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System dynamics model of Suzhou water resources carrying capacity and its application

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Abstract: A model of Suzhou water resources carrying capacity (WRCC) was set up using the method of system dynamics (SD). In the model, three different water resources utilization programs were adopted: (1) continuity of existing water utilization, (2) water conservation/saving, and (3) water exploitation. The dynamic variation of the Suzhou WRCC was simulated with the supply-decided principle for the time period of 2001 to 2030, and the results were characterized based on socio-economic factors. The corresponding Suzhou WRCC values for several target years were calculated by the model. Based on these results, proper ways to improve the Suzhou WRCC are proposed. The model also produced an optimized plan, which can provide a scientific basis for the sustainable utilization of Suzhou water resources and for the coordinated development of the society, economy, and water resources.

Key words: *system dynamics (SD); water resources carrying capacity (WRCC); eco-environmental water demand; Suzhou City*

1 Introduction

Since the concept of water resources carrying capacity (WRCC) was introduced in the 1980s, it has become a hot topic in water resources research fields, as well as a basic principle for sustainable development and water resources security strategies (Long and Jiang 2003; Cui 1998; Xiao et al. 1995; Gong and Jin 2009; Li and Gan 2000; Dong and Liu 2008). Currently, the study of WRCC in China focuses on the arid areas in northern and northwestern China, some water-deficient cities, and the Haihe River Basin, which is also an arid area (Wang and Yao 2000; Qu and Fan 2000; Zhu et al. 2010; Xu and Cheng 2002; Wang et al. 2005; Zhang and Zhao 2007; Meng et al. 2009). However, few studies of WRCC have reported on the developed southern cities (Weng et al. 2009; Feng et al. 2009). In recent years, due to the rapid economic development and population expansion in developed southern cities, the water demand has increased remarkably. The process of water exploitation and utilization in these areas has caused many environmental problems, such as serious water pollution and violation of surface water quality standards. Some polluted rivers and water bodies have lost their basic functions, and some water sources can no longer be regularly used. All of these changes have

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greatly reduced the availability of water resources and transformed the southern river network area from a water-abundant region into region of significant water shortages. Water resources have become a major restriction of economic and social development in most developed southern cities. These circumstances suggest that effective approaches must be adopted to protect water resources for sustainable use, to improve WRCC, and to avoid reducing the sustainability of economic development in developed cities.

In this study, Suzhou, a developed city in a southern China river network area, was selected for investigation, and the system dynamics (SD) method was applied to develop a model for the calculation of WRCC, providing a reference for the sustainable utilization of water resources in other similar regions.

2 Suzhou WRCC

2.1 Suzhou water resources

Suzhou, located south of the Yangtze River and east of Taihu Lake, is in a typical plain river network area. Taihu Lake is one large water source for Suzhou. Since it is also the water supply source for some cities in Jiangsu Province and Zhejiang Province, as well as Shanghai, Taihu Lake cannot completely meet the regional water requirements. In order to avoid an imbalance of the regional water supply, Suzhou limits the amount of water it takes from Taihu Lake to satisfy its water consumption requirements. Suzhou has few local water sources. Most of the water passes through the region and flows into other regions. The local average annual runoff is 2.4 km^3. Including diverted water and water that passes through the region, the total annual average water resources capacity of Suzhou is 10 km^3, of which 5.5 km^3 pass through the region, and 0.94 km^3 are groundwater. Without this, the locally produced water is far from sufficient to meet the requirements of industrial, agricultural, domestic, and environmental water consumption. Local water bodies have been seriously polluted. Serious water resource shortages, water pollution, and waste of water have caused Suzhou to become a water-deficient region where water shortage is mainly caused by deteriorating water quality, and also by diminishing water resources and increasing waste of water.

2.2 Definition of Suzhou WRCC

The definition of the Suzhou WRCC is reflected in the following aspects:

(1) Research framework of WRCC

The study of WRCC was conducted within the framework of Suzhou’s sustainable development strategy, which can be described as follows: (a) from the perspective of water resources, an integral eco-environmental cycle should be ensured, and the sustainable development and utilization of water resources should be realized; and (b) the water resources, social, economic, and eco-environmental subsystems should be coordinated with a balanced program of development.

(2) Difference from traditional method of water resources development and utilization

This approach to the sustainable development and utilization of Suzhou water resources is different from the traditional method of water resources development and utilization. The traditional method is a product of economic growth modes, while the sustainable development and utilization of Suzhou water resources aims to meet the water consumption requirements of future generations in Suzhou, to protect the ecological environment, and to promote economic growth and social prosperity, rather than to simply pursue economic profit.

(3) Effects of Suzhou regional water resources system on WRCC

The composition, structure and characteristics of Suzhou's regional water resources system strongly influence WRCC. The value of WRCC is not only related to water resources, but also to the composition, structure, and size of the socio-economic system.

(4) Constraints of water resources development and utilization and socio-economic development level

Water resources development and utilization at the socio-economic development level are constrained by historical conditions. This study was carried out at a certain stage of development. In other words, at different time scales, the definition of WRCC can be different.

(5) Study premise of Suzhou WRCC

The rational allocation and effective use of Suzhou water resources by various socio-economic and eco-environmental departments is the premise on which this study of WRCC was carried out, in order to analyze the socio-economic aspect of regional water resources.

Summarizing the above description, the Suzhou WRCC can be defined at the social, economic, and environmental development levels, based on regional water resources. These conditions include the scales in different future time periods, the basis of the foreseeable technological, economic, and social development levels, the principles of sustainable social development and sustainable utilization of water resources, the requirement of maintaining healthy development of the eco-environment, the premise of rational development and utilization, and the effective allocation of water resources.

3 SD model of Suzhou WRCC

3.1 Introduction to SD method

A water resources system is a complex system that affects both the socio-economic and ecological systems (Long and Jiang 2003; Long et al. 2004; Rijsberman 2000; Hunter 1998). Therefore, a model must be established to study the WRCC. This model should reflect the essence of the question, the technological feasibility, the scientific basis, and, finally, the multiplicity, nonlinearity, dynamics, and multiple feedbacks of carrying capacity problems. SD can combine multitudinous complex factors of society, the economy, and the natural resources environment as a whole to estimate WRCC and predict the process of dynamic change. SD not only considers system development, but also has the advantages of quick analysis, simple model structure, and the ability to use nonlinear equations. Therefore, the SD model is one of best technologies for system analysis of Suzhou WRCC, and it was applied in this study.

3.2 Model structure of SD for Suzhou WRCC

In this study, SD was applied as the system analysis method for the Suzhou WRCC. The spatial boundary of the SD model for Suzhou WRCC was the whole Suzhou area, which is 8 488 km^2. The historical review period was from 2000 to 2004, the simulated period was from 2005 to 2030, and the simulation time interval was one year. By using the supply-decided principle, Suzhou WRCC (namely, the socio-economic scale supported by Suzhou water resources) was obtained under the premise of controlling the yearly regulation of the basic balance of water resources supply and demand in a certain future period.

According to the characteristics and basic problem-solving steps of SD, the SD model for Suzhou WRCC was set up to correlate water resources with the economy, eco-environment, and population, by analyzing the water resources, ecology, and socio-economic system.

To maintain and protect the normal basic functions of the Suzhou river network ecosystem, according to the basin geographic location and characteristics of rivers in river network regions, the future variation tendency of the Suzhou WRCC was calculated and simulated with the SD model. Eco-environmental water demand was also considered in the model.

The system was divided into four components: water resources, society, economy, and eco-environment; and seven subsystems: the water resources subsystem (WRS), social life subsystem (SLS), primary industrial subsystem (PIS), secondary industrial subsystem (SIS), tertiary industrial subsystem (TIS), eco-environmental water demand subsystem (EWDS), and wastewater treatment and reuse subsystem (WTRS).

A special SD model software, Vensim, was used to establish SD model flow graphs of Suzhou WRCC. Only system flow graphs of the WRS, SLS, PIS, and SIS were selected as study examples (Fig. 1). Variables are listed in Table 1.

3.2.1 Water resources subsystem (WRS)

Water resources in the WRS indicate available water resources. Based on the water supply capacity and the sustainable potential of water resources development and utilization, the amount of water was chosen as the state variable, and the growth rate of the water supply was chosen as the rate variable. Furthermore, the tension degree of the water supply, which is the available amount of water divided by the total amount of water resources, was chosen as the control variable. Ensuring the eco-environmental water demand, all domestic and industrial water supply was regulated by adjusting the water distribution coefficients of social life, primary industry, secondary industry, and tertiary industry. If the water supply capacity was consistent, the simulated water demand was adjusted according to the supply-decided principle.

The tension degree of the water supply was set as close to 1.05 as possible, and balance between supply and demand was consequently achieved.

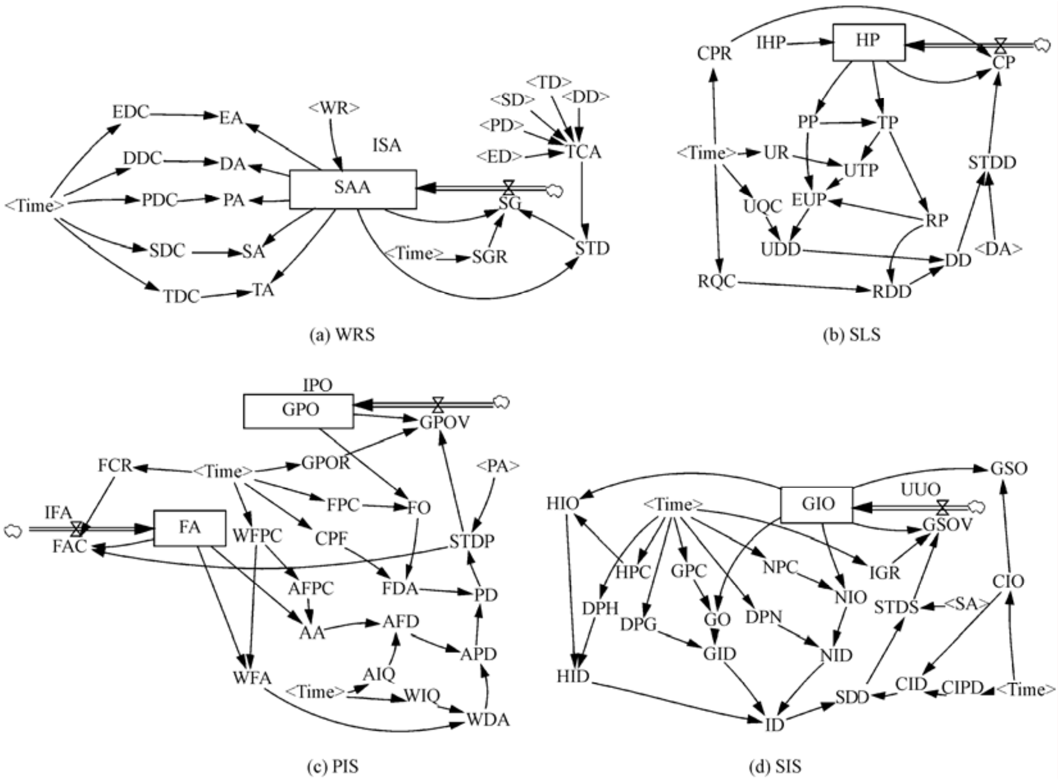

Fig. 1 SD flow chart of Suzhou WRCC

3.2.2 Social life subsystem (SLS)

Based on the available information, registered population was selected as the state variable, and population change was set as the rate variable. The tension degree of the domestic water supply was set as the control variable. Due to the significant impact of the unregistered residents of Suzhou who may have migrated from elsewhere and are still unregistered in Suzhou, water demand of these residents should be accounted for in the total water demand. This study introduces a concept of the equivalent urban population by considering one resident person to be one equivalent urban population. Meanwhile, two unregistered residents were set as one equivalent urban population.

3.2.3 Primary industrial subsystem (PIS)

Primary industry was divided into two parts: (1) agricultural cultivation; and (2) forestry, animal husbandry, and fisheries. Agricultural water demand was mainly reflected by farmland irrigation. With the remarkable reduction and degradation of arable land in recent years, the irrigation water demand kept decreasing in total. However, the water consumption of primary industry was still a large share of the total water consumption. Factors affecting agricultural water consumption included the layout of agricultural production, structure of planting,

Table 1 Variables and their meanings

Variable	Meaning	Unit	Variable	Meaning	Unit
EDC	Coefficient of eco-environmental water distribution	Dimensionless	STDP	Tension degree of primary industrial water supply	Dimensionless
DDC	Coefficient of domestic water distribution	Dimensionless	FCR	Change rate of farmland area	Dimensionless
PDC	Coefficient of primary industrial water distribution	Dimensionless	FPC	Proportional coefficient of forestry, animal husbandry, and fishery output values	Dimensionless
SDC	Coefficient of secondary industrial water distribution	Dimensionless	FO	Forestry, animal husbandry, and fishery output values	10^4 yuan
TDC	Coefficient of tertiary industrial water distribution	Dimensionless	CPF	Water consumption per 10^4 yuan output value for forestry, animal husbandry, and fisheries	10^4 m^3
EA	Available water supply of eco-environment	10^4 m^3	FDA	Water demand for forestry, animal husbandry, and fisheries	10^4 m^3
DA	Available domestic water supply	10^4 m^3	IFA	Initial value of farmland area	km^2
PA	Available water supply for primary industry	10^4 m^3	WFPC	Area proportional coefficient of paddy field	Dimensionless
SA	Available water supply for secondary industry	10^4 m^3	AFPC	Area proportional coefficient of arid farmland	Dimensionless
TA	Available water supply for tertiary industry	10^4 m^3	AFD	Water demand of arid farmland	10^4m^3
WR	Amount of wastewater reuse	10^4 m^3	APD	Water demand of agricultural planting	10^4m^3
SAA	Actual available water supply	10^4 m^3	FAC	Change of farmland area	km^2
STD	Tension degree of water supply	Dimensionless	FA	Farmland area	km^2
ISA	Initial available water supply	10^4 m^3	AA	Arid land area	km^2
TCA	Total water consumption amount	10^4 m^3	AIQ	Total irrigation quota of arid land	10^4 m^3/km^2
SG	Growth of water supply	10^4 m^3	WFA	Paddy field area	10^4 km^2
SGR	Growth rate of water supply	Dimensionless	WIQ	Irrigation quota of paddy field	10^4 m^3/ km^2
PD	Water demand of primary industry	10^4 m^3	WDA	Water demand of paddy field	10^4 m^3
SDD	Water demand of secondary industry	10^4 m^3	DPH	Water demand amount per 10^4 yuan output value by high-water-consumption industry	10^4 m^3
TD	Water demand of tertiary industry	10^4 m^3	HPC	Output value proportional coefficient of high water-consumption industry	Dimensionless
DD	Domestic water demand	10^4 m^3	GIO	Gross industrial output value	10^4 yuan
ED	Eco-environmental water demand	10^4 m^3	IIO	Initial industrial output value	10^4 yuan
IHP	Initial value of registered population	10^4 persons	STDS	Tension degree of secondary industrial water supply	Dimensionless
HP	Registered population	10^4 persons	GSO	Gross secondary industrial output value	10^4 yuan
CP	Change of population	10^4 persons	HIO	High water-consumption industrial output value	10^4 yuan
CPR	Change rate of population	Dimensionless	GPC	Proportional coefficient of general water-consumption industrial output value	Dimensionless
PP	Unregistered population	10^4 persons	NPC	Proportional coefficient of thermal (nuclear) power industrial output value	Dimensionless
TP	Total population	10^4 persons	IGR	Growth rate of industrial output value	Dimensionless
RP	Rural population	10^4 persons	CIO	Construction industrial output value	10^4 yuan
UR	Urbanization rate	Dimensionless	GO	General industrial output value	10^4 yuan
RQC	Quota of rural domestic water consumption	m^3/(person·year)	DPN	Water demand per 10^4 yuan output value of thermal (nuclear) power industry	10^4 m^3
STDD	Tension degree of domestic water supply	Dimensionless	NIO	Industrial output value of thermal (nuclear) power industry	10^4 yuan
UTP	Urban population	10^4 persons	GID	Water demand of general industry	10^4m^3
UQC	Quota of urban domestic water consumption	m^3/(person·year)	NID	Water demand of thermal (nuclear) power industry	10^4 m^3
EUP	Equivalent urban population	10^4 persons	CID	Water demand of construction industry	10^4 m^3
RDD	Rural domestic water demand	10^4 m^3	ID	Water demand of industry	10^4 m^3
UDD	Urban domestic water demand	10^4 m^3	CIPD	Water demand per construction area	m^3/m^2
GPOV	Growth of primary industrial output value	10^4 yuan	HID	Water demand of high water-consumption industry	10^4 m^3
GPOR	Growth rate of primary industrial output value	10^4 yuan	DPG	Water demand per 10^4 yuan output value of general industry	10^4 m^3
IPO	Initial primary industrial output value	10^4 yuan	GSOV	Growth of industrial output value	10^4 yuan
GPO	Gross primary industrial output value	10^4 yuan			

composition of products, effective utilization of channel water, and field irrigation methods and technologies. Thus, the gross primary industrial output value was selected as the state variable, and the change of the gross primary industrial output value was set as the rate variable. Meanwhile, the cultivated land area was also selected as the state variable, and the change of the cultivated land area was set as the rate variable. The growth rate of primary industry was set as the regulation parameter, and the tension degree of the water supply for primary industry was set as the control variable.

3.2.4 Secondary industrial subsystem (SIS)

Secondary industry included the construction industry and other industries. The construction industrial water consumption is related with construction area. The relationship between the construction industrial output value and the construction area was established through analysis of data of past years, and the construction industrial water consumption was calculated based on construction area. The water consumption of other industries may be divided into water consumptions of high water-consumption industry, general industry, and thermal (nuclear) power plant. Industrial water consumption is related not only with the industrial development rate, the production value, the internal industrial structure, the level of industrial technology, the technical process, the rate of water reuse, the rate of sewage treatment, and the degree of water conservation, but also with the regional water supply conditions, the technological conditions, and the management level. The gross industrial output value was selected as the state variable, and its growth was chosen as a rate variable. The growth rate of the industrial output value was chosen as the regulation parameter. The tension degree of the water supply for the SIS was chosen as the control variable.

3.2.5 Tertiary industrial subsystem (TIS)

Tertiary industrial water consumption is mainly water consumption of tertiary industrial employees. The proportion of employees has the same trend as the proportion of tertiary industry, and there is a strong correlation between the two according to a series of data analysis of the tertiary industrial growth value and the population of tertiary industrial employees, so the tertiary industrial employees show more predictability. The tertiary industrial water consumption can be analyzed and calculated according to the tertiary industrial employees. The tertiary industrial growth value was chosen as the state variable, and the growth of the tertiary industrial growth value was chosen as the rate variable. The growth rate of the tertiary industrial growth value was chosen as the regulation parameter. The tension degree of the tertiary industrial water supply was chosen as the control variable.

3.2.6 Eco-environmental water demand subsystem (EWDS)

The eco-environmental water demand was divided into a river's external and internal eco-environmental water demand for the analysis and calculation. A river's external eco-environmental water demand includes water demands for green belt ecology, for road spray, and for forest ecology. A river's internal eco-environmental water demand includes water to maintain the basic functions of the river, to maintain the river ecosystem service functions, and to improve water quality through dilution and self-purification. These three components overlap and enhance each other. The maximum water demand of the three components was selected as the river's internal eco-environmental water demand. According to the characteristics of Suzhou, the river dilution and self-purification of water was set as the environmental functional water demand for study of the river's internal eco-environmental water demand.

The environmental water demand of river self-purification was combined with the river assimilative capacity. According to the systematic and integrated characteristics of water resources, the watershed ecosystem was dealt with as a whole, and a model that coupled water quantity and water quality calculation for the Suzhou river network was established. This model was related to the computational model of water assimilative capacity. Based on the division of the functional area of the river network water body, the water quality target was determined. Combined with a water quantity and quality coupled model, the water assimilation capacity theory and calculation method were used to calculate the water assimilation capacity for different functional areas during different time periods. With the water quality target in environmental functional areas of different rivers, the environmental water demand of river dilution and self-purification was calculated in reverse.

3.2.7 Wastewater treatment and reuse subsystem (WTRS)

Suzhou's wastewater comes from industrial wastewater, domestic sewage, wastewater treatment plant effluent, agricultural runoff, and animal manure wastewater. Water resources pollution can be reduced through wastewater treatment, and the treated wastewater can be graded and used for agricultural irrigation, industrial cooling water, urban landscaping water, and other purposes, so as to effectively increase the available amount of water.

3.3 Model calibration

Prior to using the SD model, it is necessary to conduct effective tests to verify whether the model structure is consistent with the actual system or not. A historical test was used in this study. The historical parameters were input into the model, and the simulated results were compared with actual data to verify their degree of correspondence. Here the historical Suzhou GDP over the time period of 2001 to 2005 was used for calibration, and the results are listed in Table 2. They show that the simulated values were basically consistent with the actual values, with errors of simulated values being less than 5%, thus validating the model.

3.4 Program design and simulated results analysis

In this study the base year was 2000, the first target year was 2010, and long-term target years were 2020 and 2030. Taking into account inter-annual regulation of the water supply, a 75% guarantee degree was set for simulation in this study. According to the investigation of the Suzhou water resources, the Suzhou water supply amount in the base year was 8.4 km^3.

The primary industrial output value, the secondary industrial output value, and the growth value of tertiary industry in the base year were 16.9 billion yuan, 362.1 billion yuan, and 58 billion yuan, respectively. The urban population, including the unregistered population, was 6.8 million.

Table 2 Comparison between simulated and actual values of GDP in Suzhou WRCC-SD model

Year	Actual value (billion yuan)	Simulated value (billion yuan)	Error (%)
2001	176.028	184.613	4.88
2002	208.000	212.335	2.08
2003	280.156	282.119	0.70
2004	345.000	336.904	-2.35
2005	402.652	381.689	-4.71

3.4.1 Design of programs

In this study, three programs were designed to simulate Suzhou WRCC:

(1) Continuity of current water utilization (Plan I): Maintaining the growth trend of the water supply in the current year, based on the 4.14% annual growth rate of the Suzhou water supply from 2000 to 2004, the available water supply does not grow from 2012 to 2030. The population grows according to the growth trend of the current year. The variation of domestic and industrial water demands and water conservation was not considered, and internal structures of various industries remained consistent.

(2) Water conservation/saving (Plan II): On the basis of Plan I, the increasing domestic water demand level and the water conservation/saving of the three industry levels (primary, secondary, and tertiary) were considered. The water demand was reduced by improving scientific and technological levels and regulating the internal structure of industries. Suzhou had the highest potential of water saving in agriculture, textiles, and electrical industries. The Suzhou water planning target is that the water saving potential reaches 1.45 km^3, 30.6 km^3, and 56.2 km^3 in 2010, 2020, and 2030, respectively. The Suzhou water-saving investments in the three periods are 3.96 billion yuan, 10.20 billion yuan, and 22.82 billion yuan, respectively. The average annual investment in all periods is 396 million, 1.02 billion, and 2.28 billion yuan, respectively.

(3) Water exploitation (Plan III): On the basis of Plan II, wastewater reuse was considered. According to the estimation in the *Water Resources Protection Plan* (Zhang 2008), the amount of Suzhou wastewater reuse is 0.25 km^3, 0.59 km^3, and 0.73 km^3 in 2010, 2020, and 2030, respectively. Reused water is used for industrial, agricultural and environmental water consumption according to different distribution coefficients.

3.4.2 Analysis of simulated results

The simulated results show that:

(1) In all three programs, the gross agricultural output value increased over time (Fig. 2(a)). It can be concluded that the growth rates of gross agricultural output values in the three

programs were very close during the time period of 2000 to 2010, and a sudden increase in the slope of the growth curve occurred in 2005. This reflected the gross agricultural output value's more rapid growth after 2005. The accelerated growth must have been due to a continuous reduction and degradation of arable land from 2000 to 2005, as well as the facts that the protection of farmland and control of farmland area attracted attention in 2005 and the trend of irrigation water consumption decreased overall. During the period of 2010 to 2030, Plan I showed slow growth in gross agricultural output value, which did not grow at all after 2020. However, the agricultural water-saving degree increased in Plan II, which caused the gross agricultural output value to increase substantially, reaching 102.6 billion yuan by 2030. This is 1.87 times that of Plan I. Compared with Plan II, Plan III has no significant effects on the growth of the gross agricultural output value because of the low amount of reused water.

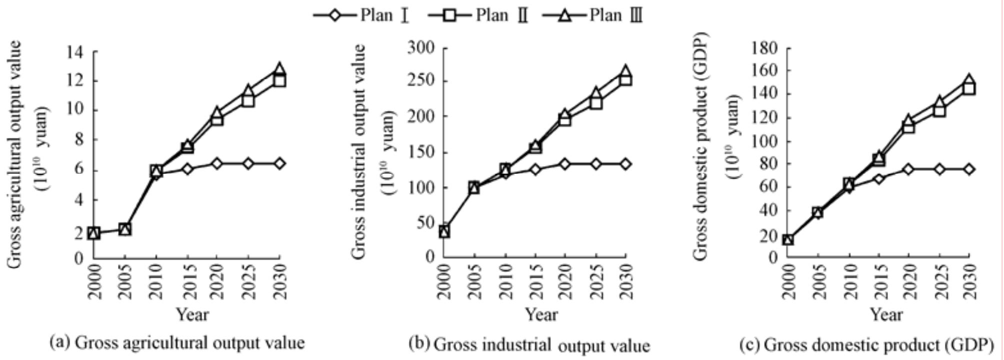

Fig. 2 Results of variables in different programs simulated by Suzhou WRCC-SD model

(2) The gross industrial output values of the three programs showed a trend of growth over time (Fig. 2(b)). From 2000 to 2010, the growth amounts of gross industrial output values in the three programs were very close. By 2010, the gross industrial output value in Plan II was only 1.06 times that of Plan I. After 2010, the gross industrial output value in Plan I grew slowly, and it stopped growing after 2020. However, due to the increased efforts in industrial water-saving in Plan II, low water-consumption industries were developed, which increased the gross industrial output value to 2.5 trillion yuan by 2030. This is twice that of Plan I. Compared with Plan II, Plan III has no significant effects on the growth of the gross industrial output value because of the low amount of reused water, only 1.06 times that of Plan II.

(3) Fig. 2(c) shows that the gross domestic product (GDP) in the three programs grew over time. From 2000 to 2010, the growth of GDP was similar in each of the three programs, between 600 and 620 billion yuan by 2010. Plan I showed slow growth of GDP from 2010 to 2020, and GDP stopped growing from 2020 to 2030. However, in Plan II GDP continued to grow to 1.45 trillion yuan by 2030, which was 1.89 times that of Plan I. Compared with Plan

II, Plan III has no significant effects on GDP growth because of the low amount of reused water, only 1.05 times that of Plan II.

4 Conclusions

Plan I (continuity of current water utilization) has the lowest water resources carrying capacity; various economic indicators of Plan I begin to slow down the growth significantly after 2010 and stop the growth after 2020, so it will be difficult for this program to meet the future socio-economic development demands of Suzhou. In the implementation of Plan II (water conservation/saving), various economic indicators steadily improve, and gross industrial, agricultural output values and GDP reach their maximum values by 2030. As the amount of wastewater reuse is low, Plan III (water exploitation) has less growth in various economic indicators than Plan II. It is concluded that the water conservation/saving program has significant impacts on Suzhou water resources carrying capacity. In the case of a shortage of water resources, water conservation/saving is an effective approach to raising the Suzhou water resources carrying capacity.

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