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Urban Industrial Water Supply and Demand: System Dynamic Model and Simulation Based on Cobb–Douglas Function

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Abstract: In order to meet the needs of water-saving society development, the system dynamics method and the Cobb–Douglas (C–D) production function were combined to build a supply and demand model for urban industrial water use. In this model, the industrial water demand function is expressed as the sum of the general industrial water demand and the power industry water demand, the urban water supply function is expressed as the Cobb–Douglas production function, investment and labor input are used as the control variables, and the difference between supply and demand in various situations is simulated by adjusting their values. In addition, the system simulation is conducted for Suzhou City, Jiangsu Province, China, with 16 sets of different, carefully designed investment and labor input combinations for exploring a most suitable combination of industrial water supply and demand in Suzhou. We divide the results of prediction into four categories: supply less than demand, supply equals demand, supply exceeds demand, and supply much larger than demand. The balance between supply and demand is a most suitable setting for Suzhou City to develop, and the next is the type in which the supply exceeds demand. The other two types cannot meet the development requirements. We concluded that it is easier to adjust the investment than to adjust the labor input when adjusting the control variables to change the industrial water supply. While drawing the ideal combination of investment and labor input, a reasonable range of investment and labor input is also provided: the scope of investment adjustment is $0.6I_0 - 1.1I_0$, and the adjustment range of labor input is $0.5P_0 - 1.2P_0$.

Keywords: industrial water; water supply and demand; system dynamics; Cobb–Douglas production function

1. Introduction

Industrial water consumption accounts for a large proportion of total urban water consumption in China. According to data from the 2017 China Water Resources Bulletin, industrial water consumption accounted for 21.1% of total national water use in the year, compared with 13.9% of domestic water consumption and 2.7% of ecological water consumption [1]. The Chinese industrial water industry is widely distributed, but it shows a large difference in regional distribution [2]. For Chinese industries, due to the water resource conditions, industrial water consumption is not allowed to grow fast, and industrial water consumption must begin from a strategic level and continue to reduce water loss [3]. Therefore, it is particularly necessary to optimize the urban industrial water supply to meet the demand. At present, the main methods used for measuring the industrial water consumption include the quota method and the sampling method. The sampling method has a higher difficulty in selecting the typical samples and is not easy to implement [4]. Therefore, the quota method has been become widely employed in the research of industrial water consumption.

With the development of the society, "set production by water and set the city by water" is an inevitable trend in the future. In terms of urban water management, many scholars have conducted a variety of research. They tried to use different methods to model water supply and demand balance. Idowu et al. [5] studied the Abeokuta and suburban drinking water supply systems in the southwestern part of Nigeria, estimating the water demand based on population growth and per capita water use in 2030. Kralisch [6] proposed the use of neural network methods to solve the balance between urban water diversion and efficiency of agricultural water. Ahmed Saad Al-Shutayri et al. [7] analyze a scenario-based modeling used in conjunction with Water Evaluation and Planning (WEAP) software to find the best combination of scenarios that meet future water demands. They think this model can analyze the unmet water demands, water demand, supply delivered, and supply requirement for each scenario. Malika Kahlerras et al. [8] build the WEAP model to assess and analyze the current and projected balance of Mazafran basin's water resource management. They also took into account the different policies and operational factors that can affect the demand up to the year 2050. A. W. Hasbiah et al. [9] conducted a study by analyzing the existing water resources and their potential as well as the city's water demand from the domestic sector. They use Bandung city water demand for analysis. The city will not be able to meet the water demand projected if it does not manage both its water supply and demand. Nan Zhang et al. [10] establish a two-way coordinated evaluation index system for mine water supply and demand based on the theory of water resources balance analysis. The analytic hierarchy process and entropy method are used to determine the weight of evaluation index. The TOPSIS method is used to evaluate Ningdong coal base in Yinchuan, Shizuishan, Lingwu, and Wuzhong. Dunia et al. [11] present an integer linear programming decision support model for the optimal treatment and allocation of water resources. Furthermore, the model is unique in its ability to account for spatially distributed water supply and demand nodes, as well as multiple water supply and demand types and qualities. Xia Wu et al. [12] established the water resources supply and demand balance model in plain water network with multi-water sources and multi-water intakes, which is based on the characteristics of plain river network. This model is utilized to calculate and analyze the water resources supply and demand balance in river networks on the south bank of Jingjiang river reach. D. Leong et al. [13] hold the view that future water use decisions will need to first determine the scale of industry and environmental protection. They analyzed the future water trade-offs which can inform water policy, water management decisions, and climate change adaptation plans, with applicability to other regions facing trade-offs between industrial development and ecosystem water needs. Ying Guo et al. [14] predicted future climate trends based on CMIP5 simulations in the arid region of northwestern China. The water availability and agricultural water demand under future climate change scenarios were estimated. Jing Han [15] chooses data of the water resource supply and demand in Beijing in previous years, adopting gray correlation analysis method to analyze three main factors of water. Sequential Combination Forecasting, Grey Forecasting, and polynomial fitting method are respectively used to predict changes of the three main factors in the future. Liu et al. [16] used system dynamics and block prediction methods to develop a model to predict the overall system under the condition of lack of data, and they can guarantee a certain degree of precision. Furthermore, through the application of examples, it provides an important reference for the comprehensive planning of regional water resources and the formulation of long-term water supply planning.

It is worth noting that in recent years, Cobb–Douglas (C–D) production functions have also been widely used in urban water management research. The C–D production function is a function that can be used to analyze various input factors in economic growth [17]. Some scholars use the C–D production function for the prediction of water demand and water supply. Zhang et al. [18] applied the C–D production function to establish a regional water demand prediction model, through which the contribution rate of regional water demand impact factors can be calculated. Comparing with support vector machine and back-propagation neural networks models, they illustrate that this proposed model possesses such advantages as simple modeling and high prediction accuracy by example of Zhuhai in China. Li [19] expressed the demand for domestic water in terms of the product of logistic function and per capita water demand, and employed a C–D production function to represent water supply, and studied the dynamic optimization of urban domestic water input. The proposed model eliminated value constrains on investment and labor input in the state equations and hence avoids the difficulty in applying these models to urban water supply institutions. Zhang et al. [20] established a fuzzy credibility-constrained interval two-stage stochastic programming (FCITSP) model based on a C–D function, predicting three major industrial water distribution problems based on water demand. Li et al. [21] designed the economic control model of multi-input and multi-output (MIMO) nonlinear systems to describe city's comprehensive water consumption, by using urban water demand function and C–D production function. Xu et al. [22] used the C–D production function and agricultural output value, labor, agricultural inputs, capital investment, agricultural water, and irrigation water as efficiency measures to calculate the economic benefits of agricultural water resources in Hainan. They concluded that the marginal benefits of irrigation water in Hainan would be increased with the increase of water saving irrigation area and infrastructure investment.

In addition, there are many scholars studying urban water supply and demand based on system dynamics, which combines qualitative and quantitative methods to explore how to effectively solve complex system problems such as population, industry, and resource environment [23]. Since the urban water resources system is an interconnected integration, many scholars have used this method to optimize the water supply and demand system in different regions. Stave [24] used system dynamics to simulate the trend of total water supply and demand in Las Vegas, Nevada over time, and give a time point for water supply and demand to reach equilibrium in different decision-making schemes. This paper discusses the potential of this kind of interactive model to stimulate stakeholder interest in the structure of the system, engage participant interest more deeply, and build stakeholder understanding of the basis for management decisions. Qi et al. [25] used the system dynamics model to simulate the urban municipal water demand estimation under the influence of uncertain economy. Chang [26] used system dynamics models to assess water security issues in arid regions of China in the context of gradual expansion of urbanization, rapid population growth, and low water use efficiency. The results show that there will be great influence of urban expansion on water resource security in Urumqi in the future. Reducing the sewage and increasing the reuse proportion of wastewater are very important methods to relieve the stress of water shortage. Ghashghaie [27] used the system dynamics model to study the impact of the dam under construction in the upper Urmiye basin on the downstream reservoir water supply. Three well known archetypes are shown in this paper that can help us to recognize the effect of a reservoir water supply on downstream flow. Qin [28] applied this method to investigate the balance of water supply and demand in Beijing, and designed three programs to improve the supply and demand of water resources. On the basis of simulation and comparison analysis, a scheme for alleviating the contradiction between water supply and demand in Beijing is proposed. Yang et al. [29] selected the best one from some five options designed to solve the differences in water supply and demand in Kunming. They hold the view that we can appropriately reduce the growth rate of urban development, implement the coordinated development plan of intensive use of water resources, sewage treatment and regeneration, and strengthen the water supply to achieve the balance of supply and demand of water resources in Kunming. Gao et al. [30] employed the system dynamics model to find solutions for the contradiction between water supply and demand in Jiangsu Province. Furthermore, they thought we should fully apply science and technology, comprehensive consideration of open source, throttling, industrial restructuring, and water pollution control, in order to solve the problem of insufficient water resources carrying capacity in Jiangsu Province. Yang et al. [31] used the system dynamics model to quantitatively simulate the supply and demand of water resources in the Manas River irrigation area, and proposed management measures combining pollution control and water conservation.

From the literatures of recent years, the methods and models for studying water supply and demand are diverse. Most of the methods are to calculate and analyze the water supply and water demand by establishing a mathematical model. Compared with these methods, it is more intuitive and clear to use system dynamics to analyze the supply and demand balance. At the same time, through the simulation analysis of real data, the prediction accuracy of system dynamics is also high. On this basis, this paper combines the C–D production function with the system dynamics to predict the industrial water supply. Through the C–D function, we can adjust the industrial water supply through investment and labor input. The theoretical significance is that we combine the two methods of system dynamics and C–D production function to study the supply and demand of urban industrial water. The practical significance is that we combine these two methods to make the study of urban water supply and demand more flexible—we can also study the supply and demand of domestic water, agricultural water, and integrated water. At the same time, the result of our paper draws the adjustment range of investment and labor input, which may provide a reasonable range of investment and labor input. In summary, we found that at present, though there are several research methods available for urban water supply and demand management research, the combination research of C–D production function and system dynamics has not been elaborated. At the same time, while there are many types of research areas, including arid, semi-arid, wet, and sub-humid areas, research on supply and demand of water resources of a specific industry in cities is still rare. In China, "13th Five-Year Plan from 2016 to 2020" emphasizes the need to "set production by water and set the city by water." Therefore, the purpose of this work is to study the supply and demand of water resources in the specific industry using C–D production functions. With the utilization of C–D production function, a more accurate prediction of the total amount of industrial water can be achieved, which provides a certain reference for the perspective of economic management and urban development. Specifically, the purpose of this study lies in not only systematically analyzing the urban industrial water system, but also obtaining certain specific prediction values on industrial water consumption, which are critically useful in investigating and optimizing the entire industrial water supply and demand.

2. Materials and Methods

System dynamics (SD) incorporates system theory, computer simulation, analysis of results, and study of feedback information to solve complex problems in complex systems. The SD model is essentially a set of first order differential equations with time delays. The Euler's numerical integration is generally used to represent the flow rate equation in the form:

$$L.K = L.J + DT(IR.JK - OR.JK), \tag{1}$$

where $L.K$ and $L.J$ are flow vectors, $IR.JK$ and $OR.JK$ are flow rate vectors, K is current moment, J is past time, JK is the time interval from time J to time K, and DT is the calculation interval. This equation can be deformed into:

$$\frac{L.K - L.J}{DT} = IR.JK - OR.JK. \tag{2}$$

The computer simulation method was utilized to study the dynamic changing process of the system model, and predict the trend of the model over time.

From the point of view of economic control, the product supply was mainly determined by factors of production. Common factors of production include capital, labor, and technology. The impact of the resource attributes of water on the difficulty of obtaining water resources was mainly reflected in the economic control of the input and output efficiency of production factors. Therefore, from the perspective of water resources economics and economic management, the urban water supply can be expressed by the C–D production function [19,21].

$$S(t) = AK^{\alpha}(t)L^{\beta}(t), \tag{3}$$

where $S(t)$ is the total industrial water supply at time t, $K(t)$ is the capital stock, $L(t)$ is the labor stock, A is the technical level coefficient, $A > 0$, α and β are the elasticity coefficients of the capital output and the elasticity coefficient of the labor output, $0 > \alpha, \beta > 1$.

From the perspective of investment theory, for the total fixed capital, its equation of variation can be expressed as:

$$\dot{K}(t) = \mu I(t) - \delta K(t),\ K(0) = K_0, \tag{4}$$

where $I(t)$ is the capital investment, μ is the capital formation rate, $0 < \mu < 1$, δ is capital depreciation rate, $0 < \delta < 1$, and K_0 is the initial capital investment.

The variation equation for the total labor force $L(t)$ is

$$\dot{L}(t) = \gamma P(t) - \sigma L(t), L(0) = L_0, \tag{5}$$

where $P(t)$ is industrial labor input, γ is the industrial effective labor formation rate, $0 \leq \gamma < 1$, σ is the industrial labor force abolition rate, $0 \leq \sigma < 1$, and L_0 is the initial labor force.

We combined the system dynamics with C–D production functions. The model is shown in Figure 1 below.

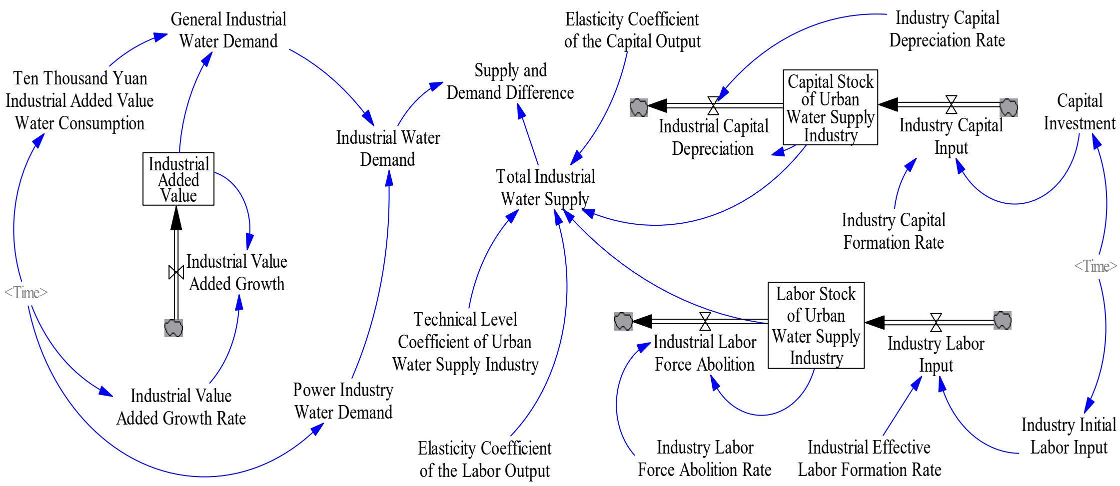

Figure 1. Urban industrial water supply and demand system.

Figure 1 shows the stock flow chart of the industrial supply and demand water system in Suzhou City. This model consists of 3 state variables, 5 rate variables, 9 auxiliary variables, and 7 constants. The industrial water demand function was expressed as the sum of the general industrial water demand and power industry water demand. Among them, the general industrial water demand was calculated by multiplying the water consumption per 10,000 Yuan industrial added value by the industrial added value.

The formula for the industrial water demand system is as follows:

$$D(t) = G(t) + E(t) \tag{6}$$

$$G(t) = W(t) \times V(t) \tag{7}$$

where $D(t)$ is the industrial water demand function at time t, $G(t)$ is the general industrial water demand, $E(t)$ is the power industry water demand, $W(t)$ is the water consumption per 10,000 Yuan industrial added value, and $V(t)$ is the industrial added value.

$S(t)$ is obtained by constructing the C–D production function, which mainly involves the two state variables of $K(t)$ and $L(t)$ in the industry. The difference between $S(t)$ and $D(t)$ directly reflects whether the system needs adjustment.

3. Comparison with Existing Models

First, many of the existing urban water supply and demand models [5,6,18–22,25,26,32] are built around one city's overall water system, and there are few analyses on the supply and demand of water resources for individual industries.

Secondly, in the study of water supply and demand model established by using system dynamics [27–31] only a few researchers incorporated C–D production functions in their models. In the traditional system dynamics, water supply and demand model is studied from the perspective of resources only. The total water supply is calculated by adding the sources of water in the city, namely the surface water, ground water, and recycled water recovery. Although this method is simple in calculation, it cannot clearly distinguish the industrial water supply, and cannot calculate the amount of water supply for individual industries. In contrast to these models, this paper studies from the perspective of economic management, and the constructed model can be used to obtain the specific industrial water supply through the C–D production function.

Finally, in comparison with the models [18–21] that also incorporate the C–D production function in calculating the total water supply, this paper adds the method of system dynamics, which is capable of constructing an overall system modeling the urban industrial water. This enhanced model can be implemented to more intuitively and clearly analyze the water supply and water demand as well as their influencing factors and the adopted optimization process becomes more convenient to implement.

4. System Parameter Setting and Authenticity Verification for Suzhou's Urban Industrial Water Supply and Demand Model

We select the urban industrial water supply and demand model for parameter setting and authenticity verification. Suzhou City is located in the southeast of Jiangsu Province in China and in the middle of the Yangtze River Delta. The geographical position is superior and the economy is developing rapidly. In terms of innovation driven development, Suzhou City will soon become a "new first-tier city". Among the top four of the top 100 counties in China's county economy, there are three cities in Suzhou, namely, Kunshan, Zhangjiagang, and Changshu. Today, with the rapid development of China's economy, such cities will be the models of other cities.

As stated earlier, the whole industrial water system is divided into industrial water demand subsystem and industrial water supply subsystem. With the year 2013 as the base year, the data from 2013 to 2017 are used to test the authenticity of the system, and then to forecast the data for 2018–2030. The data sources include: 2013–2017 "Suzhou Water Resources Bulletin", "Suzhou City Statistical Yearbook", "Suzhou City Environmental Status Bulletin", "Suzhou City National Economic and Social Development Statistical Bulletin", and "Jiangsu Province Water Resources Yearbook".

By using these data, we test the authenticity of the industrial water system. Table 1 lists the initial values of the main variables involved in the Suzhou Industrial Water Requirements Subsystem:

Table 1. Initial values of main variables of industrial water demand subsystem in Suzhou City.

Variable	Initial Value
Total Industrial Water Demand/10^8 m^3	60.08
Power Industry Water Demand/10^8 m^3	51.3
Ten Thousand Yuan Industrial Added Value Water Consumption/m^3	14.9
Industrial Added Value/10^8 yuan	6370.37
Industrial Wastewater Discharge/10^8 m^3	6.65

For the industrial water supply subsystem, we collect the data from Jiangsu Water Conservancy Yearbook and refer to the relevant literature [19,21]. For the system parameters, we set as follows: industry capital formation rate $\mu = 0.85$, industry capital depreciation rate $\delta = 0.04$, industrial effective labor formation rate $\gamma = 0.98$, industry labor force abolition rate $\sigma = 0.02$, capital stock of urban water supply industry $K(0) = 1.81339 \times 10^{10}$ Yuan, and the labor stock of urban water supply industry $L(0) = 8253$ person.

For the values of the two elastic coefficients involved in the C–D production function, the initial parameter values for α and β were set as $\alpha = 0.7, \beta = 0.3$, the same as that in Reference [19], and were brought into our system dynamic model. Then the simulation was performed using Vensim software. From the simulation results, the results in output contained a large error when compared to the actual value. Due to the model transformation, the estimates of the parameters α and β need to change as the model changes [33]. As a result, the values of the two elastic coefficients were re-determined. The initial error value is mostly around 20%, which is large. So, our paper has fine-tuned around α and β. At last, we selected the group with the least error. The parameter values for α and β were set as $\alpha = 0.7143, \beta = 0.2857$. As the total water supply in Suzhou from 2013 to 2017 is basically the same as the total water demand, the historical data of the total industrial water supply is assumed to be equal to the total industrial water demand. The data input model, after continuous debugging, finds the value of the elastic coefficient suitable for Suzhou City:

From Tables 2 and 3, the error between the simulated value and the actual value obtained from the elastic coefficient after debugging is quite a bit smaller, and this indicates that the debugging process is effective.

Table 2. Industrial water supply total error value when α = 0.7, β = 0.3.

Year	2013	2014	2015	2016	2017
Error Value	24.47%	25.44%	15.3%	11.76%	11.95%

Table 3. Industrial water supply total error value when α = 0.7143, β = 0.2857.

Year	2013	2014	2015	2016	2017
Error Value	6.91%	−8.05%	4.52%	8.92%	8.73%

After the model is built, it is necessary to test the authenticity of the model. The Vensim software is capable of doing the visual and operational inspection of the model. If the operation test passes, the relevant historical data of Suzhou City 2013–2017 can be input into the model, and the simulated result is compared with the historical data. Table 4 shows the error values of the model:

Table 4. Model authenticity test result.

Variable / Year	2013	2014	2015	2016	2017
Actual Industrial Water Demand/10^8 m^3	60.08	65.73	61.96	63.26	67.03
Analog Value of Industrial Water Demand/10^8 m^3	60.79	66.03	62.42	63.37	67.78
Error	1.18%	0.46%	0.74%	0.17%	1.12%
Actual Value of Total Industrial Water Supply/10^8 m^3	60.08	65.73	61.96	63.26	67.03
Analog Value of Total Industrial Water Supply/10^8 m^3	55.93	60.44	64.76	68.9	72.88
Error	6.91%	-8.05%	4.52%	8.92%	8.73%

From Table 4, the error between all simulated values and actual values is within 10%. Although there is currently no uniform standard for the authenticity of system dynamics, many methods have been used in actual testing [34].

The error value is the reference value for the accuracy of some papers which use system dynamics to analyze water supply and demand balance. If the error is less than 10%, the model can be considered to be accurate, and the model can be used for subsequent predictive analysis. If the error value is higher than 10%, the model should be re-adjusted [28–31,35–40]. Hence, it may also be considered that the model built in this paper is in line with the actual situation and can be used for the next step of predictive analysis.

5. Program Design and Simulation Analysis

After the model has passed the authenticity test, we can use it to carry out the next step of predictive analysis. If we continue to develop, according to the current trend, that is, without changing any parameters in the model, we find that by 2030, the supply and demand difference of industrial water in Suzhou City will be as high as 41.18×10^8 m^3. Figures 2 and 3 are the current status of industrial water supply and the demand comparison chart and supply and demand balance trend chart.

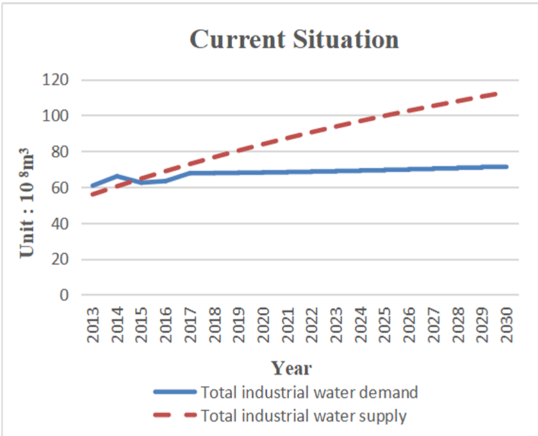

Figure 2. Comparison of supply and demand of current.

Figure 2 shows that the total industrial water supply and total industrial water demand have been increasing by 2030, and the total industrial water supply increased faster than total industrial water supply. Figure 3 shows that the difference between the total industrial water supply and total industrial water demand in 2030 will reach 41.18×10^8 m^3. The results show that if we continue to develop according to the current investment and labor input levels, the future industrial water will excess the demand largely, which is a waste of resources. It does not meet the development requirements of establishing a water-saving society in China, and may even increase the problem of conflicts in the distribution of water between various industries.

The main problem of the current situation plan is that if the current situation continues, the industrial water supply will be much more than the industrial water demand, so the solution we designed will adjust the industrial water supply. The two variables of industrial capital investment I and industrial labor input P are used as control variables to regulate the total amount of industrial water supply. Based on the current stage of industry capital investment I and industry labor input P, different parameters are set and multiplied separately. The specific case design is shown in Table 5. The initial values of the two variables of industry capital investment I_0 and industry labor quantity P_0 are from the relevant data estimates in the 2013 Suzhou Water Resources Yearbook. In our paper, $I_0 = 2.897 \times 10^9$ Yuan, $P_0 = 536$ people.

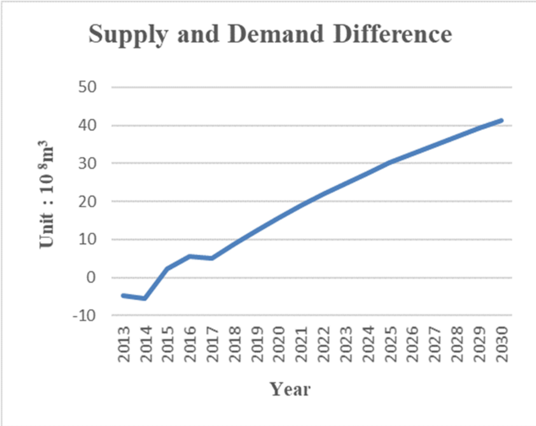

Figure 3. Supply and demand balance of current situation.

Table 5. Specific case.

P \ I	$0.4\boldsymbol{I}_0$	$0.6\boldsymbol{I}_0$	$0.9\boldsymbol{I}_0$	$1.1\boldsymbol{I}_0$
$\mathbf{0.5}P_0$	Case1	Case5	Case9	Case13
$\mathbf{0.8}P_0$	Case2	Case6	Case10	Case14
$\mathbf{1.2}P_0$	Case3	Case7	Case11	Case15
$\mathbf{1.5}P_0$	Case4	Case8	Case12	Case16

After simulating these 16 cases, we classify and sort out the simulated results, which can be divided into the following four categories: supply less than demand, supply equals demand, supply exceeds demand, and supply much larger than demand.

(1) Supply Less Than Demand

This situation appears in Case 1 and Case 2. Figures 4 and 5 are comparisons of supply and demand for Case 1 and Case 2.

Figures 4 and 5 show that when the Case 1 and Case 2 are put into practice, the total industrial water demand will always exceed the total industrial water supply, and the difference between supply and demand is always negative. These two cases cannot meet the rapid development of social and economic conditions, and are inconsistent with current productivity requirements. So, these two cases are eliminated.

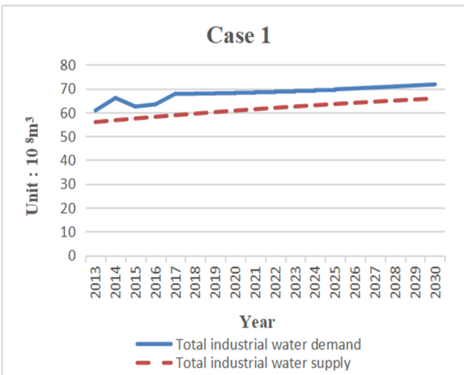

Figure 4. Supply and demand comparison of Case 1.

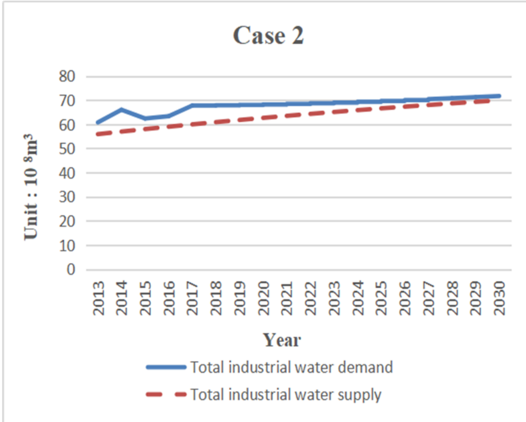

Figure 5. Supply and demand comparison of Case 2.

(2) Supply Equals Demand

The supply equals demand type is the most ideal state. The difference between industrial water supply and industrial water demand indicates that such a combination of investment and labor can meet the needs of social development without wasting water resources, while also guaranteeing a small surplus for future use. Cases 3–6 are all examples of this. Figures 6–9 are comparisons of supply and demand for these several cases.

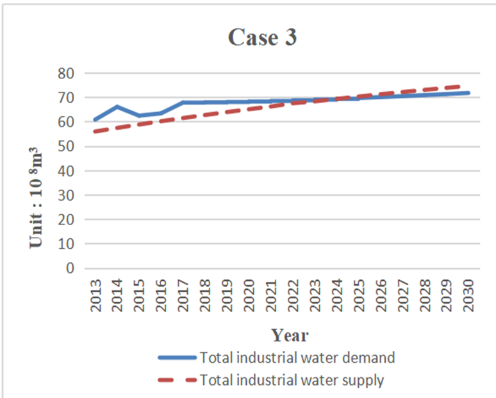

Figure 6. Supply and demand comparison of Case 3.

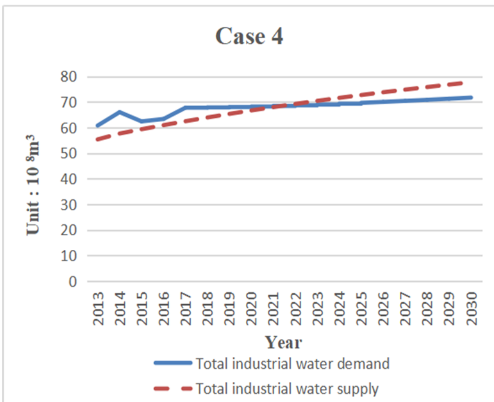

Figure 7. Supply and demand comparison of Case 4.

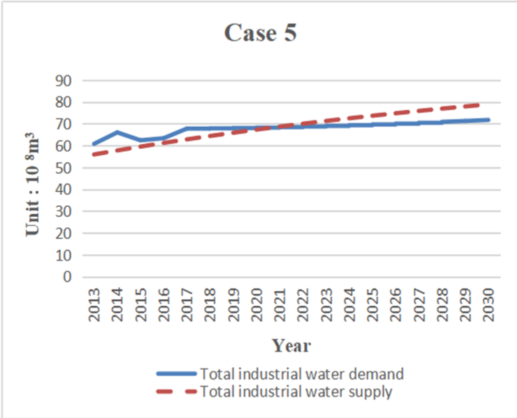

Figure 8. Supply and demand comparison of Case 5.

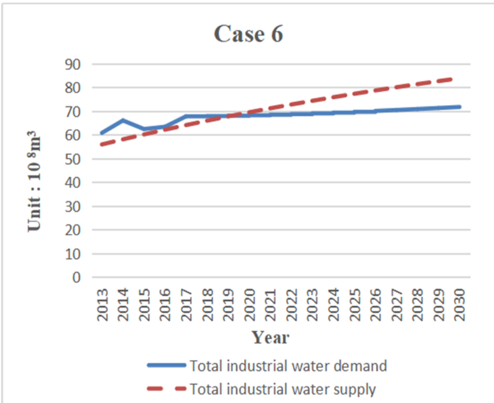

Figure 9. Supply and demand comparison of Case 6.

Figure 6 shows that the supply and demand difference in 2030 will reach 2.92×10^8 m^3 when we use Case 3, the total industrial water demand and the total industrial water supply will be equal at 2024. Figure 7 shows that the supply and demand difference in 2030 will reach 6.01×10^8 m^3 when we use Case 4, the total industrial water demand and the total industrial water supply will be equal at 2021. Figure 8 shows that the supply and demand difference in 2030 will reach 6.64×10^8 m^3 when we use Case 5, the total industrial water demand and the total industrial water supply will be equal at 2021. Figure 9 shows that the supply and demand difference in 2030 will reach 12.1×10^8 m^3 when we use Case 6, the total industrial water demand and the total industrial water supply will be equal at 2020. Among them, the investment value of Case 3 and 4 is $I_3 = I_4 = 0.4I_0$, $I_3 = I_4 = 0.4I_0$, and the labor input is $P_3 = 1.2P_0$, $P_4 = 1.5P_0$. This shows that in the case of a small investment value, the demand for industrial water supply can be met by increasing the input of labor. Similarly, when the input level of labor is insufficient, the demand can be met by raising the investment level. This conclusion can be reflected in Case 5 and 6. The investment values of Case 5 and 6 are $I_5 = I_6 = 0.6I_0$, and the labor input is $P_5 = 0.5P_0$, $P_6 = 0.8P_0$. Compared with Case 3 and 4, the labor level has dropped significantly, but at the same time the investment level has also increased. At present, the aging problem in population in China is very serious. The direct problem brought about by the aging of the population is that the labor input will be less and less. When the labor level is seriously insufficient, it can be balanced by adjusting investment.

(3) Supply Exceeds Demand

The cases in which the industrial water supply volume is higher than the industrial water demand, but smaller than the supply-demand difference value of the current-type case, are summarized as the type of supply exceeds demand. The several cases here are better than the current situation, but they are still worse than the supply equals demand. However, there are merits in these options. If the industrial structure of Suzhou changes or the investment and labor levels cannot be adjusted to the optimal state in the future, these solutions are still a good choice. These several cases are: Cases 7–13. Figures 10–15 show the comparisons of supply and demand for these cases.

Figure 10 shows that the supply and demand difference in 2030 will reach 17.72×10^8 m^3 when we use Case 7. Figure 11 shows that the supply and demand difference in 2030 will reach 21.42×10^8 m^3 when we use Case 8. Figure 12 shows that the supply and demand difference in 2030 will reach 25.27×10^8 m^3 when we use Case 9. Figure 13 shows that the supply and demand difference in 2030 will reach 31.28×10^8 m^3 when we use Case 10. Figure 14 shows that the supply and demand difference in 2030 will reach 38.18×10^8 m^3 when we use Case 11. Figure 15 shows that the supply and demand difference in 2030 will reach 36.58×10^8 m^3 when we use Case 13. From these figures, we can see these kinds of cases may have the phenomenon of water resources wasting. If these cases are implemented, the use of excess water resources should be taken seriously. Perhaps we can avoid wasting through cross-industry or cross-regional borrowing and other measures.

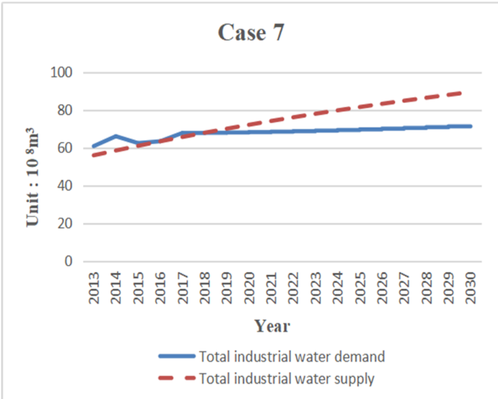

Figure 10. Supply and demand comparison of Case 7.

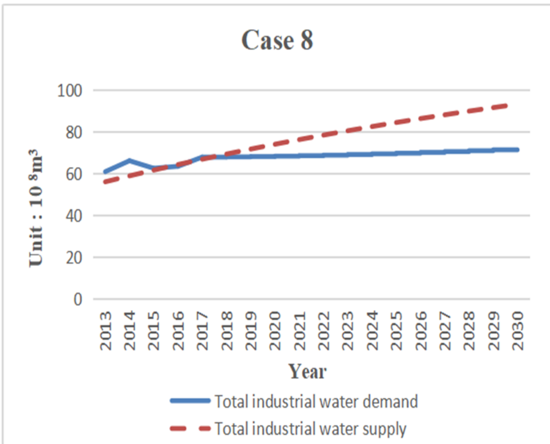

Figure 11. Supply and demand comparison of Case 8.

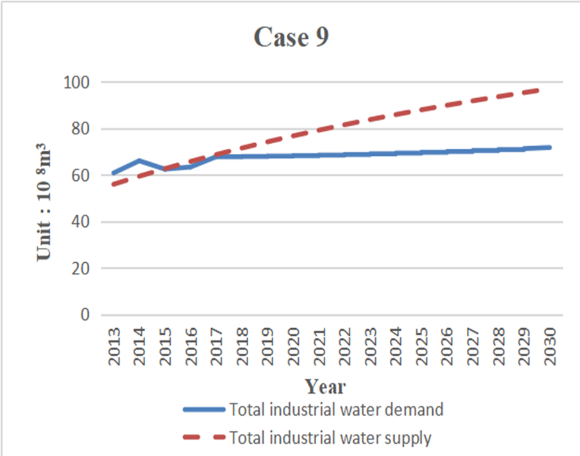

Figure 12. Supply and demand comparison of Case 9.

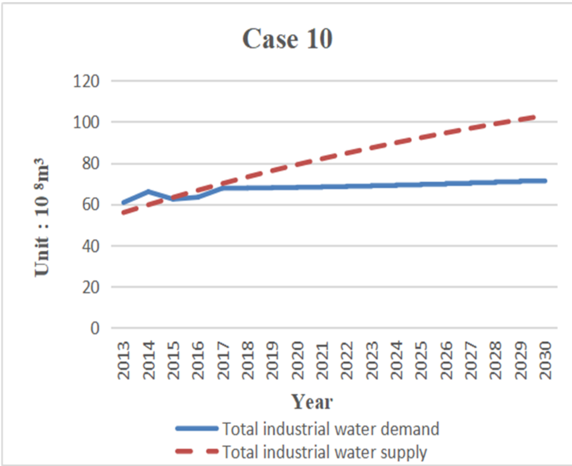

Figure 13. Supply and demand comparison of Case 10.

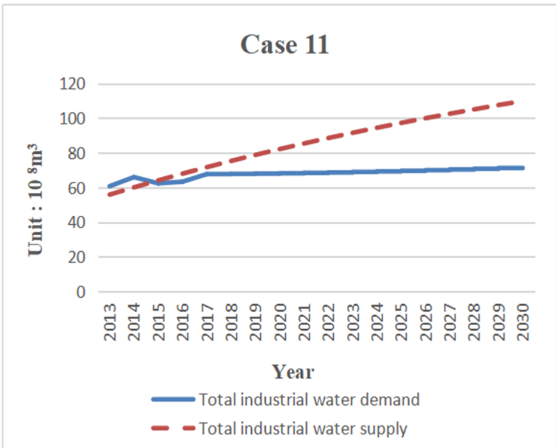

Figure 14. Supply and demand comparison of Case 11.

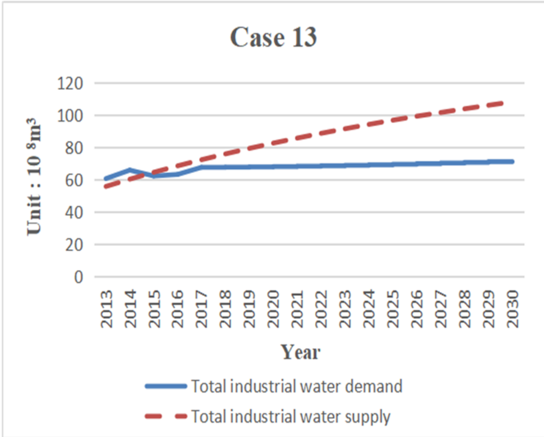

Figure 15. Supply and demand comparison of Case 13.

(4) Supply Much Larger than Demand

This situation appears in Cases 12–16. Figures 16–19 show the comparisons of supply and demand for Cases 12–16.

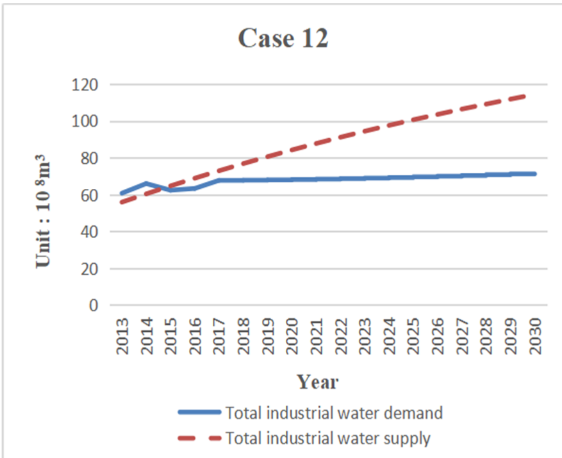

Figure 16. Supply and demand comparison of Case 12.

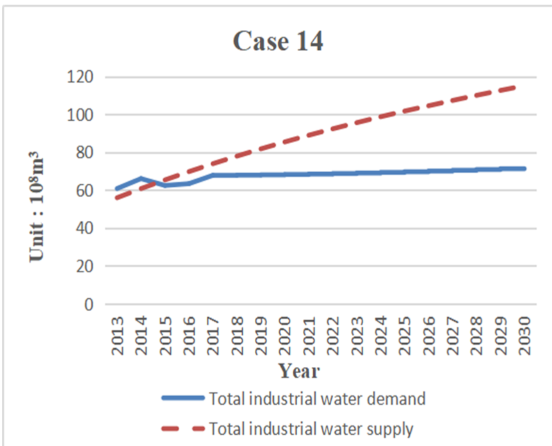

Figure 17. Supply and demand comparison of Case 14.

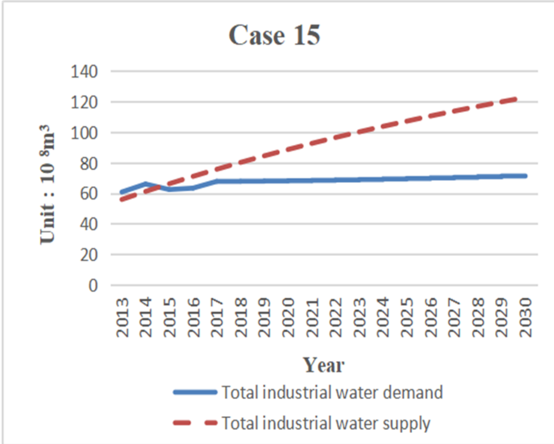

Figure 18. Supply and demand comparison of Case 15.

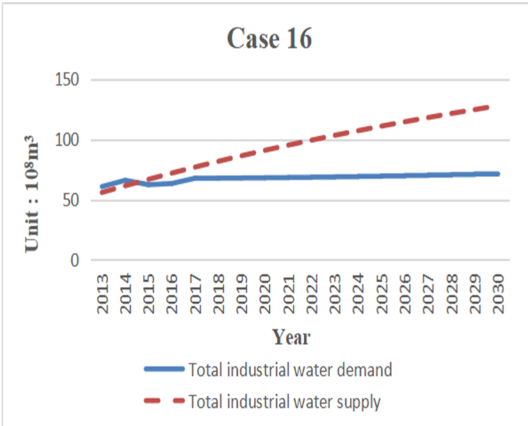

Figure 19. Supply and demand comparison of Case 16.

Figure 16 shows that the total industrial water supply is higher than the total industrial water demand since 2015, and the supply and demand difference in 2030 will reach 42.78×10^8 m^3. Figure 17 shows that the supply and demand difference in 2030 will reach 43.38×10^8 m^3. Figure 18 shows that the supply and demand difference in 2030 will reach 51.08×10^8 m^3. Figure 19 shows that the supply and demand difference in 2030 will reach 56.18×10^8 m^3. The supply and demand differences of these cases are all larger than the current situation. Therefore, the combination of these kinds of investment and labor levels does not optimize the model. So, we eliminate these cases.

Through comparing Case 12 and 13, it is found that Case 12 is inferior to the current situation, Case 13 is superior to the current situation, and investment and labor input of Case 12 is: $I_{12} = 0.9I_0$, $P_{12} = 1.5P_0$, the investment and labor input of Case 13 is: $I_{13} = 1.1I_0$, $P_{13} = 0.5P_0$. Comparing the two sets of values, the labor input of the Case 13 is significantly reduced compared with Case 12, but the increasing of investment level is very limited, which indicates that adjusting the investment level is more effective than adjusting the labor level. Moreover, from a practical point of view, it is easier to adjust the level of investment than to adjust the level of labor.

6. Conclusions

This paper combines the C–D production function and system dynamics model, establishes supply and demand model managing urban industrial water, selects investment and labor input as the control variables, takes Suzhou city as the case, and uses the data of 2013–2017 to test the authenticity of the system. By elaborating the specific situation of Suzhou City, and through a series of simulation analyses and case studies, the different investment values and labor input values were designed and 16 kinds of solutions were obtained. Furthermore, the 16 solutions were divided into four categories: supply less than demand, supply equals demand, supply exceeds demand, and supply much larger than demand. The balance between supply and demand is a most suitable setting for Suzhou City to develop, and the next is the type of supply exceeds demand. The other two types cannot meet the development requirements. When the changes in industrial structure or levels of the investment and labor cannot be adjusted to an optimal state, the type supply exceeds demand can be adopted. In conclusion, compared with adjusting the value of investment, adjusting the value of labor input is easier. While drawing the ideal combination of investment and labor input, a reasonable range of investment and labor input is also provided: the scope of investment adjustment is $0.6I_0 - 1.1I_0$, and the adjustment range of labor input is $0.5P_0 - 1.2P_0$. When the investment value rises, the labor input can be reduced; when the value of the labor input falls, the investment level can be increased in an appropriate amount. These two can be balanced by mutual balancing to achieve an overall system balance.

Author Contributions: K.L. and T.M. conceived and designed the model; K.L. and T.M. performed the case simulation and analyzed the data; T.M. wrote the paper; and G.W. reviewed and edited the manuscript. Y.Z. and X.F. participated in the revision of results. All the co-authors contributed substantially to the work reported.

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