Analysis of China's Water Shortage Model and Relevant Strategies in the Next 20 Years

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Abstract—**This paper figured out an action plan of China national water strategies to resolve the shortage of the available water resources in China in 2025. We divided our strategy mainly into three steps: prediction, solutions and impacts. We use the grey model GM (1, 1) to predict the water condition of China in 2025 at both a national level and a provincial level. Then, we provide two solutions in order to perfect the water condition in different areas separately. (1) Taking time value of capital into consideration, we use Dijkstra algorithm to optimize weighted topological structure of pipeline system. (2) We have established a cost model of desalination plant structure. Finally, we discuss the implications of our strategy from economic and physical aspects.**

Index Terms—**Water strategy, grey model, dijkstra algorithm, pipeline system, desalination, cost model**

I. Introduction

Across China, the nation’s water resources include 2,711.5 cubic kilometers of mean annual run-off in its rivers and 828.8 cubic kilometers of groundwater recharge. As pumping water draws water from nearby rivers, the total available resource is less than the sum of surface and groundwater, and thus is only 2,821.4 cubic kilometers. 80% of these resources are in the South of China. However, Over-extraction of groundwater and falling water tables are big problems in China, particularly in the north. As a result, more than 60,000 square kilometers of ground surface have sunk with more than 50 cities suffering from serious land subsidence. This paper argued an plan to resolve the shartage of the available water resources in China in future. This article takes the 2013 American Mathematical Contest in Modeling's topic and author's prize mernoir (Meritorious) as the foundation to do the systematic and comprehensive research.

Considering that it is roughly difficult to predict accurately the data of future due to the complexity and diversity of two variables and the uncertainty of elements such as precipitation and population, we use the grey model GM (1, 1), a differential equation with only one single variable, to predict the national and provincial quantity of fresh water storage and water consumed in 2025 from the corresponding data during 1999-2012. As a result, there are 17 areas estimated to have a lack of water, and we analyze 2 typical provinces of which separately.

The whole process of water supply network optimization includes three stages: planning, design, and operation management, while stage two---the optimized design of the pipeline network of water supply is the key to the whole process and has a direct impact on other two stages. Despite the considerable research being conducted on this issue, current models often ignore the time value of money since the costs of pipeline construction and management are not charged in the same period of time. Meanwhile, these models mostly build their designs of pipeline locations on experience, which severely hurts the results of optimization. Thus, combined with the current situation of fresh water shortage in Shanghai, we propose two steps to fix this problem: target function on the cost calculation of optimizing pipeline network, and topological structure of pipe system. In order to spread the model across China, we classify China into four parts in terms of economy and water resources to design the national water supply system.

Next we establish a cost model of desalination plant structure illustrated by the example of Qingdao City. We divided the overall cost into two parts---value of the desalinated seawater and initial investment fee of desalination. The former component includes values in both use and scarcity which reflects its similarity to other water resources, and that the latter one should count but is not limited to following costs: water resources survey, exploration, monitoring, planning, scientific research and management fee.

Finally, we discuss the implications of our strategy from economic and physical aspects.

II. Grey Prediction

A. Establishment of the GM (1,1) Model

To begin with, we need to inspect the given data [1], [2] to insure the feasibility of the model [3]. We treat the amount of freshwater and water consumption as the raw sequence

$$x^{(0)} = (x^{(0)}(1), x^{(0)}(2), \dots, x^{(0)}(n))$$

So ratio of the sequence is

$$\lambda(k) = \frac{x^{(0)}(k-1)}{x^{(0)}(k)} \quad (k = 2,3,\cdots,n)$$

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If all the $\lambda(k)$ fall in the accommodating range $(e^{-\frac{2}{n+1}}, e^{\frac{2}{n+2}})$, then we can use the raw sequence for the model GM (1, 1) to predict. Otherwise, we need to do translation transformation to the sequence in order to make it fall into the range.

In accordance with the principles above to establish the GM (1, 1), One-accumulated sequence can be expressed as

$$\hat{x}^{(1)}(k+1) = (x^{(0)}(1) - \frac{b}{a})e^{-ak} + \frac{b}{a}$$
$$(k = 1, 2, \cdots, n-1).$$

Therefore, the predictive value of certain moment is

$$\hat{x}^{(0)}(k+1) = \hat{x}^{(1)}(k+1) - \hat{x}^{(1)}(k) \quad (k = 1, 2, \cdots, n-1)$$

B. Prediction of Water Condition in 2025

The result of matlab program shows that there are 17 areas lacking of water supply. We choose 2 typical provinces to conduct the prediction analysis [4].

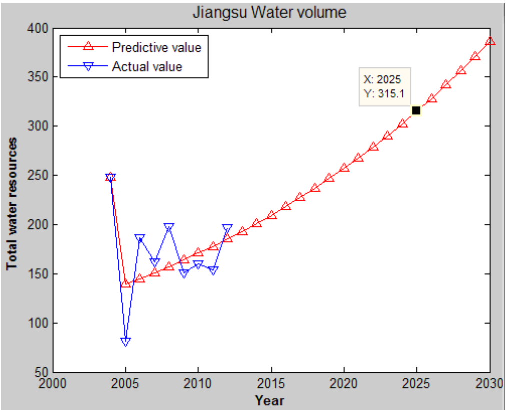

Figure 1. The total amount of fresh water of Jiangsu

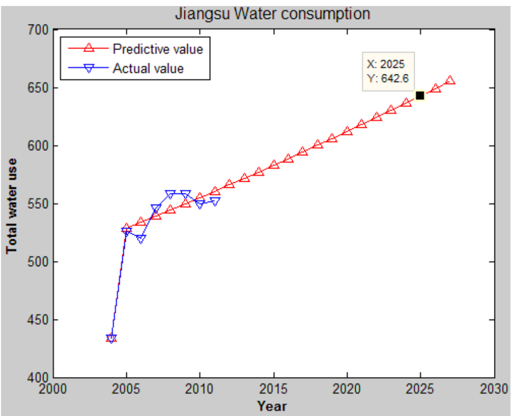

Figure 2. Water consumption of Jiangsu

In 2025, the total amount of fresh water in Jiangsu Province is 315.1 million m^3 and the total amount of water consumption is 635.1 million m^3. It is a typical city that has severe over-extraction of water resource. The gap between the supply and demand is as high as 50.97%. Besides, Jiangsu, Shanghai, Beijing and Hebei are also in the same case.

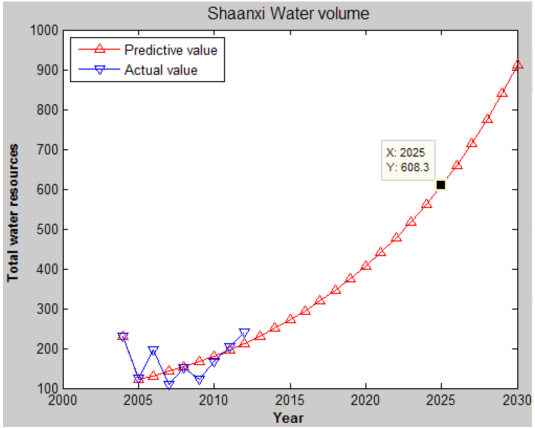

Figure 3. The total amount of fresh water of Shaanxi

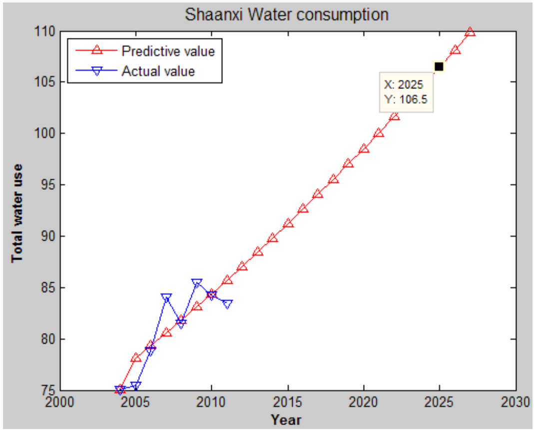

Figure 4. Water consumption of Shaanxi

In 2025, the total amount of fresh water in Shaanxi Province is 608.3 million m^3 and the total amount of water consumption is 106.5 million m^3. Although it has plenty of water resources, the available proportion is very few. Shaanxi's Urgent priority is to increase the rate of exploitation and utilization of fresh water resources.

III. Optimization of Topological Structure of Pipe System

A. Target Function on Cost Calculation of Optimizing Pipeline Network

The overall cost includes construction cost C and management cost M, while M contains operation cost M_2 and depreciation cost M_1 which is calculated in a certain proportion of construction cost. Therefore, he traditional expression of total annual fee during repayment period of investment is

$$W_t = \frac{C}{t} + M_1 + M_2$$

In order to compensate for the inadequacy of the traditional target function, we introduce a concept in engineering economics---capital recovery, uniform series. The new target function is

$$W_t = C \times \left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] + M_1 + M_2$$

Construction cost C symbols principal and i represents annual interest rate, and annual amortization of principal and interest equals $C\times\left[\frac{i(1+i)^n}{(1+i)^n-1}\right]$ and all will be paid off in n years.

B. Optimization of Topological Structure of Pipe System in Shanghai.

We use Dijkstra algorithm to realize this optimization and figure out the shortest path [5].

1) Structure in Shanghai

(1) Firstly, determine the pipe network node, which can be chosen from the road crossing point where the population is concentrated, the industry is developed and the distance is appropriate. Red-marked areas in Fig. 5 are the centers of the city and can be used as nodes of the water supply pipeline.

Figure 5. Shanghai urban system.

Figure 6. Undirected graph of Shanghai urban system [6].

(2) In order to establish the undirected graph (Fig. 6), the choice of route should avoid residential areas, and transportation lines as much as possible and more high-water-consumption regions should be passed in order to maximize the reuse rate of the water supply pipelines.

(3) The determination of cost of pipe construction on each side in the undirected graph is based on the distance and position between the nodes. Divide range and area of services in terms of the residential condition; calculate the traffic through each node in terms of the service area, the population density of each node, the standard of water use and centralized flow rate of great industrial enterprises; and conduct the calculation under the circumstance that the value of pump head equals that of pump station efficiency.

(4) Get the weighted least expenditure according to the weighted directed graph via Dijistra algorithm and arrange the distribution of the dry pipes [7].

We also notice that the nodes of water supply system in Shanghai are distributed radially. Thus we can use star topology structure to describe the overall water supply system, not only being able to accept multi-recourses of water but also ensuring the waterworks' complementary.

2) Structure in China

We classify all the provinces, in terms of GDP and water resources, into four types as shown in Table I, and draw the distribution pattern of each type showed by Fig. 7.

We draft the undirected graph (Fig. 8) and mark the weight of each line so as to design the national water supply system reasonably and rationally [8].

TABLE I. THE CLASSIFICATIONS OF CHINESD 31 PROVINCES

<table>
<tr><td colspan="3">Low GDP and few water</td></tr>
<tr><td colspan="2">The total fresh water resources is insufficient</td><td rowspan="2">The usage rate is not high</td></tr>
<tr><td>Interior</td><td>Coast</td></tr>
<tr><td>Ningxia Gansu Xinjiang Shanxi</td><td>Tianjin</td><td>Shaanxi Guizhou</td></tr>
<tr><td colspan="3">High GDP but few water</td></tr>
<tr><td colspan="2">The total fresh water resources is insufficient</td><td rowspan="2">The usage rate is not high</td></tr>
<tr><td>Interior</td><td>Coast</td></tr>
<tr><td>Henan Hebei Beijing Anhui InnerMongolia Heilongjiang</td><td>Jiangsu Shandong Liaoning Shanghai</td><td></td></tr>
<tr><td colspan="3">Low GDP but much water</td></tr>
<tr><td colspan="3">Guangxi Jiangxi Jilin Chongqing Yunnan Hainan Tibet Qinghai</td></tr>
<tr><td colspan="3">High GDP and much water</td></tr>
<tr><td colspan="3">Guangdong Zhejiang Sichuan Hunan Hubei Fujian</td></tr>
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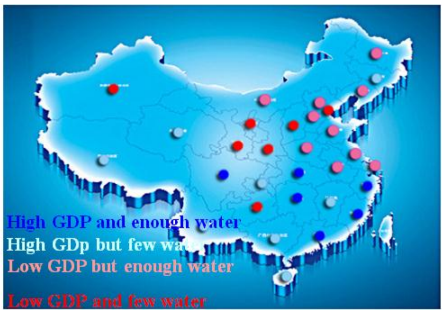

Figure 7. Distribution of 4types

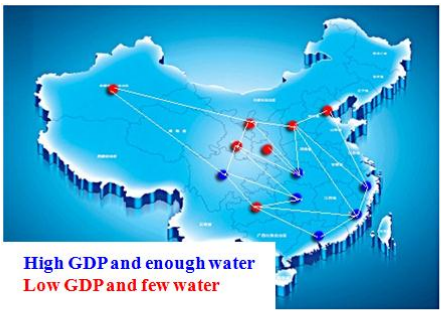

Figure 8. Design the national water supply system

IV. DESALINATION

We take Qingdao City as an example to calculate and analysis the cost of seawater desalination. The overall cost of desalination of water resources per ton, P, can be expressed as

$$P = \alpha P_1 + \beta P_2 + P_3 .$$

This project is located in the east coast of Jiaozhou Bay, and the average daily seawater here is $2.569 \times 10^9\, m^3$. However, the daily displacement and the daily requirement of seawater only account for 0.011% of the total amount. It is clear that this project does no harm to the local environment, which means the scarcity value of seawater, βP_2, here roughly equals to 0 [9].

According to the local regulations that the cost of water per hectare is no less than 1500 RMB per year, then use value of desalinated water is

$$V_{seawater} = \frac{1500}{10000 \times 7} = 0.0214\,RMB/m^3 \cdot$$

According to the different water use, we divided objects into six categories: life and food quality, industrial water, municipal water, aquaculture, forestry and agricultural water. The usefulness correction factors calculated by the Delphi method are

$$\alpha_2 = \sum_{j=1}^{6} (\omega_j \alpha_{2j}) / \sum_{j=1}^{6} \alpha_{1j} = 0.1500,$$

$$\alpha_4 = \sum_{j=1}^{6} (\omega_j \alpha_{4j}) / \sum_{j=1}^{6} \alpha_{1j} = 0.0281 \cdot$$

Therefore, the use value of desalinated water, αP_1, in this project is

$$\alpha P_1 = \frac{\alpha_2}{\alpha_4} V_{seawater} = 0.1142\,RMB/m^3 \cdot$$

We still need to explore, develop and protect the water during the desalination process. Based on the record, the total number of initial investment fee is approximately 1.2 million RMB. Assume that it will be working for 25 years, then the initial investment fee of water desalination per ton P_3 is

$$P_3 = \frac{12 \times 10^5}{10 \times 10^4 \times 365 \times 25} = 0.0013\,RMB/m^3 \cdot$$

Therefore, cost of desalination of water resource is

$$P = \alpha P_1 + \beta P_2 + P_3 = 0.1142 + 0 + 0.0013$$
$$= 0.1155\,RMB/m^3 .$$

V. The Economic and Physical Implications of the Strategy

The demand of weighted topological structure of pipeline system is very high to the local financial resource condition. Making the provinces' internal pipeline system better will promote the development of local water transportation system, and it will also improve the circulation for industrial water, agricultural irrigation and the convenience of domestic water, while also promoting the development of major local industry.

If some provinces can establish seawater desalination research and development center, they can attract more talented people to join this project and increase the influence of this technology in the scientific community. In addition, they can send the best people to the other advanced desalination technology countries to learn advanced knowledge and bring it back to China.

Acknowledgment

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