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Water resources carrying capacity of wetlands in Beijing: Analysis of policy optimization for urban wetland water resources management

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ABSTRACT

Based on analysis of the wetland water resources system in Beijing city, this paper established a system dynamics (SD) model for the water resources carrying capacity (WRCC) in Beijing city. Using a computer simulation of the SD model, the variation trends from 2006 to 2030 in population, economy, water supply and demand, and pressure on the water environment were derived for Beijing, from which 12 core variables of the model were chosen as the WRCC evaluation indices. Five cases were designed in this study. The results indicate that the WRCC will continue to decline annually by following the status quo (Case 1), since the water environment will have difficulty in supporting the long-term social and economic development of Beijing. The status quo of Beijing's socioeconomic development is therefore not sustainable. In order to address this problem, five optimization cases were put forward to improve the WRCC, and the carrying capacities and trends of the cases were compared and analyzed. Under Case 5, the WRCC (0.8 in 2030) will increase by 50%, compared to that in Case 1 (0.4 in 2030), while the water supply and demand ratio will be 20% higher than the average, and the water pollution will be 35% lower than the average in 2030. According to the analysis results, in order to guarantee sustainable utilization of water resources and social economy development in Beijing, it is necessary to increase water saving policies and pollution control investment in the future. Corresponding measures will need to be taken to ensure the implementation of water saving strategies to improve the water environment.

1. Introduction

Wetland resources are some of the fastest disappearing greenspaces during urbanization processes (Li et al., 2016; Zeng et al., 2016). Urban wetlands are mostly damaged in these wetland ecosystems (Hettiarachchi et al., 2014). Many human living resources are provided by wetlands, but people neglect their ecological capacity while simultaneously pursuing high urbanization rates (Morin et al., 2014). Large amounts of urban wetlands are encroached upon during urbanization (Wentzell et al., 2016; Ho and Richardson, 2013). The water quality of urban wetlands has been in steady decline because of massive industrial and domestic wastewater disposal. The living environment of citizens has been severely threatened, which has led people to gradually realize the significance of preserving urban wetlands. Wetland degradation gives rise to the hidden dangers of flooding, water pollution, and environmental deterioration, along with a bottleneck effect in economic development. These are all common issues that arise during the urbanization process worldwide. Among them, wetland preservation may not seem the most important, yet properly managed wetlands can alleviate all of these problems, providing comprehensive sustainable development for an entire city (Ibarra et al., 2013). In China, urban wetlands experience the problems of area reduction, functional decline, severe pollution, and especially acute eutrophication, all as a consequence of excessive human activity (Sun et al., 2016; Yin and Yang, 2013). However, the conservation of urban wetlands is faced with many difficulties mainly a lack of research, the cognitive dissonance between their functions and value in society, and a high opportunity cost to preserve them. It is therefore essential to choose the path of protecting and restoring urban wetlands during development of modern cities (Doherty and Zedler, 2014). Urban wetland restoration has been highly valued by governments and scientists from different

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countries. We need to fully understand the ecological capacity of urban wetlands, combining rational utilization with preservation, to in turn prompt their sustainable development (Hettiarachchi et al., 2015; Lane et al., 2014; Wang et al., 2014a). These are the perspectives explored in this study and reasons to conduct the research.

Many researchers from different fields have conducted research on ecological capacity by adopting a variety of methods. As water resources are significant for socioeconomic development, assessment of their ecological capacity has always been a highlight in this field. Rees (1992) introduced the Ecological Footprint (EF), and Wackernagel and Rees (1997) later improved on this calculation method and calculated the ecological capacity of Italy. Since then, the EF has been a major method in ecological capacity research and application because of its explicit definition, simplicity, and wide applicability (David et al., 2015; Manzardo et al., 2016; Nakajima and Ortega, 2016; Wang and Xu, 2015; Verhofstadt et al., 2016). Other scientists like Hoekstra and Chapagain (2007) developed a water footprint that incorporates virtual water based on the EF model. They also established an ecological footprint model for regional water resources, a calculation model for ecological capacity, and an evaluation model for the level of ecological deficit and pressure. Their scheme divided water resources into ecological water, living water, and production water. The study of carrying capacity on water resources involves the study of population resources, socioeconomic systems, and natural ecosystems. It is a large-scale, multi-objective, and multi-layer optimization problem. Therefore, research employing this framework has often adopted multi-target or multi-objective analysis (Lia et al., 2014; Martire et al., 2015; Yin et al., 2014; Yu et al., 2016; Xu et al., 2011; Zhi et al., 2015; Wang et al., 2016).

In many previous studies, an indicator system was determined and an analysis model established based on a full analysis of issues related to the water resources capacity, followed by quantitative analysis using different evaluation approaches (Pandeya et al., 2011). Prato (2009) used fuzzy comprehensive evaluation to study the social ecological capacity in reserves. Altunkaynak and Sen (2007) evaluated the dynamical changes in a lake level using the fuzzy approach, and showed that lower absolute errors are obtained with the Takagi-Sugeno fuzzy approach than with the autoregressive and moving average (ARMA) model. Rajaram and Das (2011) applied the concept of ecological capacity to environmental impact assessment (EIA) for ecological monitoring, and found that the Indian system excludes many screening activities, when compared to Europe (EU). Cuadra and Björklund (2007) used energy analysis and EF approaches to analyze the economic returns of six crops in Nicaragua. Graymore et al. (2010) proposed a novel concept and calculation method for a sustainable human carrying capacity (SHCC), and conducted empirical research. Liu and Borthwick (2011) used a comprehensive evaluation method to study the capacity of the environment, and introduced the concept of excess rate to the study of ecological capacity. Lane (2010) adopted a variety of established ecological capacity assessment methods in spatial planning studies and compared the results of the evaluation. In conclusion, for the theory study of the regional WRCC, individual research outcomes are relatively rich in the world, the most of them have been included in the theory of sustainable development. The research started late on WRCC in China, according to the regional, basin characteristics and social and economic development, following the aspect of sustainable development, using the theory and knowledge of related disciplines, applying innovation or existing methods, which are to solve the problems of WRCC. So far, the researches of WRCC are still not formed a systematic and scientific theoretical system.

Khanna et al. (1999) introduced a neural network method and spatial database technology to the calculation of ecological capacity. Slessor and Lewis (1979) proposed the ECCO model, which adopted the method of system dynamics, taking the relationships between population, resources, environment, and development into account. The model could simulate dynamic differences between demographic changes and ecosystem capacity with different development strategies (Byron et al., 2011a, 2011b; Karstensa et al., 2016; Kluger et al., 2016; Pandeya et al., 2011; Papageorgiou and Brotherton, 1999; Wang et al., 2014b; Wang and Xu, 2015).

The phrase water resources carrying capacity (WRCC) was put forward based on a profound understanding of the mutual relationships between social sustainable development and water resources. Moreover, WRCC is used as a criterion to judge whether the social economy coordinates with water environmental systems, and plays a crucial role in the comprehensive development of a country or region, as well as its development scale (De la Sen and Alonso-Quesada, 2009). At present, most international WRCC research—which has come dominantly from China—can be integrated into sustainable development (Dang and Liu, 2012; Dou et al., 2015; Wang et al., 2014a; Li et al., 2016; Ren et al., 2016; Zhang et al., 2015). However, due to the complexity of water environmental systems and the diversity of influencing factors, it is difficult to study WRCC. So far, a unified research method has not been established and agreed upon. The primary WRCC evaluation methods are comprehensive index systems, multi-objective model analysis, system dynamics, and artificial neural networks. Among them, the method of system dynamics, a kind of computer simulation technology, is able to observe the internal dynamic features of WRCC globally and analyze effects of policy changes on the WRCC development trend. In turn, the model can address the nonlinear, uncertain, and dynamic characteristics of WRCC. In addition, multi-objective programming is a branch of mathematical programming that focuses on the optimization of more than one objective function within a given space, and is also known as multi-objective optimization. Research on how to combine models of system dynamics and multi-objective programming to analyze the carrying capacities of a population with its available resources and environment is challenging.

This paper is based on theories from many researchers. The present research focuses on the urban wetlands in Beijing, with a target to achieve sustainable development. The study was designed to scientifically evaluate the WRCC in Beijing by establishing a SD model, thus providing technical support to the scientific operation and offering a scientific basis for the restoration of urban wetlands.

The contributions of this paper include:

(1) Establish a SD model for WRCC in urban wetlands in Beijing and calculate the WRCC under different modes;
(2) Simulate the change of WRCC in urban wetlands in Beijing under different circumstances, which include indices such as water consumption by agricultural production, industrial production, and tertiary industry; total water demand; supply-demand ratio of water resources; general COD emissions; and an index of pressure on the water environment; and
(3) Provide optimization strategies for urban wetland water resources in Beijing city in the future.

2. Study area

As an international metropolis, Beijing is a severely water-scarce city. The urban wetlands ecosystem plays an extremely important role in maintaining the balance of the natural ecosystem and safeguarding the security of urban ecology in Beijing. However, for a long time, the wetland has been regarded as worthless wasteland or reserved arable land, which leads to blind exploitation and utilization of wetland resources. The area of urban wetland decreases annually (Niu et al., 2011). At present, the total wetland area in Beijing is 51,400 ha, accounting for 3.13% of land area in the city. Of this area, 23,800 ha are natural wetlands, such as rivers and swamps, accounting for 46.4%; and 27,600 ha are artificial wetlands, such as water storage areas, reservoirs, irrigation ditches, and paddy fields, accounting for 53.6%. Lakes in various sizes are scattered in the metro, suburbs, and exurbs of Beijing, and make a difference in the city ecosystem.

In this study, Beijing wetland water resources are considered important, since 90% of the water in Beijing is provided by wetlands (rivers, lakes, reservoirs, etc.). Five major river systems run through Beijing from west to east: the Juma River, Yongding River, North Canal, Chaobai River, and Jiyun River. There are also 85 reservoirs in Beijing, including the large Miyun, Guanting, Huairou, and Hai Zi Reservoirs. For many years, the average groundwater capacity has been about 29.21 billion cubic meters, with an average of about 24–25 billion cubic meters that can be extracted annually. The average annual total of disposable natural water resources is 5.521 billion cubic meters. In 2013, the total water consumption in Beijing was 3.53 billion cubic meters, up by 1.4% over the previous year. Among them, domestic water-consumption was about 1.45 billion cubic meters, an increase of 4.3%; industrial water was 560 million cubic meters, down by 3.4%; and agricultural water was 1.2 billion cubic meters, down by 3.2%. Beijing's total annual water resources are only 2.1 billion cubic meters, with a deficit of 1.5 billion cubic meters, less than 100 cubic meters per capita. The national average is 2000 cubic meters per capita, meaning Beijing has the highest per capita water demand in the second smallest mainland provinces of China.

Wetland water resources in Beijing are highly developed and utilized. Over time, they have been used for urban drinking water, industrial consumption water, agricultural cultivation and irrigation, and landscaping. However, with the intensification of urbanization in Beijing, the urban wetlands were developed and utilized, followed by serious ecological damage, such as eutrophication, water pollution, and lake atrophy. The wetland WRCC is currently seriously overdrawn, and if not repaired soon, its ecological capacity will be rapidly weakened. Due to all of these reasons, it is of great practical significance to study the WRCC of Beijing urban wetlands and to optimize the allocation of water resources.

3. Data resources and analysis methods

3.1. Data resources

The main sources of data in this paper are from two places: the Beijing Statistical Yearbook (2006–2014), and the Beijing Municipal Water Resources Bureau (2006–2014) that was published by Beijing Water-affair Authority. In addition, some information was also collected from the official website of the Beijing water authority (http://www.bjwater.gov.cn).

3.2. Analysis methods

3.2.1. System dynamics model for the WRCC of Beijing wetlands

System dynamics can be employed to simulate not only microscale business systems, but also macroscale social and economic systems to deal with systematic problems that are high-step, nonlinear, multi-feedback, complex, and time varying. Based on the structure and function simulation of the urban wetland water resources system in Beijing, a SD model of WRCC was established using the Vensim system dynamics modeling tool (Fig. 1). Based on the original operation and sensitivity analysis, sensitive factors of the development of water resources allocation were identified. A complete urban wetland ecosystem includes not only wetland resources and environmental systems, but also the human population and socioeconomic systems, which are important in the complex wetland ecosystems (Morin et al., 2014; Liu and Borthwick, 2011). In this paper, the system was divided into four subsystems: population, socioeconomic, pollution, and wetland water supply. The population subsystem addressed the relationships of total, urban, and rural populations with water consumption. The economic subsystem addressed the relationships of water consumption with agricultural, industrial, and tertiary industry production. The pollution subsystem addressed the relationships between sewage treatment, wastewater discharge, and water pollution, as well as the link between pollutant emissions and water environment capacity. The wetlands water resources subsystem assessed the relationship between the total supply and total demand of wetland water resources.

At present, the shortage of wetland water resources in Beijing has been a major factor restricting economic and social development. In order to promote the coordinated development of water resources and the economy, it is necessary to fundamentally improve WRCC. According to “the 13th Five-Year Plan for National Economic and Social Development of Beijing” and “Beijing Water Development Plan during the 13th Five-Year Period,” as well as other related policies and plans, we need to understand the connotations and characteristics of WRCC and select decision variables based on the principle of rational adjustment. As a result, a variety of cases (Appendix A and Table 1) were designed to simulate how the limited water resources in Beijing could be scientifically and rationally used, and the balance between water supply and demand could be restored and maintained.

Case 1: Zero Scheme – That is, nothing would be done, the existing development model would be maintained, and the program decision variables in the index value would still follow the existing development trend (indices that exceed the threshold would be given a specific value).

Case 2: A Single Industrial Structure Adjustment Program (Reducing Water Demand) – Water resources are the most important resources to support development of China's three major industries. Rational industrial structure layout is the basis of sustainable utilization of water resources. The SD model of WRCC would be optimized by adjusting agricultural irrigation area, industrial GDP growth rate, and the growth rate in GDP of tertiary industries. The other decision variables remained the same as in Case 1.

Case 3: A Single Water-saving Option (Reducing Water Demand) – Water saving is an important link to improve the WRCC. At present, water use efficiency and application of water-saving technologies are relatively low in Beijing. There are still large possibilities for saving water in domestic water use, agricultural irrigation water, and industrial production water. As a result, in Case 3, the WRCC was optimized mainly through an adjustment of the per capita water consumption in urban and rural areas, the number of large and small livestock, industrial water consumption, and tertiary industry water consumption. The other decision variables remained the same as in Case 1.

Case 4: A Single Pollution Control Scheme (Increasing Water Supply) – The water supply capacity of wetlands could be increased through the reuse of sewage and wastewater. The pollution control scheme would also increase the sewage treatment rate, reclaimed water reuse rate, and industrial water-recycling rate. Among them, the sewage treatment rate in Beijing in 2013 was 84.6%, by 2025, the rate will not be less than 90%, and by 2030, all sewage will be treated. The other decision variables remained the same as in Case

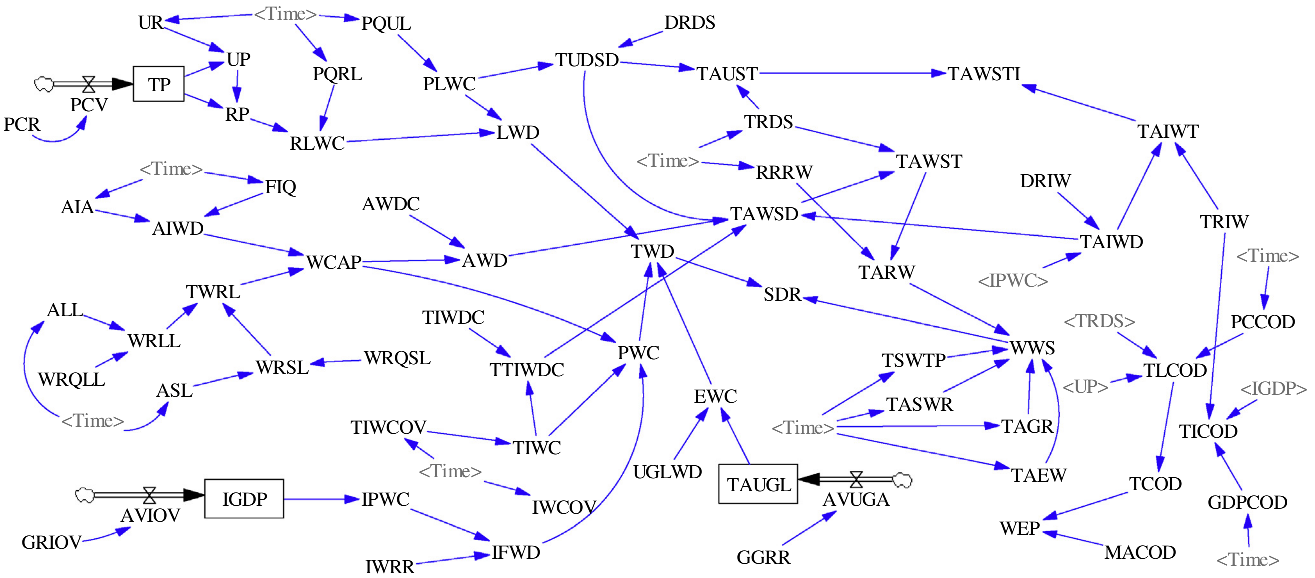

Fig. 1. SD model of Beijing wetland water resources.

1.

Case 5: Comprehensive Solution – The water supply guarantee rate of Beijing was maintained at 35 to 50 billion cubic meters, and Cases 2, 3, and 4 were considered together to further optimize the decision variables of the system dynamics model to simulate the change trends and the improvement of WRCC in Beijing city.

3.2.2. Evaluation method for the WRCC of wetlands in Beijing city

This research selected 5 variables that are closely related to water resources and the water environment, and were used as research indicators for the WRCC. The specific indicators chosen were the total population, industrial GDP, the tertiary industrial GDP, water resources supply and demand ratio, and COD emissions. In order to compare the various components with differing dimensions, the components were normalized (Wang et al., 2013) and the WRCC was calculated by Formula 1:

$$\left|\overline{E_j}\right| = \sqrt{\sum_{i=1}^{n}\left(\omega_i\overline{E_{ij}}\right)^2} \tag{1}$$

where $\left|\overline{E_j}\right|$ is the wetland WRCC index; ω_i is as the ith weight for the index; and $\overline{E_{ij}}$ is the ith index for the WRCC. Calculated weights of the total population, industrial GDP, tertiary industrial GDP, water supply and demand ratio, and COD emissions were 0.3888, 0.2453, 0.1944, 0.1443, 0.0272.

3.3. Main equation of the SD model

The whole model was divided into water resources, economic, social, and environmental subsystems. Each subsystem variable interacts to form a causal structure with multiple feedbacks (Fig. 1). Based on the area of Beijing from 2006 to 2013, a SD model of WRCC was established and consisted of nine state variables, ten rate variables, seventy-four auxiliary variables and constants, and ninety-three system dynamics equations (Appendix B).

3.4. Boundary conditions of the model

In order to facilitate the study, the administrative divisions of Beijing, that is, all subordinate counties in Beijing, were used as the spatial scale boundaries in the model. The simulation time was from 2006 to 2030, divided into two stages. The first stage was from 2006 to 2025, the second stage was from 2026 to 2030, and two time nodes were 2025 and 2030, the simulation base year was 2006, and the simulation time step was one year.

4. Results

4.1. Error test

According to standard modeling procedures, a model should be run before performing a comprehensive error test of its structure and function to ensure the validity and authenticity of the model. The error test takes the initial beginning point of the simulation, and then tests the existing historical data against the simulation results for error, correlation, and other factors. The following contains only the historical data validity test, according to the total population, agricultural production water consumption, domestic water consumption, industrial production water consumption, total water supply, and total COD emissions. Table 2 shows that the relative error of each index in the model was within ±10%, so that the simulation results of the model were well matched with the actual situation, indicating that the model reflects the complex Beijing wetland water resources and socioeconomic system.

4.2. Sensitivity test

Due to incomplete social data, the system dynamics must consider the effect of parameter changes on the model behavior through a system parameter sensitivity test. If changes in the data used in the model equations bring about changes in the model structure or behavior, then the model is sensitive to the data. On the other hand, if changes in the data used does not change (or causes a less obvious change) in the model structure or behavior, then the model is insensitive to changes of these data.

This research focused on constant parameters for the sensitivity analysis, and examined the sensitivity of 7 variables (representing the population, social and economic development, and water resources demand systems) to changes in 13 parameters to assess the

Table 2
Error test result of the SD model.

Time	TP (10,000 Capita)			agricultural production water consumption (10^9 m^3)			domestic water consumption (10^9 m^3)		
	Observed	Stimulated	Error (%)	Observed	Stimulated	Error (%)	Observed	Stimulated	Error (%)
2006	1610	1610	0	12.8	12.7	−0.78	13.7	13.3	−2.92
2007	1676	1682	0.35	12.4	12.3	−0.81	13.9	13.8	−0.719
2008	1771	1757.22	−0.78	12	11.9	−0.83	14.7	14.2	−3.40
2009	1860	1835.8	−1.30	12	11.9	−0.83	14.7	14.8	0.68
2010	1961	1917.9	−2.19	11.4	11.4	0	14.8	15.4	4.05
2011	2018	2003.67	0.71	10.9	10.8	−0.93	15.6	15.6	0
2012	2069	2093.28	1.17	9.3	9.2	−1.08	16.0	16.2	1.25
2013	2114	2186.89	3.45	9.1	8.3	−8.79	16.2	16.8	3.70

Time	**Industrial production water consumption (10^9 m^3)**			**Total water supply (10^9 m^3)**			**Total COD emission (10^4 t)**		
	Observed	**Stimulated**	**Error (%)**	**Observed**	**Stimulated**	**Error (%)**	**Observed**	**Stimulated**	**Error (%)**
2006	6.2	6.2	0	34.3	37.6	9.62	109,866	99,604	−0.09
2007	5.8	5.4	−6.89	34.8	38.3	10.05	106,500	104,187	−0.02
2008	5.2	5.3	1.92	35.1	36.0	2.56	101,266	104,303	0.05
2009	5.2	5.4	3.85	35.5	37.2	4.78	98,856	103,427	−0.08
2010	5.1	4.8	−5.89	35.2	36.4	3.41	91,997	84,248	−0.08
2011	5.0	4.7	−6.00	36.0	37.9	5.28	193,184	177,509	−0.08
2012	4.9	4.9	0	35.9	37.2	3.62	186,501	172,464	−0.08
2013	5.1	5.0	−1.96	36.4	37.7	3.57	178,475	166,533	−0.06

effects of these parameters on the system.

Test method: Each parameter was changed 10% annually from 2006 to 2030, and the effects on the 7 variables were tested. According to Liu and Shao (2015), each state variable has seven sensitivity values for 13 parameter changes, and the average degree of sensitivity represents a specific variable for a particular parameter. This research calculated an average sensitivity for 7 variables using Formulas 2 and 3.

$$S_d = \left| \frac{\Delta Q_{(t)}}{Q_{(t)}} \times \frac{X_{(t)}}{\Delta X_{(t)}} \right| \tag{2}$$

$$S = \frac{1}{n} \times \sum_{i=1}^{n} S_{d(i)} \tag{3}$$

where t is time, $Q_{(t)}$ is the value of the state variable Q at time t, $X_{(t)}$ is the value of the parameter X at time t, S_d is the sensitive degree for state variable Q to parameters X, $Q_{(t)}$ and $X_{(t)}$ are growth values for the state variable Q and parameter X at time t, respectively.

When the state variable Q is Q_1 to Qn (Q_1, Q_2, …, Q_n), the mean value of the sensitivity can be expressed using Formula 3, where n indicates the number of state variables, $S_{d(i)}$ is the sensitivity degree for state variable $Q_{(i)}$ to the parameters X, and S represents the average sensitivity.

Table 3 shows that the sensitivity values for the population change rate, growth rate of industrial output value, and growth rate of tertiary industrial output value were higher than 10%, while the others were less than 10%. The model was thus not sensitive to changes in the SD system for most parameters. According to the error test results and sensitivity analysis, the validity of the SD model was good, which implies that the model structure is robust.

4.3. Simulation results under different cases for wetland water resources, water environment, and the social economy

4.3.1. Total water demand

Fig. 2 shows that the water consumption in Case 1 (no intervention policy) became increasingly larger, and that the total water demand would reach 1 × 10^{11} m^3 by 2030, which is far higher than the water supply capacity of Beijing wetland resources. Therefore, intervention policies are needed to reduce water demand. Cases 3 and 5 could significantly reduce the total water demand in Beijing to 5 × 10^{10} m^3 or less, and were the most suitable approaches for

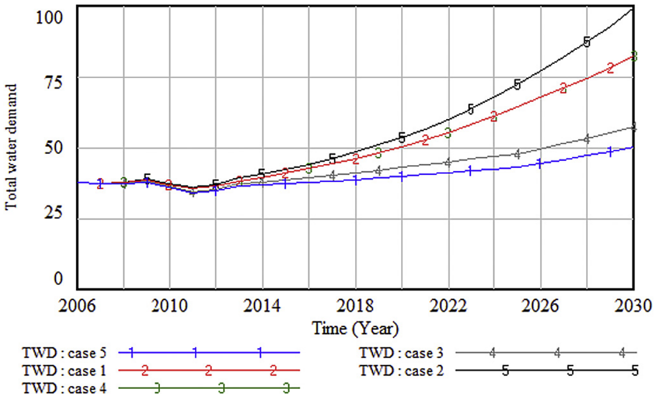

Fig. 2. Simulated total water demand (Unit: 10^9 m^3).

Table 3
The sensitivity test results for constants used in the SD model; the full names of the parameter abbreviations can been found in Appendix B.

Parameter	PCR	UR	PQUL	WRQLL	GRIOV	GRTIOV	FIQ	DRIW	UGGR	RRRW	TRDS	CODGDP	PCCOD
2025	0.05	0.02	0.004	0.0001	0.20	0.25	0.05	0.07	0.03	0.04	0.02	0.19	0.007
2030	0.07	0.01	0.003	0.0001	0.20	0.25	0.04	0.05	0.03	0.03	0.01	0.18	0.003

wetland water resources management in Beijing. In other words, a simple industrial structure adjustment or a simple pollution control policy cannot effectively solve the problem of water demand in Beijing city alone.

Wetland water demand was mainly concentrated in water production, domestic water, and ecological water. In the current situation, domestic water consumption and production account for about 80% of the water demand (Figs. 3 and 4). From Case 1, it is apparent that the water consumption and water supply will be increasing, while the supply and demand ratio will continue to shrink, thus increasing the degree of shortages in water resources. Regarding water demand, a substantial increase in the population and an annual increase in GDP will lead to an increase in the domestic water consumption from 1.323 × 10^{10} m^3 in 2006 to 3.087 × 10^9 m^3 in 2030. A substantial increase in industrial output will also compel an increase in industrial water consumption.

From Case 2, an adjustment to the production structure could cause an increase in water demand. While Beijing's urbanization rate is expected to increase between 2013 and 2030, reductions in livestock (from 140,000 to 10,000), the number of small livestock (from 25.24 million to 5 million), and farmland effective irrigation area (from 154,400 ha to 60,000 ha) are expected, while the industrial GDP growth rate is expected to increase (from 8 percent to 12 percent), along with GDP of tertiary industry (from 15% to 12%). Although water consumption by agricultural production was greatly reduced in this scenario, the continuous increase in GDP barred effective reduction in water consumption by industry and tertiary industry. Therefore, the water supply could not adapt to the social and economic development of Beijing in Case 2.

With the development of society, industrial technology has improved and the natural development of industrial water saving has been promoted. The water quota for the output value of 10,000 Yuan has been reduced, and the water consumption for a given industrial production value has been reduced annually (from 30 m^3 in 2006 to 17.581 m^3 in 2030), to reduce the industrial water demand. In addition, the development of Beijing as an ecological city will increase the area of urban grassland and woodland annually. The remediation and expansion of lakes and rivers will require significant amounts of water resources. In either case, with an increase in green and wetland areas, eco-environmental water demand will increase significantly (from 2.12 × 10^8 m^3 for 2013 to 8.75 × 10^8 m^3 for 2030) (Fig. 5), in line with the future needs of urban development in Beijing. Overall, only Case 5 is capable of keeping the demand for water resources below 5 × 10^{10} m^3 and achieving sustainable and stable development.

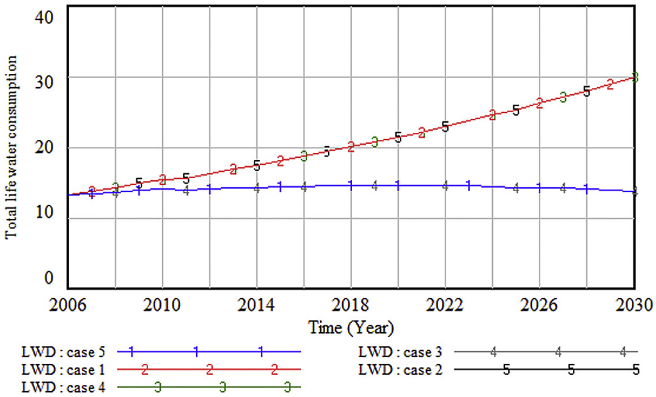

Fig. 3. Simulated total domestic water consumption (Unit: 10^9 m^3).

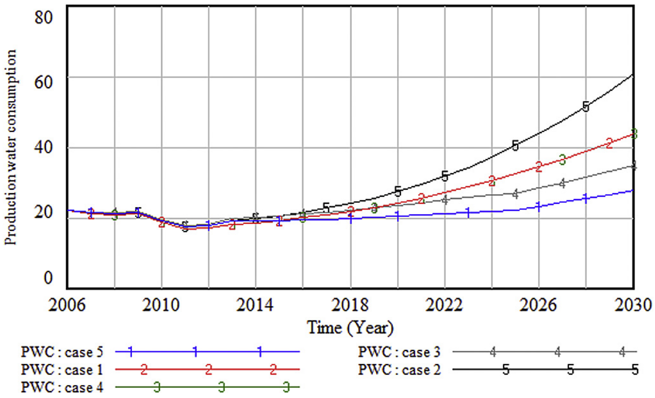

Fig. 4. Simulated total production water consumption (Unit: 10^9 m^3).

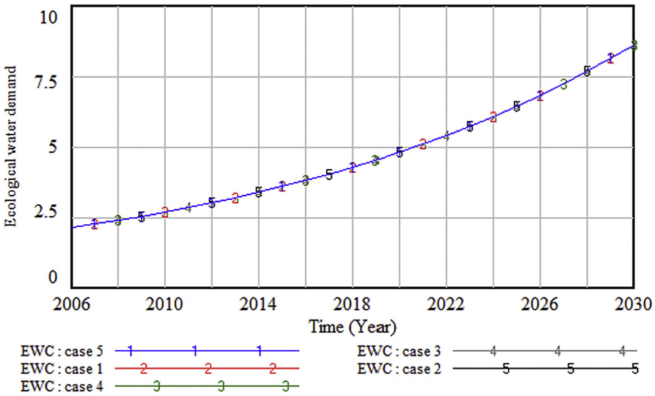

Fig. 5. Simulated total ecological water demand (Unit: 10^9 m^3).

Based on analysis of the five cases, we conclude that Case 5 would improve the WRCC in Beijing. In 2030, water consumption per unit of industrial GDP would be 40 m^3/million Yuan and the industrial water reuse rate would remain at 90%. The industrial water consumption was predicted to be 4.61 × 10^9 m^3. Water consumption by agriculture was predicted to be 1.073 × 10^9 m^3. The proportion of water savings would increase to 80%, and the water supply and demand would be essentially balanced. The sewage treatment rate would be 90% or more, with a sewage discharge quantity of 2.21 × 10^{10} t, an increase of only 4.36% over Case 1. The discharge of industrial wastewater decreased by 59.49% compared with Case 1. As the urbanization rate and the ratio of intensive livestock and poultry increased, the life COD emissions were 1.9 × 10^5 t, 150% lower than that for Case 1 in 2030, so that the COD pollution would be significantly reduced. The industrial COD emissions were 59.89% lower than were those for Case 1. From all of the above numbers, we could see that water environment pollution was effectively controlled in Case 5.

4.3.2. *Total wetland water supply*

The wetland water resources in Beijing mainly came from surface water recharge, groundwater recharge, water and stock emergency water, and reclaimed water (Fig. 6). Due to regional limitations and Beijing's economic development, the city is very short on water resources. Beijing water resources are mainly from groundwater, South to north water transfer project (SNWTP), surface water (SW), ground water (GW), emergency water (EW), and reclaimed water (RW) (Fig. 6). In 2014, Beijing city's total water supply was 3.75 billion cubic meters, which was more than 3.64

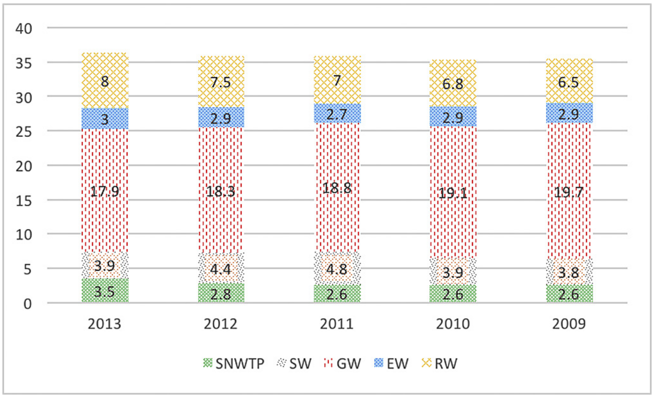

Fig. 6. Water supply sources in Beijing city (Unit: 10^9 m^3).

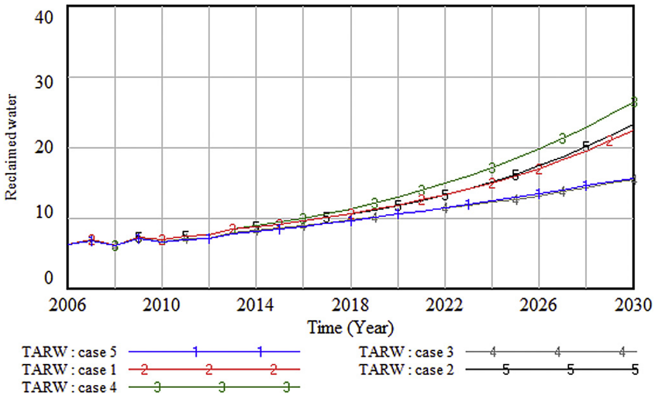

Fig. 8. Simulated total reclaimed water (Unit: 10^9 m^3).

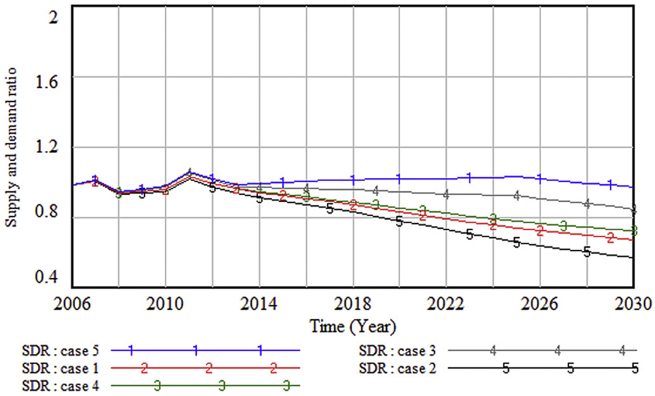

Fig. 9. Simulated the ratio of supply and demand.

billion cubic meters in 2013. The amount of SW, GW,RW, and SNWTP were respectively 0.85 billion cubic meters, 1.96 billion cubic meters, 0.86 billion cubic meters and 0.85 billion cubic meters. The proportion of total water supply were 23%, 52%, 23%, and 23% respectively. Limited SW, GW, and EW cannot significantly increase the water supply.

With regard to water supply, the annual rate of change in surface water and groundwater resources in Beijing is very small. With continuous improvement of the water supply in Beijing, surface water and groundwater supplies would increase continuously. However, due to the limited water resources of the city, the water supply could not possibly grow from 3.751×10^{10} m^3 in 2006 to 9.988×10^{10} m^3 in 2030 (as would be required in Case 1). At present, the growth of Beijing's water supply is less than the annual demand for water, so there is a shortage of water every year, and the degree of the water shortage will continue to increase annually (from 1.659×10^{10} m^3 in 2005 to 4.612×10^{10} m^3 in 2030).

Therefore, we must take measures to improve the water resource supply. An increase in the total wetland water supply would mainly depend on water from the south-north transfer project and reclaimed water. Fig. 7 reveals that each case could increase the total wetland water supply. The water supply growth rate in Case 3 was the smallest. According Case 4, with more pollution control policies, the same as reclaimed water (Fig. 8), a substantial growth would occur in the total wetlands water supply.

The water supply and demand ratio directly reflects the shortage of water resources in Beijing city. From Fig. 9, it can be seen that Cases 1, 2, and 4 cannot meet the social and economic development needs, and that the water supply cannot meet the water resources demand. The water supply and demand ratios in Cases 3 and 5 markedly improved. By 2030, the ratios of water supply and demand from the water saving cases would have increased greatly, with an average increase of about 16 percentage points. Therefore, Case 5 is the optimal choice for alleviating the shortage of water resources in Beijing city.

4.3.3. Total COD emissions

A good water environment is the foundation for ensuring healthy development in urban economies. The total COD emissions

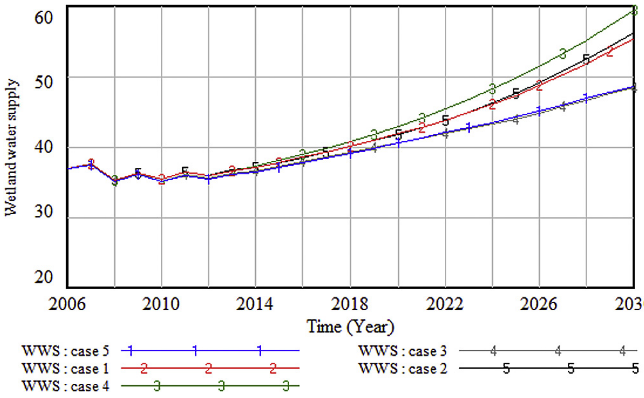

Fig. 7. Simulated total wetland water supply (Unit: 10^9 m^3).

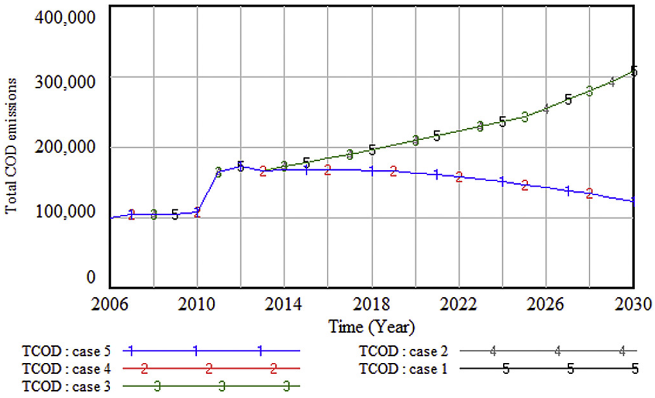

Fig. 10. Simulated total COD emissions (Unit: t).

include the life COD emissions and industrial COD emissions. Fig. 10 shows that Case 1 would directly lead to an increase in the total amount of COD, and an intervention policy must be added to ensure the health of social, economic, and environmental systems. Case 5 was a collection of many intervention policies. With the national scientific and technological level and the improvement in quality of life, the total COD emissions would decrease, from 1.7 × l0^5 t in 2013 to 1.2 × l0^5 t in 2030. Similarly, the pressure of the water environment decreased with a decrease in the COD discharge. By 2030, the water environmental stress index (Beijing water quality COD standard set to 40 mg/L) reduced from 8.8% in 2013 to 2.4%, and had no significant impact on the ecological environment.

4.3.4. Comprehensive WRCC of wetlands in Beijing city

According to Formula 1, this study calculated WRCC using the Case 1 development model and the optimal Case 5 (Fig. 11). According to the development of Case 1, the wetland WRCC in Beijing city will be reducing continuously from 0.9 in 2006 to 0.4 in 2030, and the population, economic, and social development in Beijing city will face very difficult circumstances. According to Case 5, and if the model of socioeconomic development could be improved (including improving water efficiency, increasing water conservation ability, and strengthening pollution control measures), the WRCC would decrease from 2006 to 2015. However, after 2016, the WRCC would gradually rise to more than 0.8 in 2030, indicating a sustainable development of society and economy.

5. Discussion

5.1. Comparison between case 1 and other cases

Using Case 1 as a base, single industrial structural adjustment policies were added in Case 2. In this program, the growth rate of secondary industry was significantly reduced, and water consumption was reduced accordingly. After the GDP growth rate of tertiary industry increased, the proportion of this industry steadily improved, and since the water supply was guaranteed, the position of industry in the national economy was ensured. In this scheme, the water demand was less than that in Case 1, the supply and demand of water resources correspondingly improved, and the emission of pollutants (COD) decreased. This scheme played a minimal role in improving the WRCC in Beijing.

Using Case 1 as a base, Case 3 strengthened the water-saving measures and used a water diversion project to adjust the balance of water supply and demand. The water saving plan focused primarily on domestic and industrial water, while the ecological water did not have a big adjustment, and the domestic and industrial water use and savings were the same as in Case 1. Moreover, the South-North Water Transfer Project (SNWTP) was mainly to meet water needs and used external water as little as possible. Table 1 shows that through water-saving measures and the implementation of SNWTP, water resources in Beijing could meet all needs, with a water surplus in every year. Meanwhile, the water transfer could be adjusted according to the needs of each year, minimizing water resource use and waste of funds. From the simulation results for Case 3, the annual SNWTP supply rates were about 52%, and water transfer was greater than 2.6 × l0^9 m^3 in 2009, accounting for about 10% of the total water supply. This shows that a single water-saving policy could largely reduce water demand, but at the same time would not improve the water supply and demand ratio, that is, water supply and demand did not achieve equilibrium.

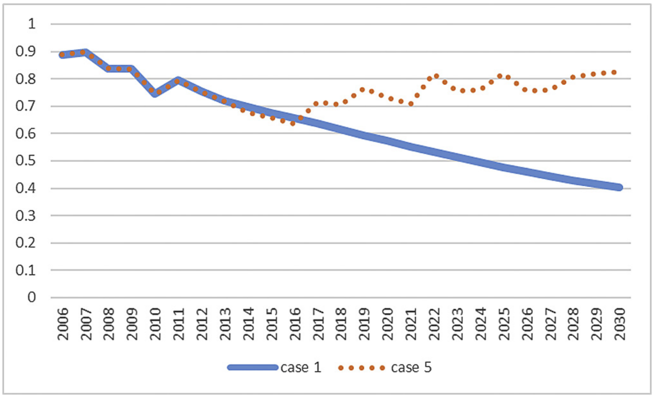

Fig. 11. Comparison of the comprehensive water resources carrying capacity of wetlands between Case 1 and Case 5 in Beijing city.

Using Case 1 as a base, Case 4 improved the sewage treatment rate, the utilization rate of recycled water, and the industrial water repetition rate, which stems from a regulation program aimed at controlling pollution. That is, Case 4 looks to solve water demand from the perspective of the supply of water resources. The main method was to improve the treatment rate of life and industrial sewage to achieve a reduction in the pollutant load of water bodies. Fig. 10 shows that by 2030, the total amount of pollutant (COD) discharged from the system would be increased by about 100% or more compared with Case 1. Therefore, the improvement of the overall pollution level would improve the WRCC in Beijing, but the WRCC was low, so it would not reach the level of water demand.

Using Case 1 as a base, Case 5 took into account water savings, pollution control, and adjustment of the industrial structure. In this scenario, growth in industrial production slowed, growth in tertiary industry increased, the water supply and demand was essentially balanced during the simulation period, great improvements were made in sewage treatment and average water consumption of industrial production (AWCIP), and the irrigation quota was reduced. Compared with the other cases, Case 5 had the best to improvement in the WRCC of Beijing, with an average increase of nearly 50% over Case 1 (Fig. 11). As an optimal program, it will benefit Beijing's coordinated social, economic, and environmental development.

5.2. Wetland water resources management

From simulation of the five cases, water saving was not only the fundamental way to improve water resources use efficiency and the WRCC, but also an effective way to reduce pollution. It was the only way for Beijing's water resources to achieve economical and sustainable development. Water saving in agriculture, industry, and daily life would bring huge environmental and social benefits. Therefore, it is urgent to strengthen water saving measures, to improve water saving levels, to vigorously develop water saving in agriculture, and to make across-the-board improvements for water conservation in industry and living. At the same time, sewage treatment capacity and wastewater reuse must increase. In Case 4, the treatment of sewage was favorable for protecting water resources, improving the water environment, and enhancing the water supply capacity. The fundamental solution to the issue of water pollution was to reduce the total COD emissions. The industry structure needs to be optimized and the efficient use of water resources should be improved. In Case 1, although a reduction in effective irrigated area and gross domestic product of tertiary industry, as well as an adjustment in industry, reduced the water consumption of agricultural production (WCAP) some, higher GDP for tertiary industry increased the overall water consumption in Beijing. Therefore, Case 1 did not reduce the water consumption effectively.

In Case 3, a decrease in the living water quota could effectively reduce the total water demand. Therefore, it is important to enhance public education regarding water resources protection, encourage water saving practices, and reduce per capita water demand of rural and urban populations. It will be necessary to strengthen water resources management measures, to reform water management mechanisms, and to establish a water market mechanism, as well as to manage surface water, groundwater, and sewage treatment and reuse through the two measures of water price and legislation.

5.3. Environmental impact of different cases

Ensuring the health of the ecological environment was one of the important prerequisites for studying the WRCC. It was also a necessary condition for realizing the sustainable development of a region. The relative sustainable development progress of the WRCC System in Beijing could be measured by pressure on the wetland water environment, while the economic effect on the environment would not be reflected. This paper chose total emissions and water pressure index to compare impacts of socioeconomic development on the environment under a conventional model and adjusted program scenarios.

The results of pollutant discharge for the different cases show that the total COD emissions and wastewater production in these pollution control models were far lower than those in the conventional model (Fig. 10). Fig. 11 shows that the WRCC under the pollution control program was not very different from Case 1 (conventional model), indicating that sewage treatment had a limited impact on the social and economic development, but an enormous contribution on the environmental development.

5.4. Uncertainty of the SD model

In this paper, a system dynamics model was used to study the WRCC of Beijing. This model reflected interrelationships among the subsystems of water resources, social economy, and environment in Beijing. The dynamical model involved a large number of parameters. The determination of relationships between a parameter and variable, and the determination of the parameter value, were both based on many documents and much data. Because it was difficult to accurately estimate the values of the parameters, the model might easily lead to some errors in practical usage. In the model, the selection of decision variables was subjective, so the predictive results had defects in the objectivity. The results of this study could serve as a reference for wetland water resource utilization and planning in Beijing, but should not play the decisive role.

6. Conclusion

Based on the characteristics of system dynamics and the advantages of system dynamics in solving complex large-scale system problems, a dynamic model of urban wetland WRCC was established. Using social, economic, ecological, and pollution subsystems, this paper analyzed the cause and effect relationship of each variable in the system, and constructed a SD model of WRCC based on Vensim software in combination with the current social and economic development trends in Beijing. The model structure flow diagram was drawn and the equations of model variables and parameters were constructed. According to the characteristics of the WRCC system in Beijing and the current social economy, 13 decision variables were determined, and an index system of WRCC decision-making variables was established. After testing the validity of the model and analyzing the status quo of social economy and water environment in Beijing, five schemes of current development, economic development, water saving, pollution control, and comprehensive development were designed. Using the “Beijing 13th Five-Year Plan” (2016–2020) for input values, the specific numbers for water demand, water supply, COD emissions, and other indicators for WRCC were obtained for each of the five schemes, after simulation and calculation.

From the SD model simulations of unconstrained and restrained water use in Beijing, it could be seen that the available water resources were not sufficient to support the future social and economic development of Beijing. The main reason was an irrational allocation of water resources in the conventional mode, the scale of water consumption by agricultural production (WCAP) was too large, and there was waste in this process. According to the simulation of five assumed policies and the analysis of the simulation results, the water saving policy could effectively alleviate pressure on Beijing’s water resources in upcoming years, but would not thoroughly solve the problem of overburdening the social economy in the future.

Case 4 had a significant inhibitory effect on the discharge of pollutants in Beijing and promoted an increase in the water supply, which had little effect on the social economy. The primary reason for significant improvement of the WRCC in Beijing using Case 2 was that the water consumption of agriculture, especially of high water consumption crops (corn and wheat), was reduced. However, Case 2 could not effectively alleviate the water shortage caused by rapid economic growth in other sectors. As the most effective way to solve the water resource overload problem in Beijing, Case 5 integrated all of the measures from the other cases. In Case 5, the water resources development and utilization control red line formulated by Beijing could essentially meet the needs of future economic development. Based on an analysis of the socioeconomic status and various simulation results in Beijing, it was suggested that the WRCC of wetlands in Beijing should be improved by saving water, adjusting industrial structure, improving the pollution control, and increasing the amount of recycled water.

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Appendix A

Table 1
Five different cases for the improvement of water resources carrying capacity in Beijing city

variables	case 1	case 2		case 3		case 4		case 5	
		2025	2030	2025	2030	2025	2030	2025	2030
Total water supply (Unit:10^9m^3)	[(2006,34.3)–(2030,50)], (2006,34.6), (2007,34.8), (2008,35.1), (2009,35.5), (2010,35.2), (2011,36.0), (2012,35.9), (2013,36.4)	≤45	≤50	≤45	≤50	≤45	≤50	≤45	≤50
Agricultucal irrigation area (Unit:10^4hm^2)	[(2006,18.15)–(2030,10.70)], (2006,18.15), (2007,17.36), (2008,17.18), (2009,16.52), (2010,16.26), (2011,16.31), (2012,15.92), (2013,15.44)	8	6	No change	No change	No change	No change	8	6
Amount of large livestock (Unit:10^4 head)	[(2006,25)–(2030,8)], (2006,25), (2007,25), (2008,24), (2009,22), (2010,18), (2011,16), (2012,15), (2013,14)	3	1	No change	No change	No change	No change	3	1
Amount of small livestock (Unit:10^4 head)	[(2006,2640)–(2030,500)], (2006,2640), (2007,2950), (2008,2724), (2009,2835), (2010,2737), (2011,2663), (2012,2596), (2013,2524)	1000	500	No change	No change	No change	No change	1000	500
Growth rate of tertiary industrial output value	[(2006,0.2389)–(2030,1)], (2006,0.2389), (2007,0.1596), (2008,0.0976), (2009,0.1552), (2010,0.1663), (2011,0.1068), (2012,0.1147), (2013,0.0833)	0.12	0.12	No change	No change	No change	No change	0.12	0.12
Growth rate of industrial output value	[(2006,0.1327)–(2030,1)], (2006,0.1327), (2007,0.1433), (2008,0.0235), (2009,0.0804), (2010,0.2001), (2011,0.1030), (2012,0.0805), (2013,0.0826)	0.08	0.08	No change	No change	No change	No change	0.08	0.08
tertiary industrial water consumption of ten thousand yuan output value (10^9m^3)	[(2006,34)–(2030,8)], (2006,34), (2007,27), (2008,24), (2009,22), (2010,18), (2011,16), (2012,15), (2013,14)	No change	No change	12	10	No change	No change	10	8
Industrial water consumption of ten thousand yuan output value (10^9m^3)	[(2006,23)–(2030,3)], (2006,23), (2007,19), (2008,17), (2009,16), (2010,13), (2011,12), (2012,11), (2013,10)	No change	No change	5	4	No change	No change	4	3
Farmland irrigation quota (unit: m^3/hm^2)	[(2006,2700)–(2030,1000)], (2006,2700), (2007,2600), (2008,2500), (2009,2450), (2010,2400), (2011,2350), (2012,2300), (2013,2250)	No change	No change	800	500	No change	No change	800	500
Per capia water consumption quata in urban life (m^3/day)	0.11	No change	No change	0.06	0.05	No change	No change	0.06	0.05
Per capia water consumption quata in urban life (m^3/day)	0.085	No change	No change	0.05	0.04	No change	No change	0.05	0.04
Treatment rate of domestic sewage	[(2006,0.732)–(2030,1)], (2006,0.732), (2007,0.762), (2008,0.745), (2009,0.779), (2010,0.81), (2011,0.817), (2012,0.83), (2013,0.846)	No change	No change	No change	No change	0.98	1	0.98	1
Reuse rate of reclaimed water	[(2006,0.53)–(2030,1)], (2006,0.53), (2007,0.57), (2008,0.51), (2009,0.58), (2010,0.54), (2011,0.60), (2012,0.59), (2013,0.62)	No change	No change	No change	No change	0.95	1	0.95	1
Per capita COD emission (kg/day)	[(2006,0.1)–(2030,0.04)], (2006,0.095), (2007,0.09), (2008,0.09), (2009,0.13), (2010,0.0.09), (2011,0.13), (2012,0.13), (2013,0.12)	No change		No change		0.04		0.04	
COD emission per unit GDP (kg/10^9 Yuan)	[(2006,1.35)–(2030,0.08)], (2006,1.35), (2007,1.08), (2008,1.91), (2009,2.12), (2010,1.77), (2011,2.77), (2012,1.9), (2013,1.7)	No change		No change		0.08		0.08	

Note: It shows that this case and case 1 have the same development trend.

Appendix B

Main SD equation of water resources carrying capacity of wetlands:

1 Rural population (RP) = total population (TP)−urban population (UP)
2 Urban population (UP) = y total population (TP) × urbanization rate (Ur)
3 Total population (t) = total population (t−△t) t × population change value (PCV)
4 Population change value (PCV) = total population (TP) × population change rate (PCR)
5 Urban life water consumption (PLWC) = urban population (UP) × Per capita water consumption quota in urban life (PQUL) × 365 × 0.001
6 Rural life water consumption (RLWC) = rural population (RP) × Per capita water consumption quota in rural life (PQRL) × 365 × 0.001
7 Total life water consumption (TWC) = Urban life water consumption (ULWC) + rural life water consumption (RLWC)
8 Agricultural irrigation area (AIA) (t) = Agricultural irrigation area (AIA) (t−△t) + t × changes of agricultural irrigation area (CAIA)
9 Changes of Agricultural irrigation area (CAIA) = agricultural irrigation area (AIA) × irrigation water consumption change rate (IWCR)
10 Agricultural irrigation water demand (AIWD) = agricultural irrigation area (AIA) × farmland irrigation quota (FIQ)
11 Water requirement of Large livestock (WRLL) = amount of large livestock (ALL) × water requirement quota of Large livestock (WRQLL)
12 Water requirement of small livestock (WRSL) = amount of small livestock (ASL) × water requirement quota of small livestock (WRQSL)
13 The total amount of water requirement for livestock (TWRL) = water requirement of Large livestock (WRLL) +water requirement of small livestock (WRSL)

14 Agricultural production water consumption (APWC) = agricultural irrigation water demand (AIWD) + The total amount of water requirement for livestock (TWRL)

15 Agricultural water consumption of ten thousand Yuan output value (AWCOV) = Agricultural production water consumption (APWC) ÷ agricultural GDP (AGDP)

16 Agricultural GDP (AGDP) (t) = agricultural GDP (AGDP) (t−△t) + △t × added value of agricultural output value (AVAOC)

17 Added value of agricultural output value (AVAOC) = agricultural GDP (AGDP) × growth rate of agricultural output value (GRAOC)

18 Production water consumption (PWC) = Agricultural production water consumption (APWC) + Industrial fresh water demand (IFWD) + Third industrial water consumption (TIWC)

19 Industrial GDP (IGDP) (t) = Industrial GDP (IGDP) (t-△t) + △t × added value of Industrial output value (AVIOV)

20 Added value of Industrial output value (AVIOV) = Industrial GDP (IGDP) × growth rate of Industrial output value (GRIOV)

21 Agricultural production water consumption (APWC) = Industrial GDP (IGDP) × Industrial water consumption of ten thousand Yuan output value (IWCOV)

22 Industrial fresh water demand (IFWD) = Agricultural production water consumption (IPWC) × (1 − Industrial water reuse rate (IWRR))

23 Third industrial GDP (TIGDP) (t) = Third industrial GDP (TIGDP) (t−△t) + △t × added value of Third Industrial output value (AVTIOV)

24 Added value of Third Industrial output value (AVTIOV) = Third Industrial GDP (TIGDP) × growth rate of Third Industrial output value (GRTIOV)

25 Third industrial water consumption of ten thousand Yuan output value (TIWCOV)

26 Total water demand (TWD) = life water consumption (LWC) + Production water consumption (PWC) + ecological water demand (EWD)

27 Ecological water demand (EWD) = Urban ecological water demand (UEWD) + Wetland ecosystem water demand (WEWD)

28 Urban ecological water demand (UEWD) = Total area of urban green land (TAUGL) × unit green land area water demand (UGLWD)

29 Total area of urban green land (TAUGL) (t) = Total area of urban green land (TAUGL) (t−△t) + △t × added value of urban green land area (AVUGA)

30 Added value of urban green land area (AVUGA) = Total area of urban green land (TAUGL) × Urban green land area growth rate (UGLGR)

31 Wetland ecosystem water demand (WEWD) = Total area of urban Wetland (TAUW) × unit urban Wetland water demand (UUWWD)

32 Total area of urban Wetland (TAUW) (t) = Total area of urban Wetland (TAUW) (t−△t) + △t × added value of Wetland area (AVWA)

33 Added value of Wetland area (AVWA) = Total area of Wetland (TAW) × Wetland area growth rate (WAGR)

34 Degree of water resources shortage = Supply and demand ratio (SDR) = total wetland water resources supply (TWWRS) ÷ Total water demand (TWD)

35 Total wetland water resources supply (TWWRS) = Total amount water of South-to-north Water Transfer Project (TSWTP) + Total amount of Surface water recharge (TASWR) + Total amount of groundwater recharge (TAGR) + Total amount of Emergency water (TAEW) + Total amount of reclaimed water (TARW)

36 Total amount of reclaimed water (TARW) = total amount of Wastewater and sewage treatment (TAWST) × reuse rate of reclaimed water (RRRW)

37 Total amount of wastewater and sewage treatment (TAWST) = total amount of Industrial wastewater treatment (TAIWT) + total amount of urban domestic sewage treatment (TAUST)

38 Total amount of urban domestic sewage treatment (TAUST) = total amount of urban domestic sewage discharge (TUDSD) × treatment rate of domestic sewage (TRDS)

39 Total amount of urban domestic sewage discharge (TUDSD) = total amount of urban domestic water consumption (TUDSD) × discharge rate of domestic sewage (DRDS)

40 Total amount of Industrial wastewater treatment (TAIWT) = total amount of Industrial wastewater discharge (TAIWD) × treatment rate of Industrial wastewater (TRIW)

41 Total amount of wastewater discharge (TAWD) = total amount of agricultural wastewater discharge (TAAWD) + total amount of Industrial wastewater discharge (TAIWD)

42 Total amount of agricultural wastewater discharge (TAAWD) = Agricultural production water consumption (APWC) × treatment rate of Agricultural wastewater (TTAW)

43 Total COD emissions (TCOD) = total life COD emissions (TLCOD) + total industrial COD emissions (TICOD)

44 Total life COD emissions (TLCOD) = Urban population (UP) × Per capita COD emission (PCCOD)

45 Total industrial COD emissions (TICOD) = industrial GDP (IGDP) × COD emission per unit GDP (CODGDP)

46 Water environment pressure (WEP) = Total COD emissions (TCOD) ÷ maximal allowable COD emission (MACOD).

References

Altunkaynak, A., Sen, Z., 2007. Fuzzy logic model of lake water level fluctuations in Lake Van, Turkey. Theor. Appl. Climatol. 90, 227–233.

Byron, C., Bengtson, D., Costa-Pierce, B., Calanni, J., 2011a. Integrating science into management: ecological carrying capacity of bivalve shellfish aquaculture. Mar. Policy 35, 363–370.

Byron, C., Link, J., Costa-Pierce, B., Bengtson, D., 2011b. Calculating ecological carrying capacity of shellfish aquaculture using mass-balance modeling: Narragansett Bay, Rhode Island. Ecol. Model. 222, 1743–1755.

Cuadra, M., Björklund, J., 2007. Assessment of economic and ecological carrying capacity of agricultural crops in Nicaragua. Ecol. Indic. 7, 133–149.

Dang, X., Liu, G., 2012. Emergy measures of carrying capacity and sustainability of a target region for an ecological restoration programme: a case study in Loess Hilly Region, China. J. Environ. Manag. 102, 55–64.

David, G.S., Carvalho, E.D., Lemos, D., Silveira, A.N., Dall'Aglio-Sobrinho, M., 2015. Ecological carrying capacity for intensive tilapia (Oreochromis niloticus) cage aquaculture in a large hydroelectrical reservoir in Southeastern Brazil. Aquac. Eng. 66, 30–40.

De la Sen, M., Alonso-Quesada, S., 2009. Control issues for the Beverton–Holt equation in ecology by locally monitoring the environment carrying capacity: non-adaptive and adaptive cases. Appl. Math. Comput. 215, 2616–2633.

Doherty, M.J., Zedler, J.B., 2014. Dominant graminoids support restoration of productivity but not diversity in urban wetlands. Ecol. Eng. 65, 101–111.

Dou, M., Ma, J., Li, G., Zuo, Q., 2015. Measurement and assessment of water resources carrying capacity in Henan Province, China. Water Sci. Eng. 8 (2), 102–113.

Graymore, M.L.M., Sipe, N.G., Rickson, R.E., 2010. Sustaining Human Carrying Capacity: a tool for regional sustainability assessment. Ecol. Econ. 69, 459–468.

Hoekstra, A.Y., Chapagain, A.K., 2007. Water footprints of nations: water use by people as a function of their consumption pattern. Water Resour. Manag. 21, 35–48.

Hettiarachchi, M., Morrison, T.H., Wickramsinghe, D., Mapa, R., De Alwis, A., McAlpine, C.A., 2014. The eco-social transformation of urban wetlands: a case study of Colombo, Sri Lanka. Landsc. Urban Plan. 132, 55–68.

Hettiarachchi, M., Morrison, T.H., McAlpine, C., 2015. Forty-three years of Ramsar and urban wetlands. Glob. Environ. Change 32, 57–66.

Ho, M., Richardson, C.J., 2013. A five year study of floristic succession in a restored urban wetland. Ecol. Eng. 61, 511–518.

Ibarra, A.A., Zambrano, L., Valiente, E.L., Ramos-Bueno, A., 2013. Enhancing the potential value of environmental services in urban wetlands: an agro-ecosystem approach. Cities 31, 438–443.

Karstensa, S., Jurasinskia, G., Glatzel, S., Buczko, U., 2016. Dynamics of surface elevation and microtopography in different zones of a coastal Phragmites wetland. Ecol. Eng. 94, 152–163.

Khanna, P., Babu, P.M., George, M.S., 1999. Carrying-capacity as a basis for sustainable development: a case study of National Capital Region in India. Prog. Plan. 52,101–166.

Kluger, L.C., Taylor, M.H., Mendo, J., Tam, J., Wolffa, M., 2016. Carrying capacity simulations as a tool for ecosystem-based management of a scallop aquaculture system. Ecol. Model. 331, 44–55.

Lane, M., 2010. The carrying capacity imperative: assessing regional carrying capacity methodologies for sustainable land-use planning. Land Use Policy 27, 1038–1045.

Lane, M., Dawes, L., Grace, P., 2014. The essential parameters of a resource-based carrying capacity assessment model: an Australian case study. Ecol. Model. 272, 220–231.

Li, N., Yang, H., Wang, L., Huang, X., Zeng, C., Wu, H., Ma, X., Song, X., Wei, Y., 2016. Optimization of industry structure based on water environmental carrying capacity under uncertainty of the Huai River Basin within Shandong Province, China. J. Clean. Prod. 112, 4594–4604.

Lia, Y., Shi, Y., Qureshi, S., Bruns, A., Zhu, X., 2014. Applying the concept of spatial resilience to socio-ecological systems in the urban wetland interface. Ecol. Indic. 42, 135–146.

Liu, B., Shao, M., 2015. Modeling soil–water dynamics and soil–water carrying capacity for vegetation on the Loess Plateau, China. Agric. Water Manag. 159, 176–184.

Liu, R.Z., Borthwick, A.G.L., 2011. Measurement and assessment of carrying capacity of the environment in Ningbo, China. J. Environ. Manag. 92, 2047–2053.

Manzardo, A., Loss, A., Fialkiewicz, W., Rauch, W., Scipioni, A., 2016. Methodological proposal to assess the water footprint accounting of direct water use at an urban level: a case study of the Municipality of Vicenza. Ecol. Indic. 69, 165–175.

Martire, S., Castellani, V., Sala, S., 2015. Carrying capacity assessment of forest resources: enhancing environmental sustainability in energy production at local scale. Resour. Conserv. Recycl. 94, 11–20.

Morin, T.H., Bohrer, G., Naor-Azrieli, L., Mesi, S., Kenny, W.T., Mitsch, W.J., Schäfer, K.V.R., 2014. The seasonal and diurnal dynamics of methane flux at a created urban wetland. Ecol. Eng. 72, 74–83.

Nakajima, E.S., Ortega, E., 2016. Carrying capacity using emergy and a new calculation of the ecological footprint. Ecol. Indic. 60, 1200–1207.

Niu, Z.G., Zhang, H.Y., Gong, P., 2011. More protection for China's wetlands. Nature 471 (7338), 305.

Pandeya, V.P., Babelb, M.S., Shrestha, S., Kazama, F., 2011. A framework to assess adaptive capacity of the water resources system in Nepalese river basins. Ecol. Indic. 11, 480–488.

Papageorgiou, K., Brotherton, I., 1999. A management planning framework based on ecological, perceptual and economic carrying capacity: the case study of Vikos-Aoos National Park, Greece. J. Environ. Manag. 56, 271–284.

Prato, T., 2009. Fuzzy adaptive management of social and ecological carrying capacities for protected areas. J. Environ. Manag. 90, 2551–2557.

Rajaram, T., Das, A., 2011. Screening for EIA in India: enhancing effectiveness through ecological carrying capacity approach. J. Environ. Manag. 92, 140–148.

Rees, W.E., 1992. Ecological footprints and appropriated carrying capacity: what urban economics leaves out. Environ. Urbanization 4 (2), 121–130.

Ren, C., Guo, P., Li, M., Li, R., 2016. An innovative method for water resources carrying capacity research—metabolic theory of regional water resources. J. Environ. Manag. 167, 139–146.

Slessor, M., Lewis, C., 1979. Biological Energy Resources. Spon Press, London.

Sun, T., Lin, W., Chen, G., Guo, P., Zeng, Y., 2016. Wetland ecosystem health assessment through integrating remote sensing and inventory data with an assessment model for the Hangzhou Bay, China. Sci. Total Environ. 566–567, 627–640.

Verhofstadt, E., Van Ootegem, L., Defloor, B., Bleys, B., 2016. Linking individuals' ecological footprint to their subjective well-being. Ecol. Econ. 127, 80–89.

Wackernagel, M., Rees, W.E., 1997. Perceptual and structural barriers to investing in natural capital: economics from an ecological footprint perspective. Ecol. Econ. 20 (1), 3–24.

Wang, S., Xu, L., Yang, F., Wang, H., 2014a. Assessment of water ecological carrying capacity under the two policies in Tieling City on the basis of the integrated system dynamics model. Sci. Total Environ. 472, 1070–1081.

Wang, S., Yang, F., Xu, L., Du, J., 2013. Multi-scale analysis of the water resources carrying capacity of the Liaohe Basin based on ecological footprints. J. Clean. Prod. 53, 158–166.

Wang, T., Xu, S., 2015. Dynamic successive assessment method of water environment carrying capacity and its application. Ecol. Indic. 52, 134–146.

Wang, Y.Y., Huang, G.H., Wang, S., Lia, W., Guana, P.B., 2016. A risk-based interactive multi-stage stochastic programming approach for water resources planning under dual uncertainties. Adv. Water Resour. 94, 217–230.

Wang, Z., Luo, Y., Zhang, M., 2014b. Quantitative evaluation of sustainable development and eco- environmental carrying capacity in water-deficient regions: a case study in the Haihe River Basin, China. J. Integr. Agric. 13 (1), 195–206.

Wentzell, B.M., Boylen, C.W., Nierzwicki-Bauer, S.A., 2016. Wetland ecosystem comparison using a suite of plant assessment measures. Ecol. Indic. 67, 283–291.

Xu, S., Chen, Z., Li, C., Huang, X., Li, S., 2011. Assessing the carrying capacity of tilapia in an intertidal mangrove-based polyculture system of Pearl River Delta, China. Ecol. Model. 222, 846–856.

Yin, X.A., Yang, Z.F., Petts, G.E., Kondolf, G.M., 2014. A reservoir operating method for riverine ecosystem protection, reservoir sedimentation control and water supply. J. Hydrol. 512, 379–387.

Yin, X.A., Yang, Z.F., 2013. A reservoir operating model for directing water supply to humans, wetlands, and cones of depression. Ecol. Model. 252, 114–1201.

Yu, H.H., Edmunds, M., Lora-Wainwright, A., Thomas, D., 2016. Governance of the irrigation commons under integrated water resources management–A comparative study in contemporary rural China. Environ. Sci. Policy 55, 65–74.

Zeng, X.T., Huang, G.H., Chen, H.L., Li, Y.P., Kong, X.M., Fan, Y.R., 2016. A simulation-based water-environment management model for regional sustainability in compound wetland ecosystem under multiple uncertainties. Ecol. Model. 334, 60–77.

Zhang, Y.M., Huang, G., Lu, H.W., He, L., 2015. Planning of water resources management and pollution control for Heshui River watershed, China: a full credibility-constrained programming approach. Sci. Total Environ. 524–525, 280–289.

Zhi, Y., Yang, Z.F., Yin, X.A., Hamilton, P.B., Zhang, L.J., 2015. Using gray water footprint to verify economic sectors' consumption of assimilative capacity in a river basin: model and a case study in the Haihe River Basin, China. J. Clean. Prod. 92, 267–273.