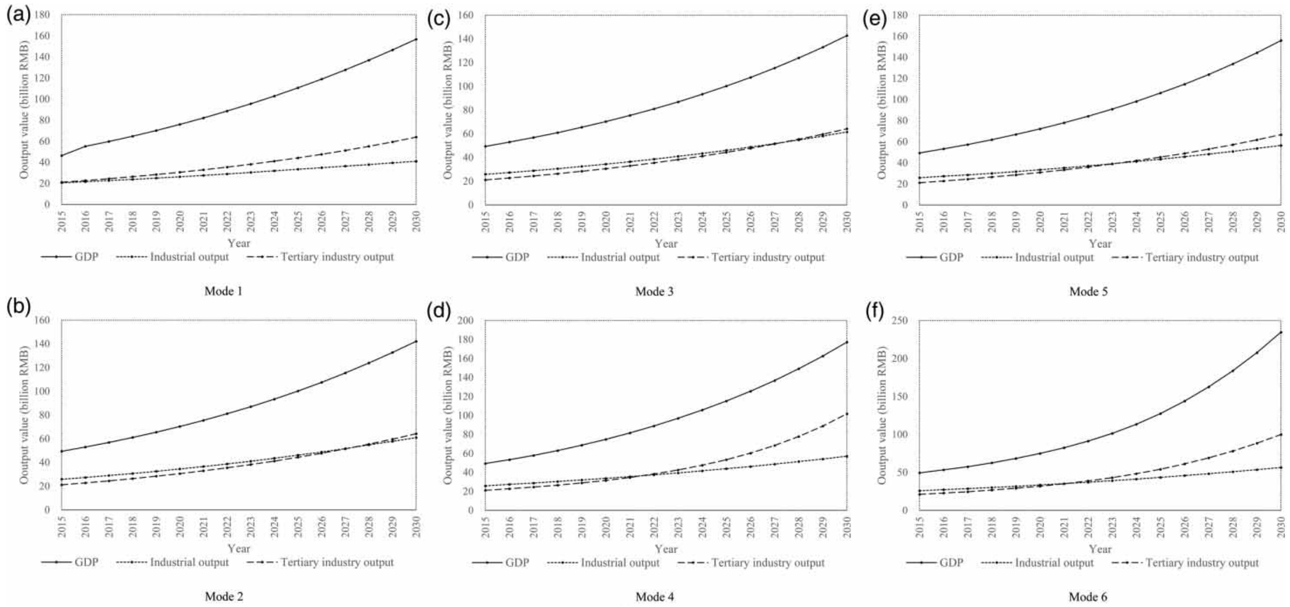

Figure 7 | Economic development of Linhai city under different modes.

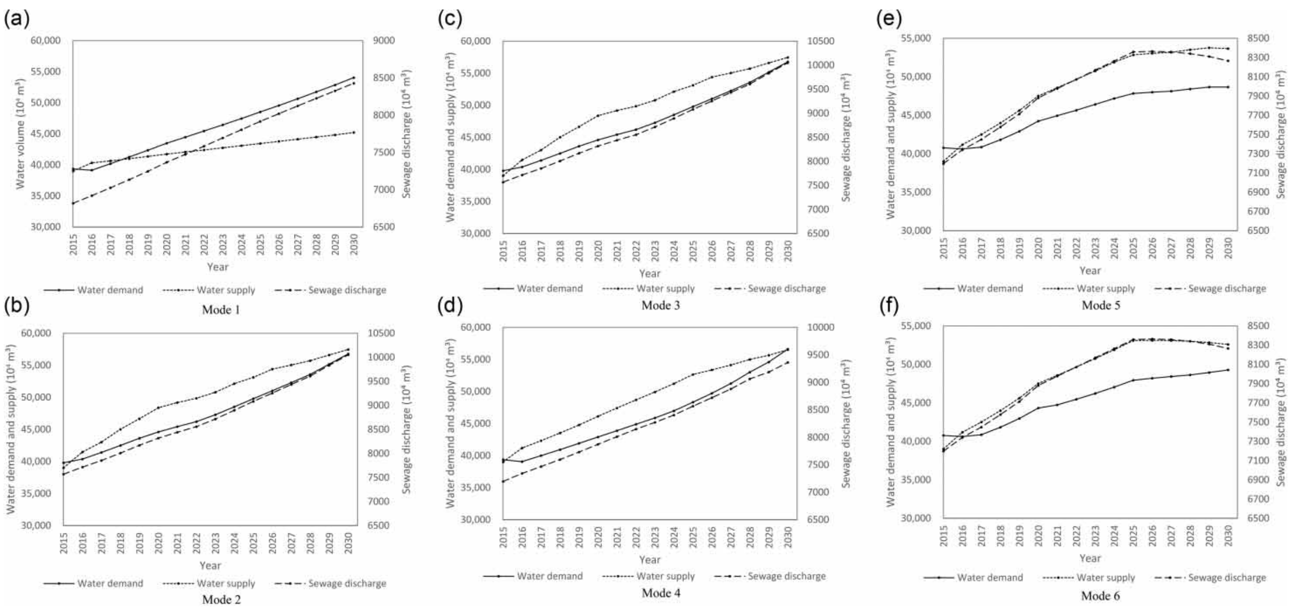

Figure 8 | Water supply, demand and sewage discharge under different modes.

The support of water resources carrying capacity of Linhai is low under mode 1. Since 2016, Linhai has maintained the current economic growth speed, and both the industry and the tertiary industry have achieved larger output within a short period. However, due to the lack of certain replenishment policies for water resources and environment, the imbalance between water supply and demand has become increasingly severe, and the sewage treatment rate has declined resulting in higher pressure on the ecological environment. The supply and demand gap begins to appear in 2018 and will expand ever since, and reach 88.3 million m^3 by 2030. The water shortage gap feeds back to the growth of population, GDP, industry, the tertiary industry and irrigation area through five water shortage impact factors (see Table 1), and thus the social and economic growth rate is restrained in the development process.

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Simulation results of mode 2

The simulation results are shown in Figures 7(b) and 8(b). The water demand decreases by 18, 7.4 and 11.2% in 2020, 2025 and 2030 compared with model 1. Water supply and demand can maintain balance until 2023. The water supply and demand gap will occur in 2023 and reach 16.16 million m^3 by 2030. Compared with mode 1, the mitigation of water shortages reduces the constraints of economic, agricultural and population growth. GDP has exceeded that of mode 1 after 2022. The population size is similar to mode 1. Sewage discharge also decreases along with the decline of water demand.

As noticed, the gap between supply and demand reduces significantly within a short period under water-saving mode. However, the water demand will keep increasing along with economic development, and the positive effect of water saving has been weakened by year. In addition, the sewage discharge has been reduced by controlling water demand in mode 2, but still be insufficient.

Simulation results of mode 3

The simulation results are shown in Figures 7(c) and 8(c). The water supply increases by 15.8 and 27.8% by 2020 and 2030 compared with mode 1, representing significant growth. The allowable population size is slightly larger than that of mode 2. GDP will reach 142.76 billion RMB by 2030, an increase of 9% over mode 1. As can be noticed from Figure 7(c), the increase in the industry output is more obvious, mainly because the impact of water shortage on the output value of the industry is greater than that of the tertiary industry. The water supply can always meet the water demand under this mode, but it can be seen that the difference between supply and demand declines gradually. The impact of the increased water supply is effective, but it is also weakening over time.

Increasing water supply has reduced the supply and demand gap and promoted economic growth. However, it also increases sewage discharge with the rise of water usage. Therefore, although this mode alleviates the contradiction between water supply and demand, it causes higher pressure on the water environment.

Simulation results of mode 4

The simulation results are shown in Figures 7(d) and 8(d). This mode focuses on the development of the tertiary industry accompanied by water supply enlargement and water saving. The total GDP multiplies, and the GDP of 2020, 2025 and 2030 will increase by 7, 15.6 and 19%, respectively, compared with mode 1. The tertiary industry output will reach 101.7 billion RMB by 2030, accounting for 57.1% of the total output value. In contrast with mode 2 and mode 3, the intensity of water saving and water supply augment is moderate. The water demand in this mode is higher than in mode 2 due to faster economic development, but water demand has been lower than in mode 1 because of water-saving measures.

According to the above development modes, mode 4 provides stimulus to the economy. Rapid economic growth has resulted in increased water demand. Thus mode 4 is supplemented with a certain water supply and water-saving measures. In the case of economic growth of 15.6% year on year, the water demand of mode 4 is similar to mode 1. The sewage discharge of mode 4 is less than mode 1 and mode 3. Water shortage still occurs with water-saving measures alone, indicating that enlargement of the water supply is necessary for better water resources carrying capacity.

Simulation results of mode 5

The simulation results are shown in Figures 7(e) and 8(e). By 2030, the water demand increases by only 3% compared with mode 2, but the GDP increases by 9.7% over mode 2. It can be noticed that the water demand has achieved zero growth since 2029. The total water supply in 2030 has been 6.6% less than that of mode 3, but there is still abundant water left.

In this mode, the sewage resources is made full use of, and the sewage treatment capacity and reclaimed water reuse are strengthened, so that water environment pressure is reduced. The reclaimed water can be replenished in the industrial water supply. Some of the treated sewage can be used as an environmental and ecological water supplement for rivers and lakes.

Simulation results of mode 6

Mode 6 takes account of focuses of other development modes, and the simulation results are shown in Figures 7(f) and 8(f). As the amount of water supply is always surplus, economic development is not affected by water shortage. Although the development of the tertiary industry is not as good as that of model 4, the GDP is the highest among all modes, reaching 23.47 billion RMB in 2030. Since the intensity of water saving is higher than in mode 5, the total water supply is slightly

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smaller than in mode 5. The total water demand under mode 6 keeps steady after 2028, and the water supply can satisfy the water demand for production, living and ecology.

The optimization of the simulation results

The years 2015, 2020, 2025 and 2030 were selected as typical years. The variables of population, economic development, water supply and demand and sewage discharge of different modes were compared as shown in Table 2. Subject to the population development ceiling, the population sizes that can be supported under development modes have little difference.

The economic development was characterized by variables of GDP, the industrial output and the tertiary industry output. Since water shortage has a negative impact on the economy subsystem, economic growth has been confined by water shortages such as modes 1, 2 and 3. Under the precondition of certain GDP, a higher percentage of industrial output would not be friendly to the water environment because of contributing much more sewage that needs to be treated with more investment. The increase in the proportion of tertiary industry can not only benefit economic development, but also alleviate the burden of the water environment. From the point of view of water demand and supply for Linhai city in the future, the implementation of water-saving mode alone can reduce water demand in the short term, but it cannot maintain the effect for a long time. The water demand is getting harder and harder to decline especially when the development of the city reaches a certain point. Therefore, it proves that Linhai city has great potential for water conservation at present, while it also shows that other water supply measures should be coordinated with water-saving practices. Sewage discharge is closely related to water demand, with similar change patterns. Among the modes which do not promote the sewage treatment capacity, the sewage treatment rate declines gradually along with the increase of sewage discharge as well as environmental pressure. Modes 5 and 6 have the highest sewage treatment rates.

Based on the above analysis, modes 5 and 6 are selected to have the highest water resources carrying capacity. The two modes have similar supporting capacity in such aspects as society, economy, water resources and water environment, and can both be optimal schemes. However, it should be noticed that, regarding increasing available water resources,

Table 2 | Variables representing water resources capacity of Linhai city in typical years

Mode	Year	Population (10^4)	GDP (billion RMB)	Industrial output (billion RMB)	Tertiary industry output (billion RMB)	Water demand (10^4 m^3)	Water supply (10^4 m^3)	Sewage discharge (10^4 m^3)
1	2015	119.7	46.3	20.6	21.1	39,354	39,003	6,818
	2020	123.3	75.9	26.3	30.6	43,480	41,735	7,367
	2025	126.9	110.7	33.4	44.3	48,524	43,437	7,915
	2030	130	156.7	41.0	63.9	54,042	45,212	8,428
2	2015	119.7	49.3	25.8	21.1	39,354	39,003	7,196
	2020	123.3	70.3	34.5	30.6	42,692	42,818	7,953
	2025	126.9	100.2	46.1	44.3	44,802	44,624	8,217
	2030	130.6	142.1	60.9	64.2	47,118	45,502	8,430
3	2015	119.7	49.3	25.8	21.1	39,791	39,003	7,568
	2020	123.2	70.2	34.4	30.6	44,599	48,364	8,317
	2025	126.9	100.1	46.0	44.3	49,792	53,113	9,082
	2030	130.7	142.8	61.6	64.2	56,773	57,457	10,049
4	2015	119.7	49.3	25.8	21.1	39,354	39,003	7,196
	2020	123.3	74.8	33.7	31.5	42,886	46,124	7,870
	2025	126.9	115.1	43.8	53.4	48,321	52,644	8,566
	2030	130.7	177.1	57.0	101.7	56,601	56,525	9,360
5	2015	119.7	49.3	25.8	21.1	40,763	39,003	7,196
	2020	123.3	72.2	33.4	30.9	44,233	47,510	7,880
	2025	127.2	106.1	43.4	45.4	47,822	52,842	8,358
	2030	131.2	155.9	56.5	66.7	48,666	53,656	8,266
6	2015	119.7	49.3	25.8	21.1	40,763	39,003	7,196
	2020	123.3	74.9	33.4	31.9	44,316	47,510	7,880
	2025	127.2	127.4	43.4	54.2	47,937	53,099	8,358
	2030	131.2	234.7	56.5	99.8	49,279	52,598	8,266

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conventional development measures are more cost-effective than unconventional water utilization. The sewage treatment plant usually costs 15 million RMB per 10^4 m^3 of water, and the cost of reclaimed water is 25 million RMB, while the cost of water supply project is only 10 million RMB on average. For cities with abundant surface water resources such as Linhai, it is more efficient by constructing water supply projects. Mode 5 performs well in aspects of water resources capacity, yet faces a problem of investment pressure. Excessive residual water does not have a positive impact on the regional water resources carrying capacity, but instead represents an excessive investment. Therefore, the final preferred solution is mode 6.

CONCLUSIONS

Based on the understanding of the water resources carrying capacity, the system was divided into subsystems such as society, economy, water resources and water environment. The proportion of tertiary industry would gradually exceed that of industry, and the population and economic structure would undergo significant changes in Linhai in the future. The analysis of the water resources system indicated that the water demand of Linhai would increase by the year. At present, problems of low water resources utilization rate, insufficient water saving and water pollution have limited water resources carrying capacity. The growing demand for water resources has been complicated and related to economic development and the water environment. The future water resources carrying capacity of Linhai needs to consider the influences of multiple factors.

The system dynamics model of the water resources carrying capacity of Linhai City was built in this research. The system dynamics transmission mechanism was analyzed to determine the parameters and quantify the logical relationship between subsystems. The constructed model simulated mode 1 of maintaining the present status, and the results indicated that the water resources carrying capacity were low in this mode. The economic growth rate was maintained since 2016, and both the industry and tertiary industries had achieved large output values. However, since the lack of certain replenishment policies for water resources and the water environment, the water demand was large and the sewage treatment capacity was not qualified. The imbalance between water supply and demand was becoming more and more serious. The water supply and demand gap will reach 88.3 million m^3 by 2030. The impact of water shortage has fed back to the growth of population, GDP, industry and tertiary industry, and the economic growth has been restrained in the development process.

The other five modes were designed by considering water saving, water supply enlargement, promoting the tertiary industry and integrated water supply system. The simulation can help to understand the characteristics of each mode and give enlightenment for Linhai to enhance its water resources carrying capacity. Linhai had excellent potential in water conservation under current conditions. The water resources carrying capacity could be rapidly promoted in recent years. However, the simple application of water saving would yield a smaller effect in the long run. Therefore, water-saving tactics must be supplemented by other means such as increasing water supply and pollution control. From the perspective of economic development, the current water demand and output values of Linhai were quite mismatched. Agriculture with only 10% of the output value, was the largest water user. Consequently, it would be necessary to expand the tertiary industry which could reduce the total water demand increase rate and enhance the regional economic level. Furthermore, the developed economy can ensure more funds are invested in water-saving facilities, sewage treatment and other water supply projects. In terms of the water environment, it was apparent from the simulation that maintaining a high sewage treatment rate and ensuring a certain quantity of reclaimed water were important measures for reducing the water supply and demand gap. Sewage treatment alleviated the environmental pressure and also contained the growth of the total water demand. The recycled sewage was expected to replenish the industrial water demand by 33.76 million m^3 by 2030, which was equivalent to a 22% reduction in industrial water demand. Assisted by industrial water reuse, zero growth of industrial water demand can even be achieved. The treated sewage also can be used as off-stream ecological water, which could reduce 50% of ecological water demand. These measures above can greatly alleviate the water supply pressure in Linhai city.

The way to resolve the contradiction between economic development and the environment lies in enabling the bonus of economic development to make up for water resources and environmental systems. The paces of economic development and water investment must be coordinated with each other. It must be noticed that excessive investment would bring certain pressure on the regional economy. With regard to Linhai, when it does not have a high level of economic development at the early stage, the water conservation and water supply projects would be more critical than unconventional water resources.

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The sewage treatment capacity does not need to be very high in the short term, and it should be decided by the calculation of sewage discharge. In 2025, the total GDP will exceed 100 billion RMB, and there will be solid economic foundation to improve the water resources protection of Linhai further.

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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.

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