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Application of System Dynamics in Analysis of Carrying Capacity of Water Resources in Yiwu City of China

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Summary

The primary scheme of unilaterally pursuing fast economic development at the expense of the environment and the secondary scheme focusing on environmental protection as the primary goal by slowing economic development are both undesirable for Yiwu. The third scheme balancing economic development with environmental protection is the most effective scheme.

Introduction

The carrying capacity of water resources is a concept with attributes related to both nature and society. This means that it is a complex large-scale system, involving numerous factors including but not limited to population, resource availability, the environment, ecology, society, economics and technology [1]. These factors interact as both cause and effect, restrict each other and act as both positive and negative feedback. The answers to several important questions about the exact population level that can be supported by water resources, whether the sustainable development of a social economy can be successfully achieved, and whether a favorable ecological system can be smoothly realized, depend exclusively upon policy parameters such as economic policy, development speed, strategic policy, etc. The choice of policy parameters is a difficult problem, which can be effectively solved through a mathematical method derived from system dynamics (SD) [2].

Analysis of the carrying capacity of water resources in Yiwu

The carrying capacity of water resources can be calculated according to the following equation, derived from system dynamics [2]:

$$BW(K) = BW(J) + DT \times BWR(JK) \tag{1}$$

Where BW represents the volume of usable water that can be carried, and J, K and JK denote the preceding time, current time and adjacent time periods, respectively. DT is the simulation step length; BWR represents the rate of change in volume of water carried, which includes increased volume due to newly built water retention works and improvements in water recycling facilities. Let TBW represent the total carrying capacity of water resources (the total volume of usable water borne by a water body) in a particular region. TBW can be divided into three parts: the volume of water suitable for agricultural use that can be carried (ABW), the volume of water suitable for industrial use that can be carried (IBW) and the volume of

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water suitable for consumption by human beings and domestic animals (*PSBW*), and can be represented as follows:

$$TBW = ABW + IBW + PSBW \tag{2}$$

Yiwu is located in a humid area and has average annual precipitation of 1403mm. In contrast to cities located in dry areas [3], water shortages in Yiwu are related not to the type of water source but to water quality and types of water conservation projects. This includes water shortages caused by pollution, and the lack of water storage projects. Therefore, protection of water sources and water storage projects such as large or middle scale reservoirs are very important factors [4]. Several indicators that have a large influence on the carrying capacity of water resources in Yiwu were selected according to the principle of simplicity. These indexes include population, industrial and agricultural output, gross domestic product (GDP), investment in environmental protection, volume of sewage discharge, lengths of polluted stretches of rivers, total required volume of usable water, water conservation schemes, water supply volume, and the volume of usable water carried by water resources.

The indicator system used in this study on the carrying capacity of water resources in Yiwu can be divided into five subsystems - population, agriculture, industry, environmental protection and water resources. As can be calculated using system dynamics, there exists a mutual relationship of cause and effect between one subsystem and another, as well as between the different factors of each subsystem. Moreover, this relationship forms a closed feedback structure. Therefore, cause and effect diagrams and system flow diagrams can be created according to the indicator system and the feedback structure of the system. Such diagrams explain the logical relationships between each variable in the system, but fail to demonstrate the quantitative relation between variables. Thus, the language DYNAMO is required to build system dynamics equations. Variables used in system dynamics include level variables, rate variables and auxiliary variables and their equivalent equations, level equations, rate equations and the auxiliary equations, respectively. System dynamics equations are organically grouped by the above dynamic equations to fully reflect dynamic variation in the carrying capacity of water resources. The most important of these equations is the level equation, as it quantitatively describes changes in dynamic systematic variables over time.

In this paper, field investigation work was conducted along rivers in Yiwu. Data related to water resources and social economic systems since 1980 were comprehensively collected by the author according to the actual situation in Yiwu and the requirements of the SD model, with ecology as the guiding ideology. System dynamics equations for the five subsystems of population, agriculture, industry, environmental protection and water resources were built according to the characteristics of water resources in Yiwu. More than one hundred variables and parameters were included in the model, which also includes nine level equations, nine rate equations and numerous auxiliary equations. The model was created using Vensim. The testing time for the historical review is 27 years (1980-2006) and the terminal time for the simulation is the year 2020, with a step length of one year. The structure of the model was proven to be reasonable through analysis of parameter error and sensitivity, and reflects the actual characteristics of the carrying capacity of water resources in Yiwu. Therefore, it can be used to accurately forecast the dynamic development of the system after future policy parameters have been implemented.

The total volume of water resources in Yiwu is $6.03 \times 10^8 \mathrm{m}^3$. In order to model the development of water resource carrying capacity and economics in the region during the next ten to fifteen years, several indicators were selected as policy parameters, according to historical data and standards for building a society with improved standards of living. These indicators include agriculture, industry, GDP, accelerated investment in environmental protection, irrigation quotas for agriculture, water consumption per unit of output with the value of the thousand RMB by industry, and volume of sewage treated [5]. Furthermore, three development schemes were further simulated using the SD model. The three schemes can be represented as a primary scheme with economic development as the main goal, a secondary scheme with environmental protection as the main goal and a third scheme balancing economic development and environmental protection. Detailed analysis of water resource carrying capacity under these three schemes is shown below.

Scheme emphasizing economic development (high scheme)

The objective of quadrupling Yiwu's GDP can be easily realized by 2009 if this scheme is selected. GDP would reach 125.4 billion RMB by 2020, as shown in Table 1 and Fig. 1 (omitted). However, unilateral pursuit of fast economic development would lead to increases in sewage discharge and decreased investment in environmental protection. Sewage discharge would increase to 67.23 million tons by 2020 and result in all sections of all rivers being rated below class IV PPR (polluted percentage of river length). Sewage would be clearly visible everywhere, and cause severe environmental damage, as shown in Fig. 2 (omitted). At the same time, the total value of industrial output would reach 247.8 billion RMB owing to rapid industrial development. A series of measures including adjustments to industrial structure, separately supplying water of different qualities for different uses and increasing the price of water were executed to decrease industrial water consumption for each unit of output valued at ten thousand RMB from $9\mathrm{m}^3$ to $7\mathrm{m}^3$ could be implemented. However, industrial water requirements would increase to

$1.98 \times 10^8 m^3$, exceeding water consumption by agriculture. This increases total water requirements to $3.57 \times 10^8 m^3$. Due to lack of investment, implementation of water conservation and recycling measures would also be limited and the ability to supply water to the city would be reduced dramatically. Fig. 3 (omitted) shows that the simulation curves would intersect in 2014, indicating that the total volume of usable water carried would already be insufficient to satisfy total water requirements. Supply of water resources would be unable to meet demand at this time. The total volume of usable water carried would be $2.94 \times 10^8 m^3$ by 2020, with a massive water shortage of $0.63 \times 10^8 m^3$.

Table 1: Variation of the main indexes in the three schemes for carrying capacity of water resources

1	2	3	4	5	6	7	8	9	10
High scheme	2005	13.82	593.20	300.30	9.86	3208	50.1	2.36	2.42
	2010	22.26	955.36	483.64	12.59	4133	64.5	2.60	2.61
	2015	35.85	1538.61	778.91	16.07	4684	73.0	2.88	2.76
	2020	57.73	2477.95	1254.44	20.50	6723	104.7	3.57	2.94
Middle scheme	2005	13.82	593.20	300.30	9.86	3208	50.1	2.36	2.42
	2010	19.84	851.62	431.12	14.16	3100	48.3	2.51	2.66
	2015	28.48	1222.61	618.93	20.33	1262	19.5	2.63	2.86
	2020	40.89	1755.21	888.56	29.18	100	1.1	2.99	3.09
Low scheme	2005	13.82	593.20	300.30	9.86	3208	50.1	2.36	2.42
	2010	17.64	757.09	383.27	15.88	2104	32.7	2.43	2.71
	2015	22.51	966.26	489.16	25.58	0	0	2.42	2.96
	2020	28.73	1233.22	624.31	41.20	0	0	2.58	3.24

Where: 1. Scheme; 2. Year; 3. Gross agricultural output value (10^8 yuan); 4. Gross Industrial output value (10^8 yuan); 5. Gross domestic product (10^8 yuan); 6. Investment of environmental protection (10^8 yuan); 7. Sewage discharge (10^4 t); 8. PPR (%); 9. Total water demand (10^8 m^3); 10. Bearing volume of water use (10^8 m^3)

Scheme emphasizing environmental protection (low scheme)

The primary goal of this scheme is environmental protection. Therefore, investment in environmental protection increases year on year and causes sewage discharge to decrease gradually. Sewage treatment rates would reach 100% by 2013 and the percentage of river length rated below class IV PPR would also gradually decrease, from 50.1% in 2005 to 32.7% in 2010 and would finally reach zero in 2013. Lengths of river with inferior water quality would disappear owing to the city's emphasis on environmental protection. Picturesque scenery with green hills and clear waters would appear around the city and its ecologic environment would be changed completely. Due to the slowing of industrial development, industrial water requirements would be merely $0.99 \times 10^8 m^3$ in 2020, which is $0.99 \times 10^8 m^3$ less than that of the primary scheme. Therefore, total water requirements would be only $2.58 \times 10^8 m^3$, far below the maximum usable water carrying capacity of water resources. Although this scheme has an outstanding effect on balancing the demand for water against supply, it will also result in reduced resource exploitation and restricted development of industry and agriculture. This is owing to decreased investment in industrial fixed assets and agriculture. Therefore, under this scheme the objective of quadrupling GDP will only be achieved in 2013, as shown in Table 1.

Scheme balancing economic development and environmental protection (middle scheme)

It is obvious that pollution is unavoidable during economic development. However, the economy cannot be developed blindly at the expense of the environment. In particular, the consumption of resources cannot exceed the regenerative ability of ecological systems. Concurrent economic development and environmental protection should be the final objective in Yiwu. The relationship between economic development and other factors, such as population, resource availability and the environment are carefully considered in the middle scheme. Resource availability, the environment, the needs of industry and market conditions must all be taken into account through the weighing of advantages and disadvantages from an ecological angle. Under this scheme, the objective of quadrupling the city's GDP by the year 2011 could easily be realized if several measures are properly executed. These include inviting outside investment, accelerating construction of the International Trade City and timely adjustment of industrial structure, as shown in Table 1. At the same time, sewage discharge would also decrease and the percentage of river length polluted would be reduced to 1.1% by 2020, creating a comfortable living environment. The total volume of usable water borne could potentially reach $3.09 \times 10^8 m^3$ by the same time, which can fully satisfy the total annual water requirement of $2.99 \times 10^8 m^3$. Equilibrium between supply and demand for water resources would be achieved.

Conclusion

Several conclusions can be drawn from the above simulation results and theoretical analysis. These are as follows:

1. The primary scheme of unilaterally pursuing fast economic development at the expense of the environment and the secondary scheme focusing on environmental protection as the primary goal by slowing economic development are both undesirable for Yiwu. The third scheme balancing economic development with environmental protection is the most effective scheme.
2. At present, water shortages in Yiwu are not due to types of water source, but

are caused by low water quality and a lack of water conservation projects. The carrying capacity of water resources of the region can only be improved through the long-term strengthening of investment in environmental protection and the undertaking of new water storage projects. These projects include the building of large or medium scale reservoirs, the adjustment of industrial procedures and the creation of a society that naturally saves water.

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