Research on regional water demand prediction of the upper and middle reaches of The Pearl River Basin based on system dynamics

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Abstract. The prediction and calculation of water resource demand play a crucial role in the balance of water resource supply and demand in the research area. Only when the water demand of the research area is accurately and reasonably grasped, it is possible to make corresponding management and adjustment according to the actual situation in the process of water resource utilization, so as to ensure the sustainable development and utilization of water resource. In this paper, the upper and middle reaches of the Pearl River basin is taken as the research area. According to the relationship between supply and demand and the social and economic situation of the Pearl River basin, VENSIM PLE is used to establish the dynamic model of the water demand forecasting system of the Pearl River Basin. The model involves four subsystems of population, industry, agriculture and water resource, and the water resource demand of the three provinces is simulated. Compared with the results of the pearl River Basin planning report, the prediction error is small, which proves that the system dynamics model is feasible to predict the water demand of the Pearl River Basin.

Keywords: Water demand prediction, system dynamics, VENSIM PLE

1. Introduction
Reviewing the research status and development trends of water demand prediction at home and abroad, it can be seen that although some achievements have been made in water demand prediction, the following problems still need to be studied and solved urgently. First of all, most of the forecasting methods are based on the existing historical water use data, and the unsound or deviation of historical water use data results in the uncertainty of water demand forecasting results. Second, all kinds factors of driving water demand growth is periodic. Along with the development of the economy, water quota will not rise without limit, that is not clear about the economic law of development and the nature of the relationship between water demand and lead to prediction of water demand is big. Thirdly, the future inflow situation under the changing environment, namely the constraint relationship between water supply and water demand, is not fully considered in the water demand forecast. The future incoming or
available water quantity may not meet the water demand. If the constraint condition is not considered, the forecast result is relatively large. Finally, a series of influencing factors, such as natural population, economy, environment, technology and society, etc. involved in the commonly used water demand prediction method are uncertain, while the prediction method can only reflect the stable geometric growth process, and does not reflect the relationship or mutual feedback relationship between various factors or subsystems.

System dynamics (SD) is a discipline born in the 1950s to explore the feedback structure of complex systems[1]. It is essentially a system of differential equations with time delay, good at explaining and dealing with nonlinear high-order, multi-variable, multi-feedback and complex time-varying problems, and good at long-term, dynamic and strategic simulation analysis and research. Because of the irreplaceable advantages of system dynamics in the study of complex nonlinear systems, it has been widely used in industry, agriculture, ecology, environment and many other fields[2,3,4,5,6]. Kotir et al.[7] constructed a system dynamics model for sustainable water resources management and agricultural development, which improved decision-makers' understanding of the long-term dynamic behavior of the system by simulating the evolution process of the system. Yu Leng[8] studied and designed the system dynamics model of water resources simulation in the basin, based on MITSIM and combining the characteristics of system dynamics and the actual needs of water resources analysis and planning in small and medium-sized basins. Wang Yanfang et al.[9] established the optimal allocation model of the water resources system by using the system dynamics method, and obtained the water resources allocation scheme according to the corresponding optimization rules, based on the structure and characteristics of the water resources system in Erhai Basin.

To sum up, for a multi-dimensional system with many internal influencing factors, complex feedback relations and strong nonlinearity, such as the balance of supply and demand of water resources, System dynamics emphasizes that it has its own advantages in water demand prediction and supply-demand balance analysis to study the dynamic change behavior and trend of each component when different parameters or different strategy factors are input on the basis of understanding system composition and interaction of each component.

2. Method
The model established by SD method can reflect the water resource system state of the research area at every moment, so as to understand and grasp the relationship between supply and demand[10]. Therefore, using SD to predict and analyze the water demand of a multi-factor coupled complex giant water resource system can accurately and quantitatively describe the relationship between various factors affecting the water demand, and provide a reliable basis for the rational utilization and sustainable development of water resources.

2.1 Modeling steps of SD
The process of applying the system dynamics model to solve the problem is shown in Figure 1.

![System dynamics modeling flow chart](image)

①Understand the problem to be solved, conduct systematic analysis, and determine the system boundary and causal relationship.
② Describe the system structure, analyze the internal feedback mechanism of the system, and draw the system flow chart.

③ A quantitative model of the system was built in accordance with related system dynamics software (e.g. VENSIM, PLE, STELLA, Simile).

④ Simulate the model and check its validity.

⑤ Computer simulation based on existing data.

⑥ Evaluation and inspection of model results.

2.2 Water demand prediction main subsystem of SD model

The SD model in this paper involves four main modules, namely, water supply prediction, domestic water demand prediction, agricultural water demand prediction and industrial water demand prediction. The water supply consists of surface water supply, groundwater supply and other water supply. According to the water supply data of each province, the water supply forecasting model is established respectively. Living water demand prediction is divided into urban living water demand prediction and rural living water demand prediction. Agricultural water demand forecast includes agricultural irrigation water demand forecast and forest, animal and fishery water demand forecast. Industrial water demand prediction includes industrial water intensity prediction, and the prediction model is established based on the actual data.

3. Dynamic Model of the System in the Middle and Upper Reaches of the Pearl River Basin

In this paper, the water demand of the three provinces from 2020 to 2030 is simulated by the established SD model, and the water demand of the pearl River basin in each province is multiplied by the area ratio of the pearl River basin in each province. Finally, the regional water demand of the Pearl River basin in each province is added to obtain the final water demand result. This section mainly introduces the system dynamics model of water demand prediction for the region above Wuzhou section (middle and upper reaches of the Pearl River Basin) and analyzes the results.

The state variables included in the system are total population, irrigated farmland area, forest land area, grassland area, fishery area, GDP, surface water supply, groundwater supply and other water supply. Rate variables are all growth quantities related to state variables, including total population change, farmland irrigation area change, forest land area change, grassland area change, fishery area change, GDP growth, surface water supply change, groundwater supply change, and other water supply change. The auxiliary variable is the rate of change of each rate variable.

The causal feedback loop of the system is listed as follows:

Economic development → + living/production/ecological water demand → + total water demand → + water shortage rate → - economic development

The above feedback loop is uniformly explained. As a result of economic development, all kinds of water demand increase, thus the total water demand rise. When the water supply cannot meet the demand, the water shortage rate gradually increases, which causes the economic growth rate to slow down. The above feedback loops are all negative feedback loops.

3.1 Formulation of SD model parameters

The historical statistical data of relevant parameters of three provinces from 2007 to 2017 were found, and based on this, parameters of the SD model were drawn up. This model involves many parameters. Taking the population, farmland irrigated area and GDP of Guangxi Zhuang Autonomous Region as an example, the estimation approaches of each parameter are illustrated.

1) Population forecast

When the model calculates the living water demand, it takes urban living water demand and rural living water demand into account respectively. Therefore, the method of estimating the annual population is also adopted. Calculate the number of urban and rural population in 2020 and 2030 by means of natural population growth rate. Based on the number of urban and rural population in Guangxi
Zhuang Autonomous Region from 2007 to 2017, the multi-year average growth rate of urban and rural population was calculated.

Figure 2. Population prediction system flow chart

Figure 2 shows the system flow chart of urban and rural population prediction. The objective of this study is to simulate the change of rural and urban population in Guangxi Zhuang Autonomous Region from 2007 to 2080. Population is defined as state variable, population change as rate variable, birth rate, death rate and natural growth rate as intermediate or auxiliary variables. For the population prediction system, birth and death rates determine the natural rate of population growth. The population number shall be determined by the population base and the added value of the population. The number of urban population is determined by the urbanization rate and the total population. Thus, the number of urban and rural population and total population can be calculated.

2) Forecast of farmland irrigation area

The calculation method of irrigated area growth rate is the same as that of population. There is a certain relationship between the irrigated farmland area and the population. Theoretically, the larger the population is, the greater the requirement for the irrigated farmland area is. According to the previous forecast, Guangxi's population will increase from 48 million today to 51 million in 2030. Farmland irrigated area grows slowly, so we use the average annual growth rate of farmland irrigated area instead of the growth rate of farmland irrigated area table function. Figure 3 shows the system flow chart of irrigated farmland in Guangxi Zhuang Autonomous Region.

Figure 3. Irrigation area forecast in Guangxi Zhuang Autonomous Region

3) GDP forecast

In the process of simulating GDP, this paper considers the influence of social water shortage rate on social economy, and establishes the relationship between social water shortage rate and GDP growth. The growth of social economy will lead to the increase of water demand, and in the case of relatively stable water supply, the rate of social water shortage will rise. Based on this, the forecast model of gross domestic product is established. Figure 4 shows the system flow diagram of the GDP forecasting system.

Figure 4. Gross Domestic product forecast system flow chart
3.2 System dynamics equation
Based on the model analysis and index setting of the regional water demand prediction system of the Pearl River Basin, the dynamic flow diagram of the regional water demand prediction system of the Pearl River Basin is obtained, and the system dynamic equation of the model simulation is obtained. The equations of some water supply subsystem, domestic water demand forecasting subsystem, industrial water demand forecasting subsystem and agricultural water demand forecasting subsystem are as follows:

(1) Natural population growth rate = birth rate - death rate
(2) Change in population size = natural growth rate of population * Total population (unit: 1,000)
(3) Total population = \( \text{INTEG}(\text{population change},4855) \) (unit: 10,000)
(4) The urbanization rate = WITH LOOKUP (Time ([(2009, 0) - (2030, 1)], (2009,0.39)(2010,0.4),(2011,0.42),(2012,0.43),(2013,0.44),(2014,0.46),(2015,0.47),(2020,0.54),(2030,0.66)))

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(33) Total water demand = domestic water demand + industrial water demand + agricultural water demand (unit: 10m³)

3.3 Model validity test
Before the model is applied in practice, it is necessary to check whether the simulation results of the model and the actual value are within a certain error range, so as to ensure that the model can reflect the actual system behavior and make the model have correctness and reliability. In this paper, there are two aspects to the test. First, we test run the model in VENSIM PLE to detect the performance of a single variable. Judge whether the output value of the model is normal by combining common sense and actual data. The results show that the value is normal. Secondly, the model is used to simulate the historical data, and the actual statistical value is compared with the simulated value. If the simulated value is within a certain error range, the model is proved to be feasible. The SD model of Guangxi Zhuang Autonomous Region was taken as an example to test the validity of historical values of the model. The model involved many variables, so some variables were selected for testing. Taking total population, urban population, rural population, GDP and total water demand as examples, the simulated values from 2009 to 2015 were tested by historical values, and the time step was 1 year. The simulation results were consistent with the historical data through calibration.

Comparison and analysis of urban population, rural population, total water demand simulation value and the actual value of fitting. The simulation results of the water demand prediction model in the autonomous region are in good agreement with the actual results. Combined with the relative error between the simulated value and the actual value of each parameter, it is statistically found that the relative error of each parameter is between -3.09%~5%. Absolute relative error is within 5%. The results show that the SD model in Guangxi Zhuang Autonomous Region has a good fitting effect with the real value and meets the requirements of validity test.

3.4 Water demand results and analysis
In this study, the basin above wuzhou control point of the Pearl River was taken as the basic research area. The simulation time was from 2007 to 2080, and the time step length and the interval of result output were 1 year. Among them, 2017 to 2017 is the parameter calibration stage, and 2018 to 2080 is the prediction stage. The former corrects the model, makes a comparison based on 11 years of historical data, adjusts the corresponding parameter data, and obtains reliable parameters for the latter. In this paper, the research area is divided into three parts according to the provincial administrative regions, namely Guangxi, Yunnan and Guizhou. Each part contains three subsystems. They are domestic water demand, industrial water demand and agricultural water demand respectively. The base year data of the three provinces were input into the model, and the model parameters were changed to estimate the total water demand. According to the domestic water demand, industrial water demand and agricultural
Water demand, the final results were counted. The water demand forecast results of the three provinces in 2020 and 2030 were shown in Table 1.

| Table 1 Provincial water demand forecast results table |
|-----------------------------------------------------|
| **Guangxi Zhuang Autonomous Region**                |
| **Hundred million m³**                             |
| **Domestic water**                                 |
| **Industrial water**                               |
| **Agricultural water**                             |
| **The total water requirement**                     |
| 2020       | 33.37 | 36.38 | 169.63 | 239.38 |
| 2030       | 34.64 | 36.66 | 162.15 | 233.45 |
| **The guizhou province**                           |
| **Hundred million m³**                             |
| **Domestic water**                                 |
| **Industrial water**                               |
| **Agricultural water**                             |
| **The total water requirement**                     |
| 2020       | 5.65  | 6.42  | 21.83  | 33.9   |
| 2030       | 6.01  | 6.64  | 23.31  | 35.96  |
| **The yunnan province**                            |
| **Hundred million m³**                             |
| **Domestic water**                                 |
| **Industrial water**                               |
| **Agricultural water**                             |
| **The total water requirement**                     |
| 2020       | 7.51  | 4.09  | 47.14  | 58.74  |
| 2030       | 8.47  | 6.21  | 48.03  | 62.71  |

The results of water demand prediction and the results of the Pearl River Basin planning report can be combined. In horizontal years, the Pearl River Basin planning report predicts that the total water demand of the Pearl River Basin in 2020 and 2030 will be 68.9 billion m³ and 9.2 billion m³ respectively. It is close to the prediction results of the system dynamics method, which proves that the system dynamics model is feasible to predict the water demand of the Pearl River Basin.

4. Conclusion
In view of the uneven distribution of water resources in time and space, insufficient runoff regulation capacity, and increasingly prominent contradiction between water supply and demand in the Pearl River Basin, a water demand forecasting system dynamics (SD) model was established to study the total water demand, water demand structure and water demand law of each water department at different levels in different years on the basis of model calibration.

By comparing the results of annual water demand of different levels, this paper discusses the current situation of water resources supply and demand in the Pearl River Basin area in the future, and provides scientific basis for the rational allocation and utilization of water resources in the Pearl River Basin area, and meanwhile provides effective schemes and suggestions for the solution of water resources shortage in the Pearl River Basin area.

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