Research on the Optimization of Water Resource for the First Phase of the Central Route of the South-north Water Diversion Project

Xiao ZHENG[1,a], Chui-Yong ZHENG[1,b,*], Min ZHAO[1,c]

[1]Business School, Hohai University, Nanjing 210098, P.R.China

[a]842081896@qq.com, [b]chyzheng@hhu.edu.cn, [c]minzhao@hhu.edu.cn

*Corresponding author

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Abstract. Ministry of Water Resources and the State Water Diversion Office issued a "optimal allocation of water diversion project together key technologies," the research main results will be introduced .This manuscript seeks to analyze the guiding ideology, the basic principles, decision variables, and constraints, propose the necessity of a study of South-North Water Diversion Project optimal allocation of water resources, and objective functions for the First Phase of the Central Route of the South-North Water Diversion Project, and suggest an optimized model for water resource allocation. Its main innovation is to coordinated regional development theory and the combination of multi-objec, and aims to explore the optimization of model parameters based on the model for the First Phase of the Central Route of the South-North Water Diversion Project. Calculation of values and analysis on the practicality of this model would provide guidance for governmental decision-making.

Introduction

The South-North Water Diversion Project encompasses over the Yangtze River Basin and the Yellow River Basin, and involves many stakeholders, such as Beijing, Tianjin, Hebei, Hubei, and other provinces (cities). Water resource management is complex. Different local departments may have biased opinion in how to use diverted water and local water to support local functions, such as production, daily living, and ecology. In addition, due to the seasonal dependence of water supply and water demand, there is mutual coordination and mutual constraint in terms of water resource management and decision-making for both Water Source Area and Water Receiving area. For such a huge project that involves multiple basins, regions, and objectives, a critical issue is how the government can use macro-controls and market mechanisms to balance the interests of various stakeholders. Hence, the success or failure of the South-North Water Diversion Project hinges on how scientific, reasonable, and efficient management is carried out to maximize the desired economic, social, and ecological benefits.

Optimization of Water Resource for the First Phase of the Central Route of the South-North Water Diversion Project

The Basic Ideas and Principles of Model Construction.

There are several principles for water resources allocation. The first is to ensure the fulfillment of special demands, and determine investment proportions based on the principle of “who invests, who benefits”. The second is to meet the minimum water requirement of daily living. The third is to meet the minimum water requirement of three industries. The fourth is to meet the minimum water requirement of two industries. The last is to optimize allocation of water resource based on the aforementioned four principles.

Model Construction

This model uses a multi-objective programming approach and sets four objectives: maximizing GDP contribution for water sector, minimizing water scarcity for water receiving area, maximizing net profits for water company, and maximizing fiscal revenue for Water Receiving Area. The four goals are expressed in weight functions, and each variable is divided by the average for generalization.

Decision Variables

Decision variable x_i : x is the variable with possible values from 1, 2, 3, …to i.

Mathematical expression of the Model

$$\mathrm{Z} = \max\ f(x) = \alpha + \beta \sum_{i=1}^{k} x_i m_i + \gamma \sum_{i=1}^{k} x_i b_i - \theta \sum_{i=1}^{k} p_i \frac{k(d_i - x_i)}{\sum_{i=1}^{k} (d_i - x_i)}$$

In the formula, x_i represents the configuration of water at the i-th port door. αβγθ denote the weight function for each variable respectively, and α + β + γ + θ = 1. p_i is a weight function that denotes the different degrees of importance for each outlet door, and there is $\sum_{i=1}^{k} p_i = 1$, g_i indicating the GDP per unit of water after generalization. There is $g_i = \frac{gdp_i}{\frac{1}{k}\sum_{i=1}^{k} gdp_i}$, where gdp_i is the GDP per unit of water at the i-th entrance. m_i is the fiscal revenue per unit of water at the i-th entrance after generalization, and there is $m_i = \frac{M_i}{\frac{1}{k}\sum_{i=1}^{k} M_i}$, where M_i is the actual fiscal revenue per unit of water at the i-th entrance. b_i is the net profit per unit of water at the i-th entrance after generalization and there is $b_i = \frac{B_i}{\frac{1}{k}\sum_{i=1}^{k} B_i}$, where B_i is the actual net profit per unit of water at the i-th entrance. d_i is the water demand at the i-th entrance, and k is the number of port doors for Water Receiving Area.

Constraints

a. Non-negative constraints: $x_i \geq 0$, where i = 1, 2,……,k (1)

b. Constraints on available water supply: $\sum_{i=1}^{k} x_i \leq W_{\max}$ (2)

where $W_{\max}$ represents the amount of water available for distribution.

c. Constraints embedded in distribution principles: $x_i \geq R_{1i}P_i + \eta_i R_{2i} SV_i + \delta R_{3i} TV_i - W_{0i}$ (3)

In the this formula, R_{1i}, R_{2i} and R_{3i} are quota of domestic water at the i-th entrance, quota for industrial water, and quota for three industries, respectively. P_i is the population of the Watering Receiving Area at the i-th entrance. SV_i and TV_i represent the total value of industrial output and the total output value of three industries at the i-th entrance. W_{0i} is the sum of local water supply and diverted water supply according to its proportion of investment at the i-th entrance. η_i and δ_i are priority coefficients. Under normal circumstances, their values are equal to one. During extremely dry years, their values are set to zero.

d. Constraints on water demand: $D_{\min} i \leq x_i \leq D_{\max} i$ (4)

In the formula, $D_{\min} i$ and $D_{\max} i$ represent the minimum water demand and the maximum water demand at the i-th entrance, respectively.

e. Constraints on water carrying capacity: $x_i \leq Q_{\max} i$ (5)

In this formula, $Q_{\max} i$ is the maximum carrying capacity at the i-th entrance .

f. Constraints on coordinated regional development:

$$\mu = \sqrt{\mu_{B_1}(\sigma_1) * \mu_{B_2}(\sigma_2) * \mu_{B_3}(\sigma_3)} \geq \mu^* \quad (6)$$

In this formula, μ is the index of regional development coordination. μ^* is the minimum value for regional development coordination. σ_1, σ_2 and σ_3 represent the ratio of water supply to water demand, and the ratio of water demand to fiscal revenue, respectively.

For the coordinated regional development constraints, "μ" is chosen to measure the level of development in social, economic, resource, environmental aspects for that region. It entails to coordination in three aspects: water supply and water demand, regional economic development and utilization of water resources, as well as regional economic development and water environment. Since degree of coordination is a vague concept, membership function from fuzzy mathematics is used to denote coordination in these three aspects.

σ_1 has the following formula:

$$\begin{cases} \sigma_1 = \dfrac{\sum_{i=1}^{k} \lambda_i x_i}{\sum_{i=1}^{k} d_i} \\ \sum_{i=1}^{k} \lambda_i = k \end{cases}$$

In the formula, x_i is the water supply at the i-th entrance; d_i is the water demand at the i-th entrance; λ_i is the degree of the importance for water supply at the i-th entrance, and $\lambda_i \approx 1$.

$$\mu_{B_i}(\sigma_1) = \begin{cases} 1.0 & \sigma_1 \geq \sigma_1^* \\ \exp\left[-4(\sigma_1 - \sigma_1^*)^2\right] & \sigma_1 < \sigma_1^* \end{cases}$$

In this formula, σ_1^* is the ratio of regional water supply to demand, and is generally set to have a value of 1.0. B_1 is the fuzzy subset coordination for water supply and demand.

σ_2 has the following formula:

$$\begin{cases} \sigma_2 = \dfrac{\sum_{i=1}^{k} \varphi_i F_i}{\sum_{i=1}^{k} E_i} \\ \sum_{i=1}^{k} \varphi_i = k \end{cases}$$

In the formula, F_i is the water use at the i-th entrance. E_i is the economic indicator (i.e. GDP, fiscal revenue) at the i-th entrance. φ_i is the degree of importance for water demand at the i-th entrance.

Constraints on the coordination of development:

$$\mu = \sqrt{\mu_{B_1}(\sigma_1) * \mu_{B_2}(\sigma_2)} \geq \mu^*$$

Constraints on Fairness:

$$\frac{\sum_{i=1}^{k} d_i}{\sum_{i=1}^{k} x_i}(1-20\%) \leq \frac{d_i}{x_i} \leq \frac{\sum_{i=1}^{k} d_i}{\sum_{i=1}^{k} x_i}(1+20\%)$$

Parameter determination for the First Phase of the Central Route of South-North Water Diversion Project.

To Determine the Weight Function of Indexes in the Objective Function

In the objective function, parameters αβγθ are used to denote the weight function s of GDP, fiscal revenue, water company's net contribution (NC), water loss and other indexes. ρ_1 is the weight function of different outlet doors. How to determine the index weight becomes one of the key issues in deriving an optimal model for resource allocation. Analytic network process (ANP) is used to determine the weight for each indicator, and α= 0.272089, β= 0.137215, γ= 0110521, θ= 0480175.

The First Phase of the Central Route of the South-North Water Diversion Project has a static total investment of 91.74 billion Chinese yuan. 14.68 billion Chinese yuan goes to strengthening Danjiangkou Reservoir Dam and the associated resettlement compensation costs, in which 80% comes from the capital (central government is responsible for 60%, while local governments are responsible for 40%), and 20% comes from loans. The mid-lower reaches of the Hanjiang River project has an investment of 68.6 billion Chinese yuan, all provided by central funding.

The First Phase of the Central Route is estimated to have an annual water diversion of 9.5 billion cubic meters on average. Taking into account the losses from distribution, the net amount of water that can be diverted to North is 7.8 billion cubic meters. According to the investment proportions (central government 70%, local governments 30%), the central government is entitled to 2.34 billion cubic meters of water. The local shares are calculated according to each stakeholder's investment proportion: 314 million cubic meters for Henan, 885 million cubic meters for Hebei, 632 million cubic meters for Beijing, and 509 million cubic meters for Tianjin.

Due to optimization of allocation for the central investment, the available water is $\mathrm{W}_{\max} = 5.46$ billion m^3. The constraint on available water supply is:

$$\sum_{I=1}^{k} x_i \le 54.6$$

b. Constraints embedded in distribution principles:

$$x_i \ge R_{1i}P_i + \eta_i R_{2i} SV_i + \delta R_{3i} TV_i - W_{0i}$$

In the this formula, R_{1i}, R_{2i} and R_{3i} are quota of domestic water at the i-th entrance, quota for industrial water, and quota for three industries, respectively. P_i is the population of the Watering Receiving Area at the i-th entrance. SV_i and TV_i represent the total value of industrial output and the total output value of three industries at the i-th entrance. Results are shown in Table3.1

Table3.1

Index / Region	Gross industrial output value (0.1 billion, Chinese yuan)	The total output value of three industries(0.1 billion, Chinese yuan)	Population (10thousand)
Henan	3453.68	2085.21	1969.00
Hebei	2606.19	1947.91	561.35
Beijing	1707.00	4764.30	1286.10
Tianjin	1885.04	1534.07	783.06

W_{0i} is the sum of local water supply and diverted water supply according to its proportion of investment at the i-th entrance. Results are shown in Table3.2:

Table3.2 (0.1 billion, cubic meters)

Regions	Total net water demand	The local water supply			investment share of the North Water Transfer	Water supply sub total
		Surface water	Under ground water	other		
Henan	44.90	6.37	1.15	4.04	3.14	14.70
Hebei	35.18	1.07	3.11	1.84	8.85	14.87
Beijing	31.22	7.32	6.72	7.40	6.32	27.76
Tianjin	23.14	9.12	1.21	2.96	5.09	18.38

η_i and δ_i are priority coefficients. Under normal circumstances, their values are equal to one. During extremely dry years, their values are set to zero.

According to the parameters above determined values, embodied in the principle of the model configuration constraints:

Henan $x_1 \geq 19.63$ Hebei $x_2 \geq -1.84$ Beijing ≥ -3.38 Tianjin ≥ -6.06

c. Constraints on water demand:

$$D_{\min} i \leq x_i \leq D_{\max} i$$

In the formula, $D_{\min} i$ and $D_{\max} i$ represent the minimum water demand and the maximum water demand at the i-th entrance, respectively.The $D_{\min} i$ and $D_{\max} i$l imits can be calculated using the following formula: $d_i \times$（1±10%）, Results are shown in Table3.3:

Table3.3 (0.1 billion, cubic meters)

Regions	Total net water demand	Available water supply	Water demand (d_i)	Maximum water demand ($D_{\max} i$)	Minimum water demand ($D_{\min} i$)
Henan	44.90	14.70	30.20	33.22	27.18
Hebei	35.18	14.87	20.31	22.34	18.28
Beijing	31.22	27.76	3.46	3.81	3.11
Tianjin	23.14	18.38	4.76	5.24	4.28

d. Constraints on carrying capacity:

$$x_i \le Q_{\max} i$$

In this formula, $Q_{\max} i$ is the maximum carrying capacity at the i-th entrance .

maximum carrying capacity here according to the *south to north water diversion project the project proposal* related data sorted out: Henan 35.78(0.1 billion, m^3) Hebei 30.39(0.1 billion, m^3) Beijing 10.52(0.1 billion, m^3) Tianjin 8.63(0.1 billion, m^3)

e. Constraints on the coordination of development:

$$\mu = \sqrt{\mu_{B_1}(\sigma_1) * \mu_{B_2}(\sigma_2)} \ge \mu^*$$

$\mu_{B_1}(\sigma_1)$ is the water resources supply and demand coordination degree , λ_i is the degree of the importance for water supply at the i-th entrance, is regional water resources supply and demand ratio, value is 1:

$$\sigma_1 = \frac{0.89x_1 + 0.94x_2 + 1.25x_3 + 0.91x_4}{58.73}$$

Since $\sigma_1 < \sigma_1^*$, there are :

$$\mu_{B_1}(\sigma_1) = \exp\left[-4\left(\frac{0.89x_1 + 0.94x_2 + 1.25x_3 + 0.91x_4}{58.73} - 1\right)^2\right]$$

$\mu_{B_2}(\sigma_2)$ is regional economic development and water resources utilization degree of coordination, σ_2^* is water base year actual water consumption per unit of GDP:

$$\sigma_2 = \frac{0.25x_1 + 0.69x_2 + 1.6x_3 + 1.47x_4}{2.35}$$

Since $\sigma_2 \le \sigma_2^*$, there are :

$$\mu_{B_2}(\sigma_2) = 1.0$$

μ^* is the minimum value of the regional coordinated development index

f. Constraints on Fairness:

$$\frac{\sum_{i=1}^{k} d_i}{\sum_{i=1}^{k} x_i}(1-20\%) \le \frac{d_i}{x_i} \le \frac{\sum_{i=1}^{k} d_i}{\sum_{i=1}^{k} x_i}(1+20\%)$$

According to the water requirement (d_i) in table 3.3, the fairness constraint conditions:

$$\frac{46.98}{\sum_{i=1}^{k} x_i} \le \frac{d_i}{x_i} \le \frac{70.48}{\sum_{i=1}^{k} x_i}$$

There are: $\frac{46.98}{\sum_{i=1}^{4} x_i} \le \frac{30.2}{x_1} \le \frac{70.48}{\sum_{i=1}^{4} x_i}$

$$\frac{46.98}{\sum_{i=1}^{4} x_i} \le \frac{20.31}{x_2} \le \frac{70.48}{\sum_{i=1}^{4} x_i}$$

$$\frac{46.98}{\sum_{i=1}^{4} x_i} \le \frac{3.46}{x_3} \le \frac{70.48}{\sum_{i=1}^{4} x_i}$$

$$\frac{46.98}{\sum_{i=1}^{4} x_i} \le \frac{4.76}{x_4} \le \frac{70.48}{\sum_{i=1}^{4} x_i}$$

Results and Analysis

Analysis on before and after allocation optimization

The results from the allocation model are shown in Table A. The results from the proposal for the First Phase of the Central Route of the South-North Water Diversion Project are shown in Table B.

Table A: Results from the optimized allocation model.

Regions	Water Supply (0.1 billion, m^3)			GDP (0.1 billion, Chinese yuan)	Fiscal Revenue (0.1 billion, Chinese yuan)	Net Profit (0.1 billion, Chinese yuan)	Value of the Objective Function
	Local Water	Diverted Water	Sum				
Henan	11.56	30.32	41.88	6579.35	324.99	2.93	21.49
Hebei	6.02	27.22	33.24	5515.85	194.45	5.98	
Beijing	21.44	10.13	31.57	6963.39	1018.76	13.58	
Tianjin	13.29	10.33	23.62	3774.24	740.96	9.21	
Total	52.31	78	130.31	22832.83	2279.17	31.7	

Table B: Results from proposal for the First Phase of the Central Route of the South-North Water Diversion Project.

Regions	Water Supply (0.1 billion, m^3)			GDP (0.1 billion, Chinese yuan)	Fiscal Revenue (0.1 billion, Chinese yuan	Net Profit (0.1 billion, Chinese yuna)	Value of the Objective Function
	Local Water	Diverted Water	Sum				
Henan	11.56	31.63	43.19	6785.15	335.15	3.02	20.45
Hebei	6.02	28.6	34.62	5744.84	202.53	6.23	
Beijing	21.44	9.76	31.2	6881.78	1006.82	13.42	
Tianjin	13.29	8.01	21.3	3401.93	667.87	8.3	
Total	52.31	78	130.31	22813.7	2212.37	30.97	

From comparing values in Table A and Table B, the total amount of diverted water before and after model optimization is the same. But the amounts of diverted water are different for each Water Intake Area. The amount of diverted water to Henan and Hebei are reduced, while the amount to Beijing and Tianjin are increased. Optimization of allocation model allows for improvement of economic indicators. GDP is increased from 2.28137 trillion Chinese yuan to 2.283283 trillion Chinese yuan, a net increase of 19.2 billion Chinese yuan. Fiscal revenue is increased from 221.237 billion Chinese yuan to 227.917 billion Chinese yuan, a net increase of 6.679 billion Chinese yuan. Net profts of the water companies is increased from 3.097 billion Chinese yuan to 3.17 billion Chinese yuan, a net increase of 73 million Chinese yuan. The objective function value is also increased from 20.45 to 21.49. Since this study takes full consideration of the various objective functions (i.e. maximizing the Water Receiving Area's GDP, maximizing net profits of the water supply companies, and etc) and constraints (i.e. constraints on water supply, cosntraints on coordinated development, and etc.), each indicator is much better after model optimization than before. Therefore, the model proposed by this study provides a more scientific and reasonable allocation than the one detailed in the project proposal.

Sensitivity analysis of bound variables

The constraints in this model are determined using a combination of data from existing research and statistics. However, the reality is that the constraints are not static as they would change according to the actual water diversion project. To make our model more feasible, the following discussion is a sensitivity analysis of the possible impacts on objective functions due to changes in bound variables.

The basic idea of sensitivity analysis is to examine changes in the values of the objective function that are brought by changing the upper and lower limits of the bound variables. A 5% change is applied to parameters to examine the resulting objective function values. Preliminary findings are as follows. Parameters ± 5% has no significant effect on constraints embedded in distribution principles (i.e. Constraint 3), constraints on water capacity (i.e. Constraint 5), constraints on coordinated development (i.e. Constraint 6), and constraints on fairness (i.e. Constraint 7), indicating that these constraints have a weak effect on the objective function. Parameters ±5% has some effect on constraints on supply capacity (i.e. Constraint 2), and constraints on water demand (i.e. Constraint 4). Results are shown in Table.

It is clear from the Table that a positive correlation exists between the available water (W) and the value of the objective function: as the amount of water increases, the objective function value also increases, and vice versa. In addition, the objective function value (21, 32) during water demand (D) decrease is greater than that (21, 21) during water demand (D) increase, but both are smaller than the initial value (21, 49) during allocation optimization.

In order to reflect more on the sensitivity of the bound variables, the following figure is used. As one can see from the Figure, the slope of the curve for water demand is significantly greater than the slope of the curve for water supply, indicating that objective function is more sensitive to constraints on water demand than to constraints on water supply. We conclude that during the implementation of the South-North Water Diversion Project, it is important not only to optimize the allocation of water to each Water Receiving Area, but also to pay attention to how water supply can be regulated. Only fulfillment of both requirements can achieve optimal water allocation results.

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