System Dynamics Simulation and Scenario Optimization of China's Water Footprint under Different SSP-RCP Scenarios

Qiuxiang Jiang[1], Xingtao Ouyang[1], Zilong Wang[1], Qiang Fu[1], Yunxing Wu[1], and Weipeng Guo[1]

[1]Northeast Agricultural University

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Abstract

Under the dual influence of socioeconomic development and climate change, water resources in China are under increasing stress. It is of great significance to comprehensively explore the changing trend of China's water footprint (WF) in the future, clarify the water resource challenges that China will face, and alleviate water shortage and water pollution problems. This paper uses System Dynamics (SD) to build a simulation model of China's WF, calculate China's WF from 2000 to 2019, and for the first time, simulate and optimize China's WF from 2020 to 2050 under the SSP-RCP scenario matrix composed of Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs). The results are as follows. (1) From 2000 to 2019, China's WF increased to 2009 and began to decline. The main contributors are gray WF and agricultural WF. (2) From 2020–2050, different socioeconomic development and climate change conditions under the five SSP-RCP scenarios will lead to different trends in China's WF and its composition. (3) Based on the changes in WF and water resources supply/demand ratio under different scenarios, the SSP1-2.6 scenario is the best scenario to mitigate a future water shortage and water pollution in China. The research results can help decision-makers formulate relevant management policies and socioeconomic development models for water resource utilization and provide decision support for alleviating water shortages and water pollution in China.

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School of Water Conservancy and Civil Engineering, Northeast Agricultural University, Harbin 150030, China

Corresponding author: Zilong Wang (wangzilong2017@126.com)

Key points

- Use System Dynamics model to simulate China's water footprint (WF) under different SSP-RCP scenario matrices first time.
- Agricultural WF is the main contributor to China's water footprint at present and is expected to increase further in the future.
- SSP1-2.6 is the best scenario to alleviate water shortage and water pollution in China.

Abstract: Under the dual influence of socioeconomic development and climate change, water resources in China are under increasing stress. It is of great significance to comprehensively explore the changing trend of China's water footprint (WF) in the future, clarify the water resource challenges that China will face, and alleviate water shortage and water pollution problems. This paper uses System Dynamics (SD) to build a simulation model of China's WF, calculate China's WF from 2000 to 2019, and for the first time, simulate and optimize China's WF from 2020 to 2050 under the SSP-RCP scenario matrix composed of Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs). The results are as follows. (1) From 2000 to 2019, China's WF increased to 2009 and began to decline. The main contributors are gray WF and agricultural WF. (2) From 2020–2050, different socioeconomic development and climate change conditions under the five SSP-RCP scenarios will lead to different trends in China's WF and its composition. (3) Based on the changes in WF and water resources supply/demand ratio under different scenarios, the SSP1-2.6 scenario is the best scenario to mitigate a future water shortage and water pollution in China. The research results can help decision-makers formulate relevant management policies and socioeconomic development models for water resource utilization and provide decision support for alleviating water shortages and water pollution in China.

Keywords: Water footprint; System dynamics; SSP-RCP; Shared socioeconomic pathways; Representative concentration pathways; Climate change;

1. Introduction

Since the 1980s, the United Nations Water Resources Conference has often warned the world that water resources are gradually declining, global social and economic development will be constrained, and a water shortage would become a global crisis (Ivey et al., 2004). Faced with this pressure, researchers have deepened their understanding of the evolution of water resources and have generated new water resource management concepts (Kumar and Singh., 2005). In 1993, the concept of virtual water, proposed by British scholar Tony Allan (1993), broadened people's understanding of water resources, and many new water resources management concepts were generated based on it, making up for the limitations of traditional water resource management concepts in the virtual water trade. In 2002, the Dutch scholar Hoekstra (2002) first proposed the water footprint (WF) concept based on virtual water research and with reference to the ecological footprint. Unlike traditional water intake indicators, WF includes both direct and indirect water use by consumers or producers and is a multi-level indicator that reflects water consumption, pollution, water source type, and pollution type (Zhu and Tian., 2012; Hoekstra et al., 2011). WF combines people's production and consumption activities with water resource consumption and pollution, which can effectively reveal water resource dependence and crisis state and lay an important foundation for water security strategy research. As a rapidly developing country, China is also facing a severe situation in regards to its water resources (Liu and Yang., 2012). The rapid growth of the population, the acceleration of the urbanization process, and the change of people's production mode and consumption have aggravated the problem of water resource shortage and water pollution in China (Li et al., 2021). The introduction of the concept of WF provides a new idea for alleviating the severe problems with water resources in China (Hoekstra and Mekonnen., 2012; Cai et al., 2020)

The SSPs are the global socioeconomic development scenarios launched by the Intergovernmental Panel on Climate Change (IPCC) in 2010 (Moss et al., 2010). The five basic pathways have qualitatively and quantitatively described the future socioeconomic development under different resource utilization models, economic and technological levels, and environmental protection awareness, and have been widely recognized by the scientific community (Guo et al., 2021). RCPs are emission scenarios proposed by the IPCC in 2005 describing future greenhouse gas concentration changes and related climate impacts (Eyring et al., 2016). Some researchers utilized SSPs and RCPs in research on WF predictions to explore the challenges of water resources brought by social and economic development and future climate change. For example, Xu et al (2020) predicted the WF of China's various economic sectors under the five SSPs. Jia (2019) simulated and evaluated the response of agricultural WF to climate change in the Haihe River basin under typical concentration paths (RCPs). Shrestha et al (2017) quantified the impact of climate change on Thailand's rice production footprint under RCP4.5 and RCP8.5 scenarios. Reddy et al (2022) predicted the blue and green WF of xerophytes in Saudi Arabia under different RCPs scenarios. However, most of the current studies only consider the impact of climate change or socioeconomic development on the WF. The combined effect of the two on the WF cannot be ignored. van Vuuren et al (2014) combined SSPs and RCPs to form a new scenario matrix SSP-RCP in 2014. The scenario matrix combines different climate model predictions, socioeconomic conditions, and relevant climate policy assumptions, and realizes the description of future socioeconomic development and climate change within a unified framework. As the WF is jointly affected by many factors, such as social progress, improvement of economic and technological levels and frequent occurrence of extreme weather, the prediction of WF under the SSP-RCP development framework will more comprehensively reflect the future water resource utilization under different socioeconomic development and climate change models.

The System Dynamics (SD) model roots the behavior mode and characteristics of the system in the dynamic structure and feedback mechanism inside the model. It can simulate a model under the premise of considering the interaction between different modules inside the model (Winz et al., 2009). Therefore, SD can dynamically present the mutual constraints of different users in the process of water resource utilization and can comprehensively and systematically predict the dynamic changes in WF. In addition, SD is a simulation method that combines qualitative and quantitative analysis and integrates analysis, synthesis, and reasoning. SD applies to the study of the problem of insufficient data (Qiting., 2007) and can effectively remedy the lack of a quantitative description of some socioeconomic development characteristics under the SSP-RCP scenario. In summary, under the premise of comprehensive consideration of the impact of climate change and socioeconomic development, exploring the characteristics of WF change under the joint action of multiple users in the future from the perspective of the system will be valuable for alleviating the problems of water shortages and water pollution.

Therefore, the objectives of this study were as follows: (1) Establish a simulation model of China's WF through SD to calculate the WF in historical years; (2) Based on SSP-RCP feature analysis and multi-source data retrieval, carry out an SD simulation of China's WF in 2020–2050 under the SSP-RCP scenario; and (3) Based on the simulation results, analyze the changing trend of China's WF under different SSP-RCP scenarios in 2020–2050 from multiple perspectives, selecting the optimal scenario for China's water resource utilization. This study is helpful for decision-makers to formulate and optimize China's water resource utilization policies based on the analysis results and scenario characteristics. It provides decision support for alleviating China's water resource shortage and water pollution problems.

2. Materials and Methods

2.1 Data sources

The historical annual urbanization rate, birth rate, mortality rate, GDP, and other social and economic statistical data used in this study were from the China Statistical Yearbook (NBS., 2001-2020), China Environmental Statistical Yearbook (NBS., 2001-2020), China Tertiary Industry Statistical Yearbook (NBS., 2001-2020), and other statistical data (http://www.stats.gov.cn/english/Statisticaldata/AnnualData/), compiled by the National Bureau of Statistics of China. Domestic, industrial, and ecological water indicators were from the China Water Resources Bulletin (NBS., 2001-2020) (http://www.mwr.gov.cn/sj/tjgb/szygb/), compiled by the Ministry of Water Resources of China. Nine crops (rice, wheat, corn, beans, potatoes, cotton, peanuts, sugar cane, and apples) were selected as research objects for agriculture. The statistical data of the yield and planting area of different crops were from the China Statistical Yearbook (NBS., 2001-2020), and the crop growth period and growth coefficient were from the crop coefficient table recommended by the Food and Agriculture Organization of the United Nations (FAO) (Allen et al., 1998). Meteorological data, such as temperature, precipitation, wind speed, and sunshine duration in historical years, were from the CLIMWAT 2.0 database (Gabr., 2022). The population and urbanization rate data under the five basic SSPs paths were from the SSP database (https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=welcome).

2.2 WF calculation

In this study, China's WF was divided into domestic, industrial, agricultural, and ecological WF based on water users. The formula is as follows:

$$WF_T = WF_D + WF_I + WF_A + WF_E \ , \tag{1}$$

where WF_T is the total WF, m^3; WF_D is the domestic WF, m^3; WF_I is the industrial WF, m^3; WF_A is the agricultural WF, m^3; and WF_E is the ecological WF, which can be replaced by actual ecological water use data (Zhang et al., 2019), m^3.

2.2.1 Domestic WF calculation

As the consumption of water resources does not include green water resources stored in the soil, the domestic WF only consists of domestic blue WF and domestic gray WF. The domestic blue WF can be replaced by the actual domestic water use data (Zhang et al., 2019). The chemical oxygen demand (COD) and ammonia nitrogen (NH_4^+-H) are the main pollutants in domestic wastewater (Huang and Xu. , 2022). Because the purification capacity of the water body for different pollutants is different and multiple pollutants can be diluted at the same time, adding the WF consumed by different pollutants will lead to repeated calculations. Therefore, the maximum water consumption required for diluting different pollutants was used as the domestic gray WF. The formulas are as follows:

$$WF_D = WF_{blue}^D + WF_{grey}^D \, , \tag{2}$$

$$WF_{grey}^D = \max(WF_{grey}^{DCOD}, WF_{grey}^{DNH_4^+-N}) \, , \tag{3}$$

$$WF_{grey}^{DCOD} = \frac{L_{COD}^D}{C_{max}^{COD} - C_{nat}^{COD}} \, , \tag{4}$$

$$WF_{grey}^{DNH_4^+-N} = \frac{L_{NH_4^+-N}^D}{C_{max}^{NH_4^+-N} - C_{nat}^{NH_4^+-N}} \, , \tag{5}$$

where WF_{blue}^D is the domestic blue WF, m^3; WF_{grey}^D is the gray WF, m^3; and WF_{grey}^{DCOD} and $WF_{grey}^{DNH_4^+-N}$ are the domestic COD gray WF and domestic NH_4^+-H gray WF, m^3, respectively. L_{COD}^D and $L_{NH_4^+-N}^D$ are the COD and NH_4^+-H load in the domestic sewage, respectively, kg; C_{max}^{COD} and $C_{max}^{NH_4^+-N}$ are the standard concentration of COD and NH_4^+-H, respectively, or the maximum allowable concentration of the environment, kg/m^3, according to China's Surface Water Environmental Quality Standard (GB3838-2002) (Ministry of Environmental Protection of China, 2002). The values are 0.02 kg/m^3 and 0.001 kg/m^3, respectively. C_{nat}^{COD} and C_{nat}^{COD} are the COD and $\mathrm{NH_4^+}$-H natural background concentration in the receiving water body or environment, respectively, both of which were taken as 0 kg/m^3 (Meng et al., 2022).

2.2.2 Industrial WF calculation

Like domestic WF, the consumption of water resources by industrial production does not include green water resources, so the industrial WF consists of industrial blue WF and industrial gray WF. Industrial blue WF can be replaced by the actual industrial water use data (Zhang et al., 2019). COD and $\mathrm{NH_4^+}$-H are the main pollutants in the industrial wastewater (Su et al., 2010), so the maximum water consumption required for dilution of both was used as the industrial gray WF. The formulas are as follows:

$$WF_I = WF_{blue}^{I} + WF_{grey}^{I}\ , \tag{6}$$

$$WF_{grey}^{I} = \max(WF_{grey}^{ICOD}, WF_{grey}^{INH_4^+-N})\ , \tag{7}$$

$$WF_{grey}^{ICOD} = \frac{L_{COD}^{I}}{C_{max}^{COD} - C_{nat}^{COD}}\ , \tag{8}$$

$$WF_{grey}^{INH_4^+-N} = \frac{L_{NH_4^+-N}^{I}}{C_{max}^{NH_4^+-N} - C_{nat}^{NH_4^+-N}}\ , \tag{9}$$

where WF_{blue}^{I} is the industrial blue WF, m^3; WF_{grey}^{I} is the industrial gray WF, m^3; WF_{grey}^{ICOD} is the industrial COD gray WF, m^3; and $WF_{grey}^{INH_4^+-N}$ is the industrial $\mathrm{NH_4^+}$-H gray WF, m^3. L_{COD}^{I} and $L_{NH_4^+-N}^{I}$ are the COD and $\mathrm{NH_4^+}$-H loads in industrial wastewater, respectively, kg.

2.2.3 Agricultural WF calculation

The proportion of irrigation water for the planting industry in China's agricultural water use has reached more than 90%, and the proportion of other water use is small (Cao et al., 2015). Therefore, only the planting industry was considered in the agricultural WF of this study. The consumption of water resources by crop growth includes not only blue water resources, such as surface water and groundwater, but also green water resources derived from precipitation and stored in the soil around the crop roots. The use of chemical fertilizers during crop planting pollutes water resources. Therefore, the agricultural WF of this study consists of agricultural blue water, green water, and gray WF. The amounts of agricultural blue water and green WF were calculated based on the field crop evapotranspiration and crop yield per unit area, and the gray WF was estimated by the nitrogen content entering the water body due to leaching during the application of chemical fertilizers (including nitrogen fertilizer and compound fertilizer) (Hoekstra et al., 2011)

. The formulas are as follows:

$$WF_A = WF_{blue}^A + WF_{green}^A + WF_{grey}^A \lg p \,, \tag{10}$$

$$WF_{blue}^A = 10 \times \sum_{d=1}^{\lg p} \max(0, ET_c - P_{eff}) \times A \,, \tag{11}$$

$$WF_{green}^A = 10 \times \sum_{d=1}^{\lg p} \min(ET_c, P_{eff}) \times A \,, \tag{12}$$

$$ET_c = K_c \times ET_0 \,, \tag{13}$$

$$P_{eff} = \begin{cases} P \times \dfrac{126 - 0.6 \times P}{125}, P \le 250/3 \\ \dfrac{125}{3} + 0.1 \times P, P > 250/3 \end{cases} , \tag{14}$$

$$WF_{grey}^A = \frac{(Appl_n \times C_n + Appl_c \times C_c) \times a}{C_{max}^N - C_{nat}^N} \,, \tag{15}$$

where WF_{blue}^A is the agricultural blue WF, m^3; WF_{green}^A is the agricultural green WF, m^3; and WF_{grey}^A is the agricultural gray WF, m^3. $\lg p$ is the length of the crop growth period, d; ET_c is crop evapotranspiration, mm; and P_{eff} is the effective rainfall during the crop growth period, mm. A is the planting area of crops, hm^2; K_c is the crop coefficient; and ET_0 is the reference crop evapotranspiration, calculated by using the Penman-Monteith formula from the CROPWAT model (Cai et al., 2022), mm. P is the precipitation, mm; $Appl_n$ and $Appl_c$ are the annual application amount of nitrogen fertilizer and compound fertilizer, respectively, kg/a; and C_n and C_c are the nitrogen content of nitrogen fertilizer and compound fertilizer, respectively, taking up 46% and

30%, respectively (Wang et al., 2021). C_{max}^{N} is the standard concentration of nitrogen, which determines the water quality. According to the Environmental Quality Standard for Surface Water (GB3838-2002) (Ministry of Environmental Protection of China., 2002), the value is 0.01 kg/m^3. C_{nat}^{N} is the natural local concentration of nitrogen in the receiving water body, and the value is 0 kg/m^3 (Meng et al., 2022). a is the loss rate of chemical fertilizer, which is 10.1% (Wang et al., 2021).

2.3 Construction and verification of SD model

This research combined the relevant theories and formulas of the WF calculation and used Vensim DSS software to build China's WF simulation model (Fig. 1–2). The time boundary of the model is 2000–2050, and the time step is 1 year, of which 2000–2018 is the historical year, 2019 is the current year, and 2020–2050 is the forecast year. The space boundary of the model is China (Hong Kong, Macao, and Taiwan in China are temporarily unavailable). The model is composed of five subsystems (domestic subsystem, industrial subsystem, agricultural subsystem, ecological subsystem, and water supply and demand subsystem), including 111 variables. The agricultural subsystem (Fig. 2) is connected with other subsystems through agricultural WF variables. The model structure equation of each variable in the model was determined using the theory of WF, the principle of water resource utilization, and the basic relationship between variables.

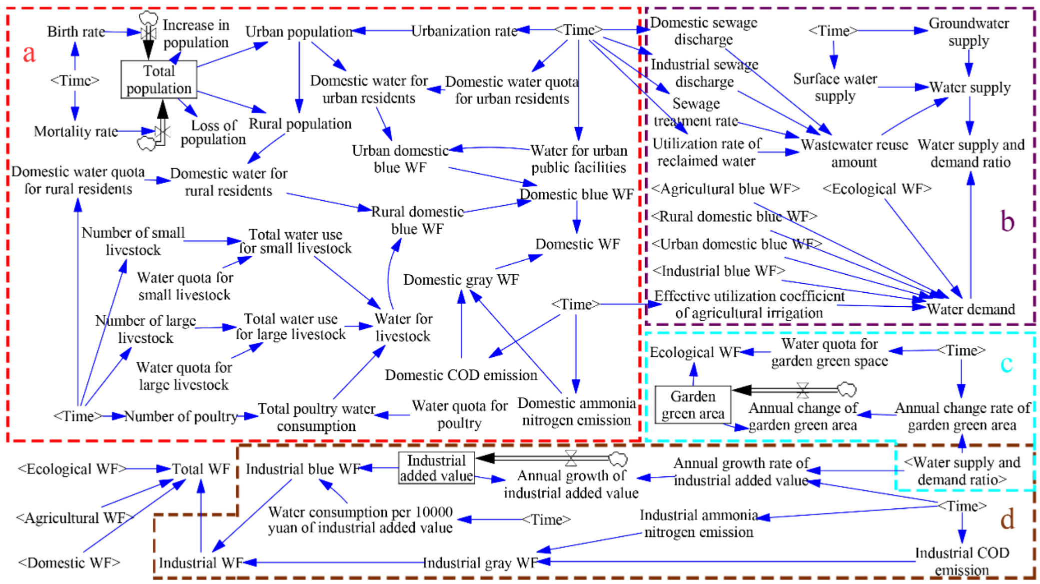

Fig. 1. Simulation model of China's WF (Part): a) domestic subsystem; b) water supply and demand subsystem; c) ecological subsystem; and d) industrial subsystem

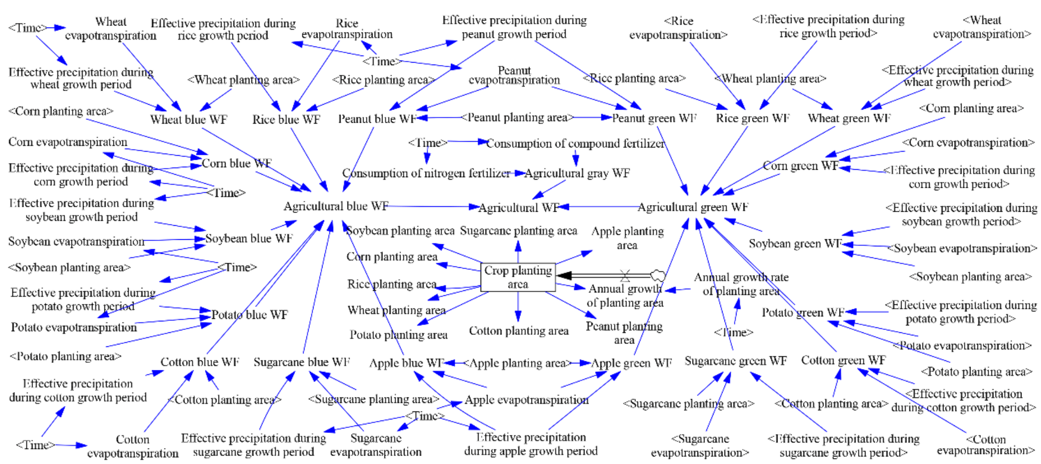

Fig. 2. Simulation model of China's WF agricultural subsystem

To ensure the model's accuracy, validity, and credibility, the China WF Simulation Model was tested for system structure, dimensional consistency, and history. The system structure and dimensional consistency check of the model were conducted through the Cause Tree and Units Check toolboxes in Vensim DSS software, and both of them passed the check. Six variables were selected for the historical test, and the determination coefficients R2 of the test variable simulation value and the actual value were greater than 0.85 (Fig. 3), indicating that the simulation results of the model were in good agreement with the actual situation, that is, the basic structure of the model could reflect the real system.

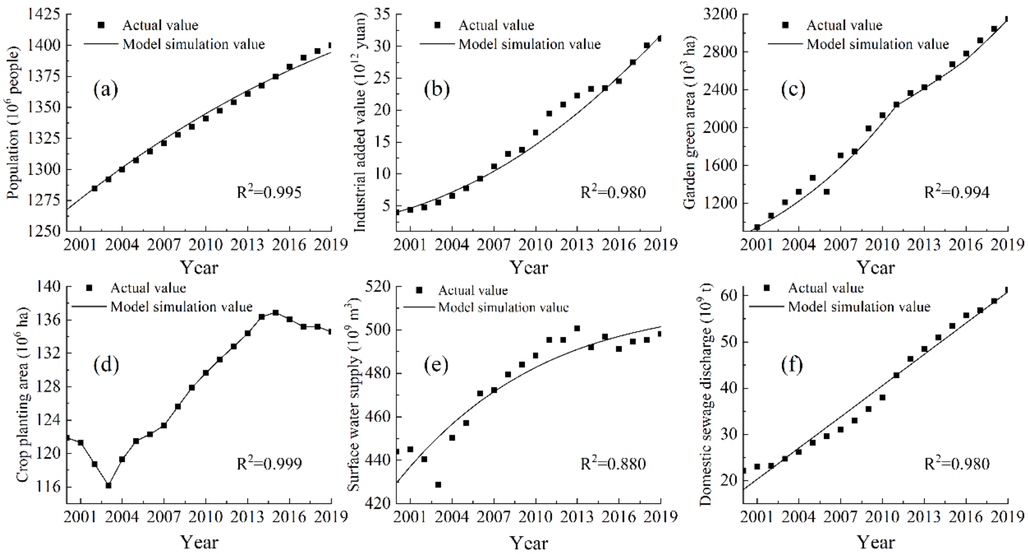

Fig. 3. Fitting of the variable simulation value and historical actual value. a) Population. b) Total industrial output value. c) Garden green area. d) Crop planting area. e) Surface water supply. f) Domestic sewage discharge.

2.4 Model variable setting under the SSP-RCP scenario

In this study, the SSP-RCP scenario matrix in the 6th International Coupling Model Comparison Plan (CMIP6), namely SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-6.0, and SSP5-8.5, was selected as the prediction scenario of China's WF.

2.4.1 Setting of variables related to socioeconomic development

The five basic paths of SSPs include the sustainable path SSP1, the intermediate path SSP2, the regional competition path SSP3, the unbalanced path SSP4, and the high emission development path SSP5. Each path describes different socioeconomic developments in the future from the aspects of technology level, water use efficiency, land use, economic development, and environmental protection awareness (Fig. 4) (O'Neill et al., 2014; Hanasaki et al., 2013; Popp et al., 2017; Murakami et al., 2021). These aspects also directly affect the changes in the WF. Therefore, this paper utilizes five basic SSPs as the socioeconomic development scenarios for predicting China's WF.

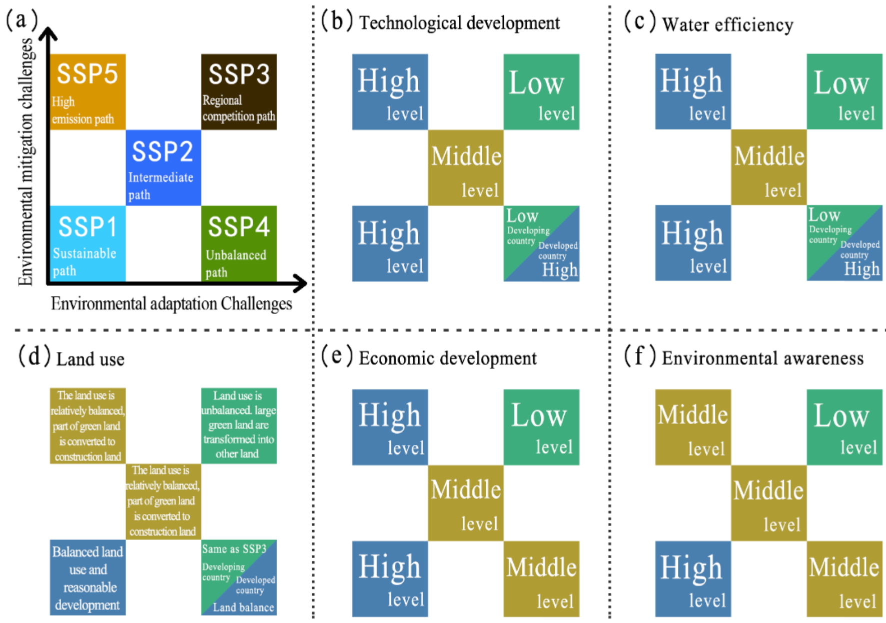

Fig. 4. Social development characteristics under five SSPs

Based on the path characteristics of different SSPs and WF influencing factors, and in combination with relevant references (Xu et al., 2020; Fan et al., 2019), the controllable variables of different subsystems in China's WF simulation model were screened (Table 1). Because the SSP database only contains quantitative values of the total population and urbanization rate, while the rest of the controllable variables only have qualitative descriptions, and considering that SSP2 is close to the current social development situation in China (Zhuang et al., 2021), we set the values of the rest of the controllable variables in different planning level years under the SSP2 path concerning China's 5th Five-Year Plan (FYP) and the National Water Resources Comprehensive Plan and other medium and long-term plans (Table 1). According to the quantitative description of the characteristics of life (Hanasaki et al., 2013), industry (Murakami et al., 2021), agriculture (Fricko et al., 2017), ecology (Popp et al., 2017), and water supply and demand (Hanasaki et al.,

2013) under different SSPs paths in the relevant literature, the differences between other path characteristics and SSP2 path characteristics were compared and analyzed to determine the change amplitude of the controllable variables under other paths compared with SSP2 (Table 2).

Table 1 Value setting of controllable variables under SSP2

Subsystem	Adjustable variable	Unit	Planning level year		
			2030	2040	2050
Domestic	Total population	10^6 people	1430	1440	1427
	Urbanization rate	%	75.5	80.0	80.0
	Domestic water quota for rural residents	L (one person one day)	105	120	134
	Domestic water quota for urban residents	L (one person one day)	238	251	265
	Urban public water	10^8 m^3	13.8	14.9	19.5
	Domestic ammonia nitrogen emission	10^4 t	3.0	1.6	0.4
	Domestic COD emission	10^4 t	67.7	5.94	0.16
Industry	Annual growth rate of industrial added value	%	4.83	3.74	2.07
	Industrial ammonia nitrogen emission	10^4 t	2000	860	380
	Industrial COD emission	10^4 t	14.79	2.21	0.33
	Water consumption per 10,000 yuan of industrial added value	m^3	11.6	4.0	1.4
Agriculture	Crop planting area	10^8 ha	1.38	1.42	1.45
	Consumption of nitrogen fertilizer	10^4 t	1293.5	607.1	210.5
	Consumption of compound fertilizer	10^4 t	3301.9	4090.3	4878.6
Ecology	Annual change rate of garden green area	%	0.04	0.03	0.02

Water supply and demand	Irrigation effective utilization coefficient	Dmnl	0.6	0.61	0.62
	Utilization coefficient of reclaimed water	%	0.308	0.417	0.526
	Sewage treatment rate	%	0.62	0.64	0.66
	Domestic sewage discharge	$10^8 m^3$	781.6	944.3	1107.1
	Industrial sewage discharge	$10^8 m^3$	14.7	7	1.3

Table 2 Change of controllable variables under other paths (%)

Subsystem	Adjustable variable	Scenario Assumptions											
		SSP1			SSP3			SSP4			SSP5		
		2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Domestic	Total population	-2.9	-4.6	-6.6	1.6	2.0	3.4	-3.6	-6.3	-9.7	-2.9	-4.6	-6.6
	Urbanization rate	-9.9	-5.9	0.9	-28.2	-29.3	-27.2	-9.9	-5.9	0.9	-9.9	-5.9	0.9
	Domestic water quota for rural residents	-5.0	-10.0	-15.0	5.0	10.0	15.0	2.0	5.0	8.0	3.0	8.0	10.0
	Domestic water quota for urban residents	-5.0	-10.0	-15.0	5.0	10.0	15.0	2.0	5.0	8.0	3.0	8.0	10.0
	Urban public water	-10.7	-15.5	-20.4	6.4	9.0	11.7	-2.8	-3.6	-4.4	-9.7	-13.8	-18.1
	Domestic ammonia nitrogen emission	-2.3	-4.6	-6.9	2.4	5.1	8.4	-1.1	-2.3	-3.6	-2.5	-4.8	-7.3
	Domestic COD emission	-2.3	-4.6	-6.9	2.4	5.1	8.4	-1.1	-2.3	-3.6	-2.5	-4.8	-7.3
Industry	Annual growth rate of industrial added value	25.0	48.0	26.0	-15.0	-42.0	-62.0	1.0	2.0	-8.0	46.0	77.0	51.0
	Industrial ammonia nitrogen emission	-2.3	-4.6	-6.9	2.4	5.1	8.4	-1.1	-2.3	-3.6	-2.5	-4.8	-7.3

	Industrial COD emission	-2.3	-4.6	-6.9	2.4	5.1	8.4	-1.1	-2.3	-3.6	-2.5	-4.8	-7.3
	Water consumption per 10,000 yuan of industrial added value	-2.0	-4.0	-7.0	2.0	5.0	7.0	2.0	5.0	7.0	-2.0	-4.0	-7.0
	Crop planting area	-1.9	-3.6	-5.1	3.2	5.9	8.5	0.0	0.0	0.0	-1.3	-2.4	-3.4
Agriculture	Consumption of nitrogen fertilizer	-9.6	-14.7	-24.2	-3.4	-3.2	-8.6	0.0	0.0	0.0	-4.0	-4.4	-10.1
	Consumption of compound fertilizer	-9.6	-14.7	-24.2	-3.4	-3.2	-8.6	0.0	0.0	0.0	-4.0	-4.4	-10.1
Ecology	Annual change rate of garden green area	50.0	50.0	50.0	-20.0	-20.0	-20.0	0.0	0.0	0.0	20.0	20.0	20.0
	Irrigation effective utilization coefficient	2.0	4.0	7.0	-2.0	-4.0	-7.0	-2.0	-4.0	-7.0	2.0	4.0	7.0
	Utilization coefficient of reclaimed water	2.0	4.0	7.0	-2.0	-4.0	-7.0	-2.0	-4.0	-7.0	2.0	4.0	7.0
Water supply and demand	Sewage treatment rate	2.0	4.0	7.0	-2.0	-4.0	-7.0	-2.0	-4.0	-7.0	2.0	4.0	7.0
	Domestic sewage discharge	-2.4	-3.5	-5.1	2.0	3.3	5.0	-3.1	-5.2	-8.2	-2.4	-3.5	-5.1
	Industrial sewage discharge	10.3	10.6	11.0	15.2	16.0	16.0	3.3	4.0	4.0	25.2	25.3	26.0

Note: The values in the table represent the magnitude of change compared to the variables corresponding to SSP

2.4.2 Setting of variables related to climate change

Precipitation and temperature are significant elements for identifying climate change (Chen et al., 2004), and they directly impact the effective precipitation and evapotranspiration during the growth period of crops in the agricultural subsystem (Fig. 2). Therefore, precipitation and temperature were selected as the main meteorological factors affecting the WF in this study. The temperature change under the SSP-RCP scenario matrix was from the sixth IPCC assessment report (Table 3) (Arias et al., 2021), and the precipitation change was selected based on the prediction results of Tian et al (2021) for China's precipitation in the 21st century under the SSP-RCP scenario matrix (Table 4).

Table 3 Temperature change under the SSP-RCP scenario matrix (°C)

Planning level year	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP4-6.0	SSP5-8.5
2030	0.7	0.7	0.7	0.7	0.8
2040	1.5	1.5	1.5	1.5	1.7
2050	2.3	2.5	2.6	2.5	2.9

Note: The values in the table represent the temperature increment compared with the current year 2019.

Table 4 Precipitation change under the SSP-RCP scenario matrix (%)

Planning level year	SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP4-6.0	SSP5-8.5
2030	8	4	3	1	6
2040	9	10	6	7	11
2050	13	11	9	8	13

Note: The values in the table represent the percentage increase in precipitation compared with the current year 2019.

3. Results and Analysis

From the perspective of water users (domestic, industrial, and agricultural) and water source types (blue water, green water, and gray water), this study analyzed the change characteristics of China's WF in historical years and the simulation under the SSP-RCP scenarios in the prediction years. We compared the supply and demand of China's water resources under different SSP-RCP scenarios to select the best scenario to alleviate China's water shortage and water pollution.

3.1. Total WF

Fig. 5a shows that during the historical year, affected by the rapid development of China's socioeconomic in the early 21st century, China's total WF increased from 19349×10^{8} m^3 in 2000 to 26574×10^{8} m^3 in 2011. During that time, the imbalance between the supply and demand of water resources and the problem of water pollution became increasingly prominent in China. With the promulgation of the 12th FYP for the Construction of a Water-saving Society (Ministry of Water Resources in China., 2010) and the 12th FYP for National Environmental Protection (General Office of the State Council in China., 2011), China stepped up efforts to save water and prevent water pollution, so that the total WF began to decline after reaching its peak in 2011 and dropped to 18392×10^{8} m^3 in 2019. During the forecast year, the changing trend of China's total WF under the five SSP-RCP scenarios is the same, which will gradually decrease from 2020 to 2035 and slowly increase from 2035 to 2050. Under the comprehensive influence of water-saving technology, environmental governance, climate change, and other factors, the total WF under the SSP3-7.0 and SSP5-8.5 scenarios remains high, while the total WF under the SSP1-2.6 scenario is the lowest.

Fig. 5b shows that, with the continuous development of society and change of climate, the consumption of blue water and green water by production and daily human life continues to rise. During the forecast year, the rapid urbanization process and economic development make blue WF grow the fastest in the SSP5-8.5 scenario, and the growth rate in other scenarios is relatively close. As industry and life do not consume green water resources, green WF only includes agricultural green WF. As the temperature and precipitation increase rapidly under the SSP3-7.0 scenario, and the cultivated land area is the largest, the green WF grows fastest under this path. In contrast, the growth rate of green WF is the slowest under the SSP1-2.6 scenario (Fig. 5c). As China's efforts to prevent and control water pollution continue to increase during the 12th FYP period, the gray WF changes from an increase to a decrease and tends to be stable under all scenarios after 2035. A relatively complete water pollution prevention system makes the gray WF the lowest under the SSP1-2.6 scenario (Fig. 5d). Fig. 5(e–h) shows that under the constraints of the 10th FYP for Industrial Water Saving (General Office of the State Council in China., 2001) and the 10th FYP for the Construction of a Water Saving Society (State Economic and Trade Commission in China., 2001), the industrial WF and domestic WF changed from increasing to decreasing in 2002 and 2007, respectively, and the agricultural WF and ecological WF continued to increase in the historical and forecast years.

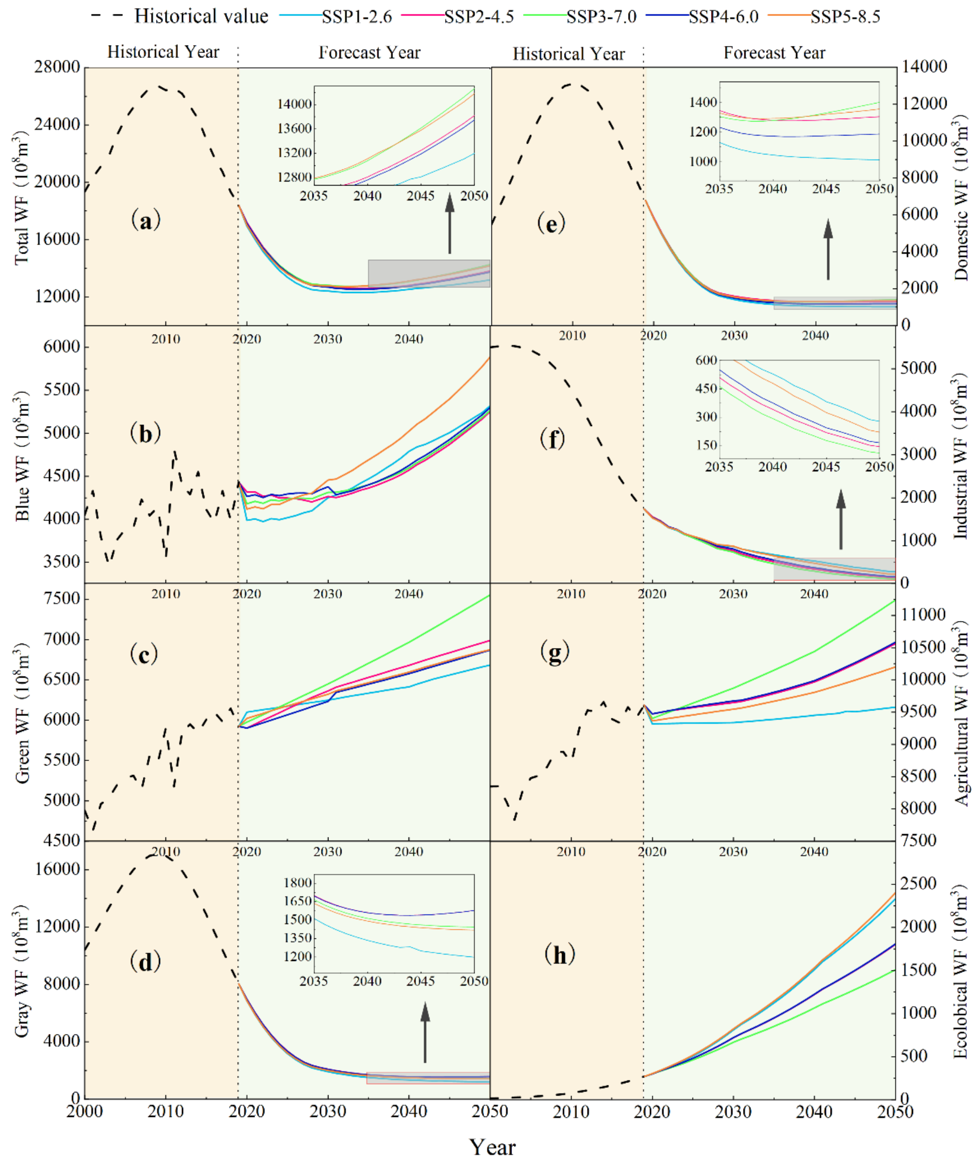

Fig. 5. Historical measurement and future simulation diagram of China's WF

To analyze the total amount and composition of China's WF more intuitively and quantitatively under different scenarios in the future compared with the current year, the composition of the WF in 2019 and 2050 and the proportion of different users' WF were drawn (Fig. 6). Fig. 6 (a) shows that the total WF under all scenarios in 2050 is lower than that in 2019. The total WF under the SSP1-2.6 scenario decreases by the largest amount (28.2%), while that under the SSP3-7.0 scenario decreases by the smallest amount (22.4%). Compared with 2019, the gray WF in 2050 has the largest decrease (85.1%) under the SSP1-2.6 scenario, and it also has a large reduction in other scenarios. The blue WF and green WF increased to varying degrees under all scenarios.

Fig. 6(b) shows that because agriculture developed to varying degrees in all scenarios, and the increase in temperature increased the water demand of crops, the proportion of agricultural WF in the total WF increased from 52% in 2019 to more than 70%, with the largest increase (27%) in the SSP3-7.0 scenario. The proportion of ecological WF in each scenario increased from 2% in 2019 to more than 10%, and the proportion in SSP1-2.6 and SSP5-8.5 scenarios increased to 17% and 16%, respectively. As the water-saving technology and water efficiency of all scenarios in 2050 improved compared with the current year, the proportion of domestic WF and industrial WF in the total WF is lower than that in 2019.

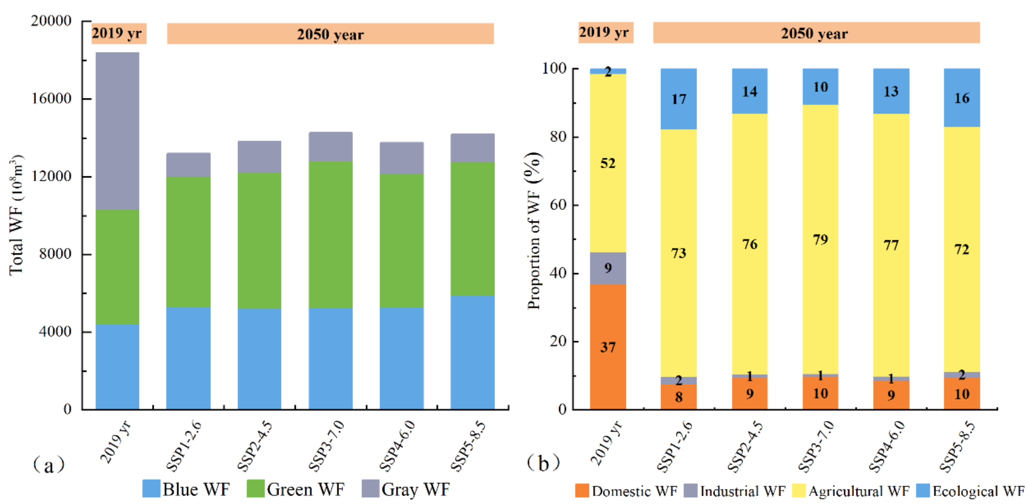

Fig. 6. Composition of total WF in 2019 and 2050 and proportion of WF of different users

3.2. Domestic WF

Fig. 7 shows the dynamic changes of domestic WF, domestic blue WF, domestic gray WF, urban domestic WF, and rural domestic WF under different SSP-RCP scenarios in five years. The sparse lines of the parallel coordinate graph indicate that the value changes rapidly with time, while the dense lines indicate that the value changes slowly with time. It can be seen from the figure that China is in a period of rapid population growth and social development at the beginning of the 21st century. Weak public awareness of water conservation and water environment protection led to the rapid growth of domestic WF before 2010, with an average annual growth of 763×10^8 m^3. However, with the increasing shortage of water resources and water pollution, the government realized the importance of water resource protection and vigorously promoted the formulation and improvement of laws and regulations related to water conservation and water pollution prevention. The decline of the domestic water quota and the reduction of pollutant emissions made the domestic WF gradually decline after reaching its peak (13114×10^8 m^3) in 2010. The domestic WF of all scenarios in the forecast year shows a downward trend, and the decline rate is relatively slow during the period from 2030 to 2050. As there is a strong public awareness of water conservation and environmental protection under the SSP1-2.6 scenario, the domestic WF was kept at the lowest level under this scenario.

The increase in population and the improvement of people's living standards make the domestic blue WF rise continuously. Compared with other scenarios, the population and residential water quota under the SSP3-7.0 scenario are both the highest, so the domestic blue WF is the highest under this scenario, and the lower population and residential water quota make the domestic blue WF the lowest under the SSP1-2.6 scenario. With the increase in China's population and the acceleration of urbanization, the blue WF of urban life in all scenarios in the historical and forecast years will increase, but the growth rate will gradually slow down. As the population and urbanization rate of China under the SSP5-8.5 scenario are higher than those under other scenarios, the blue WF of urban life in 2050 under this scenario is the highest (1169×10^8 m^3). The smaller population and lower domestic water quota make the blue WF of urban life the lowest (872×10^8 m^3) under the SSP1-2.6 scenario. As the domestic water consumption of rural residents in China is guaranteed, although the water consumption of rural residents is gradually increasing, the increase of the urbanization rate leads to the decline of the rural population. Therefore, the blue WF of rural life has a trend of first increasing and then decreasing in the historical years. In the forecast year, the rural domestic water quota under the SSP3-7.0 scenario is relatively high, so the blue WF of rural life is still rising slowly under this scenario, while other scenarios are greatly affected by the reduction of the rural population, showing the characteristics of a gradual decline in the blue WF of rural life.

Weak public awareness of water environment protection increased the domestic gray WF from 4858×10^8 m^3 in 2000 to 1229×10^8 m^3 in 2010. After the Chinese government issued the Opinions on Strengthening the Key Work of Environmental Protection (General Office of the State Council in China., 2011) and formulated the 12th FYP for National Environmental Protection (General Office of the State Council in China., 2011), the gray WF began to decline gradually in 2011. In the forecast year, the gray WF of domestic sewage will continue to decline under all scenarios. The relatively perfect water pollution prevention system under the SSP1-2.6 scenario will make the domestic gray WF lower under this scenario than that under other scenarios. On the contrary, the domestic gray WF is the highest under the SSP3-7.0 scenario.

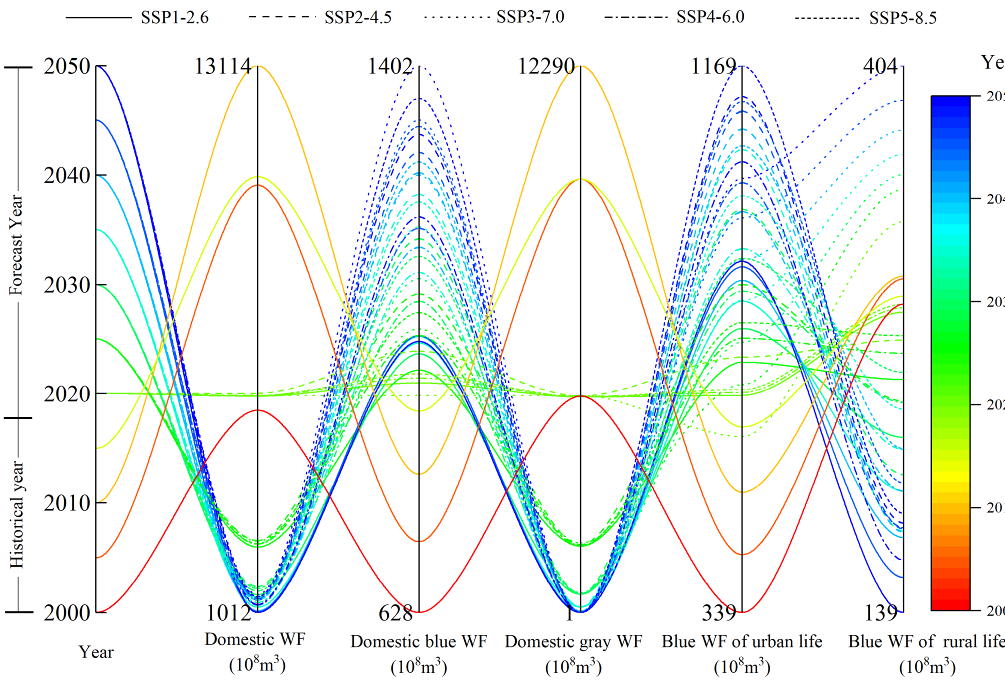

Fig. 7. Parallel coordinates of historical measurement and future simulation of domestic WF

3.3. Industrial WF

Fig. 8 shows the dynamic changes of industrial WF, industrial blue WF, and industrial gray WF under different SSP-RCP scenarios. Due to the development of China's industry from 2000 to 2010 (Shen and Ni., 2022), the industrial blue WF showed an increasing trend in this period. However, with the improvement of industrial wastewater treatment technology, the industrial gray WF continued to decline in this period. The industrial gray WF accounted for a high proportion of the industrial WF in this period (more than 67.8%). Therefore, the industrial WF also continued to decline from 2000 to 2010, but the decline rate was slower than the industrial gray WF. After 2010, with the promulgation of the 12th FYP for the Construction of a Water Saving Society (Ministry of Water Resources in China., 2010), China's industrial water consumption per 10000 yuan of added value decreased rapidly, so the industrial blue WF began to decline. At this time, the decline rate of industrial WF accelerated. With the further improvement of industrial wastewater treatment technology and water-saving technology, the industrial WF, industrial blue WF, and industrial gray WF under all scenarios in the forecast year will show a downward trend. As the industrial pollutant emissions under different scenarios are relatively close, there is no significant difference in industrial gray WF under different scenarios. By 2050, the total industrial WF will be the highest under the SSP1-2.6 scenario with rapid industrial development and the lowest under the SSP3-7.0 scenario. In this period, the proportion of industrial blue WF in industrial WF is relatively high (more than 73.7%), so the predicted annual change trend of industrial blue WF is the same as that of industrial WF.

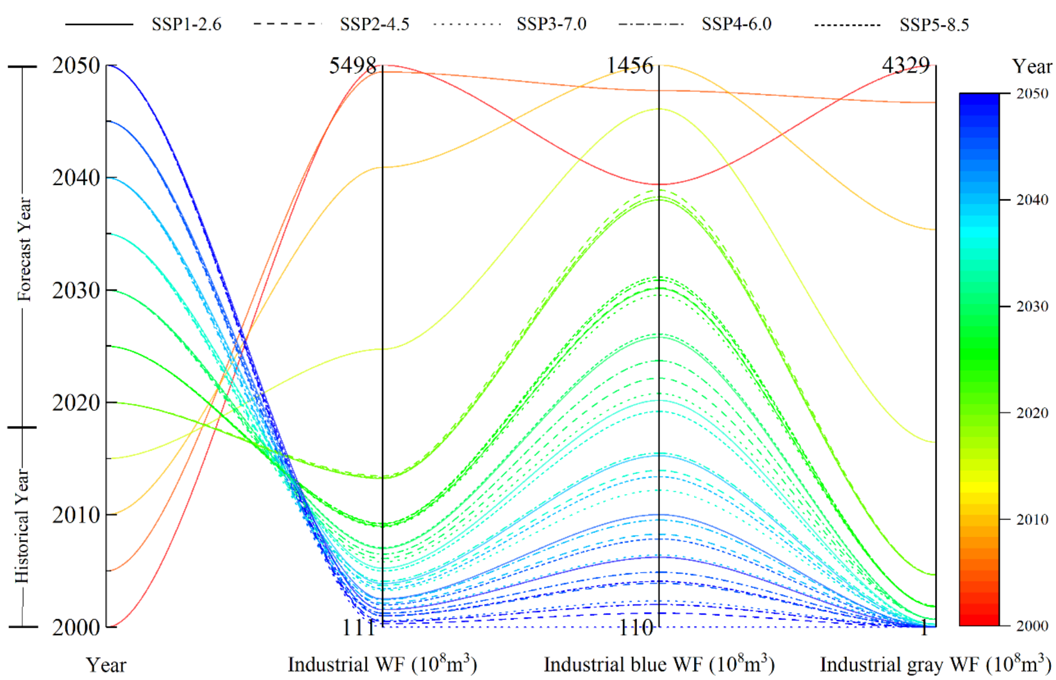

Fig. 8. Parallel coordinates of historical measurement and future simulation of industrial WF

3.4. Agricultural WF

Fig. 9 shows the changes in agricultural WF and its composition under different SSP-RCP scenarios. It can be seen from the figure that agriculture is the guarantee that supports the development and progress of the entire Chinese national economy. The state has continuously increased its investment in agriculture. With the gradual guarantee of agricultural water use and the increase of the effective irrigation area (Pei et al., 2018), the agricultural WF has gradually increased in the historical years. The agricultural WF still shows an increasing trend under all SSP-RCP scenarios in the forecast year, among which the agricultural WF remains the highest under the SSP3-7.0 scenario, while the agricultural WF remains the lowest under the SSP1-2.6 scenario due to the rational development and utilization of cultivated land, effective control of non-point source pollution, and relatively stable climatic conditions.

Affected by the shortage of water resources, China's agricultural planting structure was in the adjustment stage from a rice-based planting type to a multi-combination planting type (Liu et al., 2016) from 2000 to 2010, and the planting area of rice, the most water-consuming crop, decreased, so the agricultural blue WF decreased in this period. With the improvement of the agricultural planting structure and the increase of the effective irrigation area, the agricultural blue WF began to increase after 2010. In the forecast year, the agricultural blue WF still shows an increasing trend. Due to the high degree of cultivated land development and utilization and large irrigation area under the SSP3-7.0 scenario, the agricultural blue WF will remain the highest under this scenario, reaching 2243×10^{8} m^{3} in 2050. In the SSP1-2.6 scenario, there is less food demand and less arable land required, so the agricultural blue WF was kept at the lowest level in this scenario and declined since 2045. The rise of temperature and the increase of cultivated land area make the agricultural green WF in the study period continue to rise. It is predicted that the agricultural green WF will remain the highest in the year under the scenario of SSP3-7.0, the fastest warming scenario, and reach 7555×10^{8} m^{3} by 2050. On the contrary, under the scenario of SSP1-2.6 with the slowest temperature rise, the agricultural green WF will always remain the lowest, reaching only 6684×10^8 m^3 by 2050. During the historical years, China's agriculture developed rapidly, and the use of fertilizer also increased rapidly (Hou et al., 2017), so the agricultural gray WF continued to rise in the historical years. However, in the forecast year, the decline in fertilizer use and the improvement of fertilizer efficiency will cause the agricultural gray WF to show a downward trend under all scenarios. The agricultural gray WF has always been the highest under the SSP4-6.0 scenario with the largest amount of fertilizer use and the lowest under the SSP1-2.6 scenario with the least amount of fertilizer use.

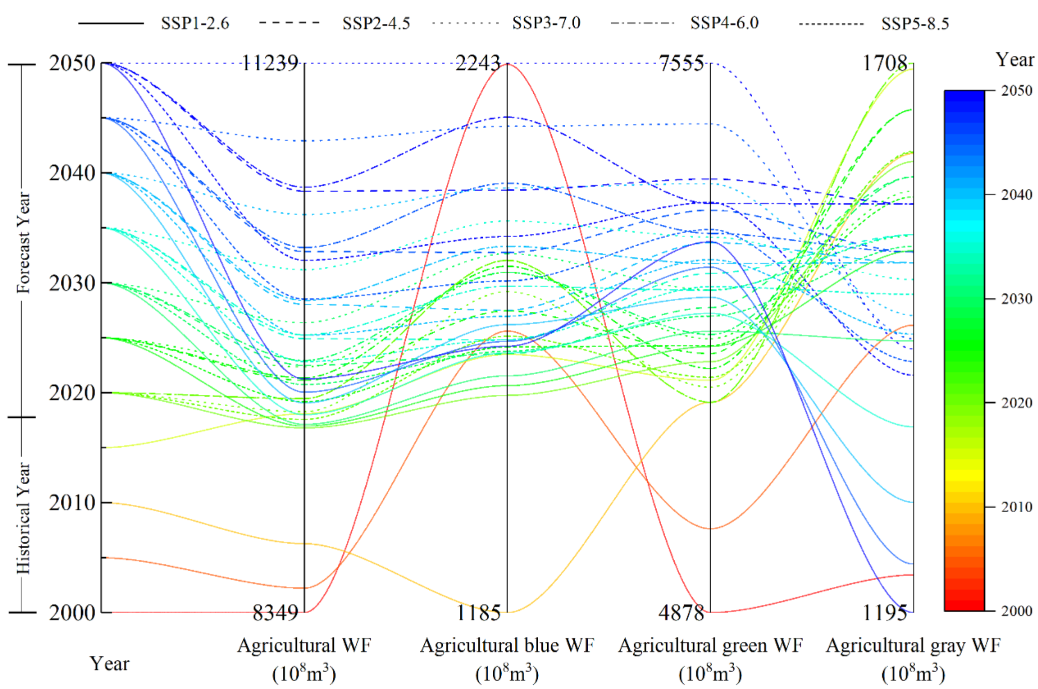

Fig. 9. Parallel coordinates of historical measurement and future simulation of the agricultural WF

3.5. Ecological WF

Fig. 10 shows the changes in ecological WF and its proportion in total WF in different SSP-RCP scenarios. During the historical year, with the gradual improvement of people's awareness of environmental protection, the ecological environment and construction of an ecological civilization improved, so the ecological WF and its proportion in the total WF continued to rise in this period, from 16×10^8 m^3 and 0.08% in 2000 to 270×10^8 m^3 and 1.47% in 2019. The ecological WF and its proportion in the total WF also show an upward trend under all scenarios, in which the ecological civilization construction is relatively strong under the SSP1-2.6 and SSP5-8.5 scenarios, and the area of garden green space increases rapidly. As the utilization efficiency of water resources under the SSP1-2.6 scenario is relatively high, the ecological WF is the highest under the SSP5-8.5 scenario, but the total WF under the SSP1-2.6 scenario is lower than SSP5-8.5, Therefore, the proportion of ecological WF in total WF is the highest under the SSP1-2.6 scenario. The ecological WF and its proportion in the total WF are slightly lower under the SSP4-6.0 and SSP2-4.5 scenarios and are relatively close to each other. People's low awareness of ecological environmental protection makes the ecological WF and its proportion in the total WF the lowest under the SSP3-7.0 scenario, reaching only 1511×10^8 m^3 and 10.59% in 2050.

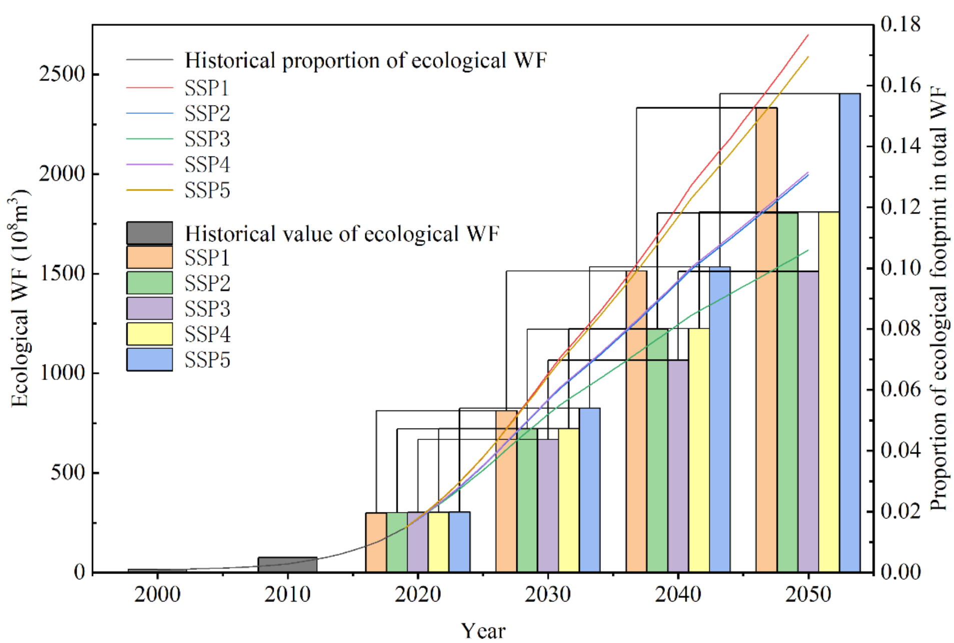

Fig. 10. Historical calculation and future simulation diagram of the ecological WF

3.6. Water supply and demand

Fig. 11 shows the changes in the water supply, water demand, and water resource supply/demand ratio in China under different SSP-RCP scenarios. The water demand in this paper is from the perspective of the WF, considering the real consumption and demand of water resources by industry, life, agriculture, and ecology. It can be seen from the figure that the Chinese government has improved the water-saving policies of various industries in the past years, and the water demand has fluctuated and declined in this period. However, this period is also in the stage of rapid socioeconomic development, so the decline of water demand is relatively slow. At this time, forced by the contradiction between the supply and demand of water resources, the development of water resources in China was rapidly enhanced, and the exploitation of surface water and groundwater continued to rise. The water supply increased from 5348×10^8 m^3 in 2000 up to 6094×10^8 m^3 in 2019, However, a series of ecological problems, such as over-exploitation of water resources, rivers drying up, and land subsidence, emerged. To deal with these problems, the government introduced the water intake permit management method, improved the water intake permit system, and actively promoted the development and utilization of unconventional water sources (Ma et al., 2020). Therefore, the increased rate of the water supply in historical years gradually slowed. Under the combined effect of the decrease in the water demand and the increase in water supply, the supply and demand ratio of water resources trended upward in historical years. Although the supply and demand ratio of water resources is still less than 1, the contradiction between the supply and demand of water resources was alleviated to a certain extent.

Under the influence of multiple factors, such as water efficiency and water-saving technology, the predicted annual water demand is the lowest under the SSP1-2.6 scenario and will be flat after dropping to 2030. In other scenarios, the water demand will decline first and then rise. Due to the strong protection of surface water and groundwater under the SSP1-2.6 scenario, the water supply will gradually decrease to 6002×10^8 m^3 in 2040. However, with SSP1-2.6 gradually improving and maintaining a high level of utilization of unconventional water sources, the water supply will slowly increase during 2040–2050. Water supply in other scenarios continues to decline, with the fastest decline rate in the SSP4-6.0 scenario. The supply and demand ratio of water resources continues to grow under the SSP1-2.6 scenario, rising to 1.080 in 2050 after exceeding 1 in 2026. The changing trend of the water resource supply and demand ratio in other scenarios is relatively consistent, which will rise by 2030 and begin to decline; the peak value will not exceed 1. It can be seen from this that under the joint influence of climate change and socioeconomic development, the SSP1-2.6 scenario can achieve the balance between the supply and demand for water resources in China in the forecast year and solve the problem of water shortages in China.

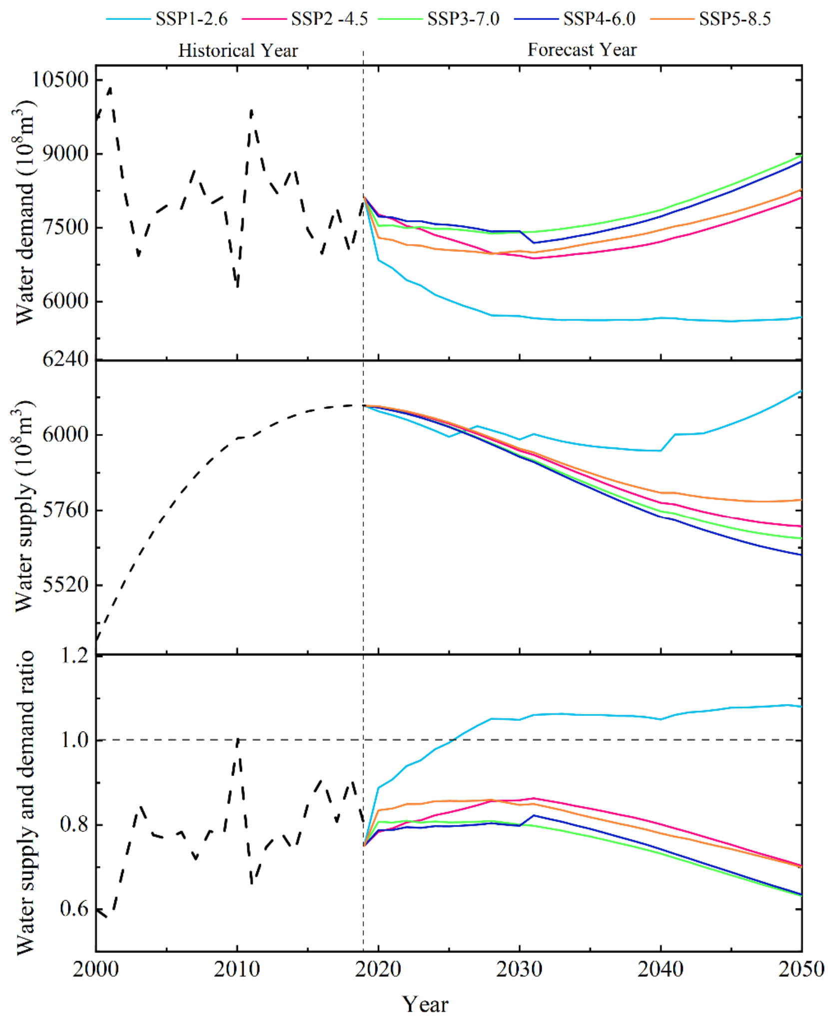

Fig. 11. Historical calculation and future simulation diagram of water supply and demand

4. Discussion

It can be seen from the research results that the WF consumed by different users in the historical years have different trends under the influence of socioeconomic development and climate change. The changing trend of WF and its composition shows that the problems of water resource shortage and water pollution faced by China in the past two decades have been gradually alleviated, but the situation of water resource shortage and water pollution is still serious, which is consistent with the research conclusion of Zhang et al (2019). However, the specific values are different because of different calculation models and relevant parameter settings. In addition, the calculation of gray WF is different from that of Hou et al (2021), who selected the maximum gray WF of different users as the total gray WF. This study considered that the dilution of pollutants is completed by different water bodies, and China's gray WF is obtained by adding the gray WF of daily human life, industry, and agriculture (Wang et al., 2015). The changes in China's WF and its composition under different scenarios in the forecast year are quite different, indicating that different climatic conditions and socioeconomic development conditions have a great impact on China's WF. Compared with other scenarios, China's WF under the SSP1-2.6 scenario is in a good state among all users, which is consistent with the research results of Xu et al (2020).

This study had some limitations. First, considering that livestock water is domestic water, we divided livestock-related variables into living subsystems and did not consider the gray WF generated by livestock. In future research, we will add this calculation to improve the accuracy of the classification of research objects. Second, this study did not consider the adjustment of industrial production structure and agricultural planting structure in the future when making scenario predictions and predicted the changes of industrial and agricultural WF according to the current production structure. In future research, we will update the relevant parameters in the model according to China's development planning and relevant policies to improve the timeliness of the results. Finally, we regarded the study area as a whole, but China has a vast territory, and different regions have great differences in social and economic development and climate conditions. In future research, we will adjust the model parameters based on the characteristics of regional social and economic development and climate conditions and conduct WF research on different basins or provinces in China to improve the regional applicability of the results.

5. Conclusion

In this study, SD was used to build a simulation model of China's WF. The changes in China's WF and its composition in the historical years (2000–2019) were calculated. These changes were simulated under five SSP-RCP scenarios in the prediction years (2020–2050). The results were analyzed, and our main conclusions are as follows:

(1) During the historical year, China's WF increased to 2009 and began to decline. From the perspective of the water source type, gray WF is the main contributor to China's WF, but it began to decline in 2009, indicating that China made achievements in water pollution prevention and control. From the perspective of users, agricultural WF is the main contributor to China's WF, which experienced a wavelike rise during this period. During this period, the supply and demand ratio of the water resources increased, indicating that the problem of water resource shortages in China had improved. However, because the values did not exceed 1, the water resource shortage is still severe.

(2) During the forecast year, different socioeconomic development and climate change conditions lead to different change trends of China's WF and its composition under five SSP-RCP scenarios. Socioeconomic development is the main factor affecting China's WF, which has a direct impact on life, industry, agriculture, and ecological WF. Different climate change scenarios increase China's agricultural green WF to varying degrees. Influenced by social and economic development and climate change, only the supply and demand of water resources in SSP1-2.6 scenarios exceed 1, realizing the balance between the supply and demand of water resources and solving the problem of the water shortage in China.

(3) By 2050, except for the blue WF, industrial WF, and ecological WF, the total WF and

other WF under the SSP1-2.6 scenario are lower than those under other scenarios, while the high blue WF, industrial WF, and ecological WF also indicate the steady development of industrial and ecological civilization construction under the SSP1-2.6 scenario. In all aspects, the SSP1-2.6 scenario is the best scenario to alleviate water shortages and water pollution in China. According to SSP1-2.6 scenario characteristics, China should continue to increase investment in water-saving technology development, improve water resource utilization efficiency and water pollution treatment capacity, rationally develop and balance land resources, improve people's environmental awareness, and build an environmentally-friendly society.

Acknowledgments

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Data Availability Statement

The historical annual urbanization rate, birth rate, mortality rate, GDP, and other social and economic statistical data used in this study were from the China Statistical Yearbook (NBS., 2001-2020), China Environmental Statistical Yearbook (NBS., 2001-2020), China Tertiary Industry Statistical Yearbook (NBS., 2001-2020), and other statistical data (http://www.stats.gov.cn/english/Statisticaldata/AnnualData/), compiled by the National Bureau of Statistics of China. Domestic, industrial, and ecological water indicators were from the China Water Resources Bulletin (NBS., 2001-2020) (http://www.mwr.gov.cn/sj/tjgb/szygb/), compiled by the Ministry of Water Resources of China. Nine crops (rice, wheat, corn, beans, potatoes, cotton, peanuts, sugar cane, and apples) were selected as research objects for agriculture. The statistical data of the yield and planting area of different crops were from the China Statistical Yearbook (NBS., 2001-2020), and the crop growth period and growth coefficient were from the crop coefficient table recommended by the Food and Agriculture Organization of the United Nations (FAO) (Allen et al., 1998). Meteorological data, such as temperature, precipitation, wind speed, and sunshine duration in historical years, were from the CLIMWAT 2.0 database (Gabr., 2022). The population and urbanization rate data under the five basic SSPs paths were from the SSP database (https://tntcat.iiasa.ac.at/SspDb/dsd?Action=htmlpage&page=welcome).

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