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Comprehensive Benefit Assessment of the Middle Route of South-to-North Water Diversion Project Based on Markowitz Theory

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Abstract: In the context of global climate change and the water-carbon peak target, improving water security in arid regions is a persistent challenge in global water resources management. Water diversion projects can serve as an important measure to effectively alleviate the uneven distribution of water resources, achieve rational allocation and efficient utilization of water resources. However, how to achieve the maximization of comprehensive benefits during the process of water allocation is also an urgent problem that needs to be solved. This study focuses on the Middle Route Project of the South to North Water Diversion Project in China, selecting four important municipalities and provinces during 2015 to 2021, namely Beijing, Tianjin, Hebei Province, and Henan Province, based on the actual benefits of the water receiving areas of the middle line project. Nine representative indicators related to social, economic, and ecological benefits were selected to evaluate the optimal combination of water resource allocation in the water receiving areas along the central line, in order to achieve the maximum comprehensive benefits and solve the problems of high water safety guarantee requirements and difficult balanced water distribution in urban agglomerations in the water receiving areas. Through the calculation of the Markovsky theoretical model, the results show that when 79.9% of the water conveyance is used to generate social benefits, 15.8% of the water conveyance is used to generate ecological benefits, and 4.5% of the water conveyance is used to generate economic benefits, the project achieves the maximum comprehensive benefits. This computational model method can be used to provide technical support and scientific reference for the optimal allocation of water resources in cross regional water transfer projects.

Keywords: Middle Route of South-to-North Water Diversion Project; Markowitz; benefits; water allocation

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1. Introduction

As an important project to effectively alleviate the uneven distribution of water resources and achieve rational allocation and efficient utilization of water resources, water diversion projects have played or will play an important role in the construction of water conservation and water ecology in many countries [1–4]. Among complex water diversion projects, the Middle Route of South-to-North Water Diversion Project is the most representative one. Its water canals are artificially constructed new ones. It has many types of water conveyance structures, complex and changeable operating conditions, limited water storage space, no online regulation reservoirs, and obvious hydraulic coupling effects between multiple canals and pools. Meanwhile, the regulated water volume and hydrodynamic processes are influenced by the regulation of gates along the route as well as human activities such as water diversion and drainage along the route [5]. Since climate change along the route is relatively great, and the water transfer has brought about a geographical spatial change from subtropical to temperate zones, algae reproduce faster [6,7]. In spring and autumn, and some sections of a river freeze in winter while some other sections of the river thaw at the same time. Regarding these issues, research has also been conducted worldwide on binary reservoir water supply systems [8], clean water source utilization in coastal areas [9], flood prevention in flood-prone areas [10], and so on. How to operate such a magnificent project efficiently to maximize its effectiveness, and how to maximize the comprehensive benefits to the areas along the route with minimal investment under normal operation, have become the main concern after the realization of smooth operation of the middle route project. In addition, in such a large inter-basin water diversion project, how to reasonably allocate water resources and maximize the balance of economic, ecological, and social benefits is also a great challenge.

Researches on water dispatch of the Middle Route of South-to-North Water Diversion Project have yield some results, including the study of flooding caused by canal crossing structures [11], the study of water level stabilization by optimizing pump operation to control water volume for the safety of long-distance water delivery system [12], the study of water control during water delivery under ice conditions [13], the spatial and temporal analysis of land use and water production in the water source area of the project [14], and the study of the optimal water allocation during flooding through joint operation of reservoirs and flood plains to improve flood utilization [15].

Markowitz theory is a very classical investment portfolio theory in modern finance, which aims to maximize the total return for a given risk or minimize the risk for achieving the expected return by reasonably allocating the total assets to different investment projects. As a very mature and market-tested theory, Markowitz theory has been widely used in many other fields and has achieved fruitful results. This theory has been applied in the joint power market [16], medical science [17], physics [18] and chemistry [19].

Most of the studies on the benefits of complex water diversion projects are focused on a single area [20] or a single benefit [21], as well as studies on the balance between pollutant emissions and economic benefits in a certain section of the project [22] and the evaluation of the ecological and economic benefits of water supply in the receiving area of Hebei of the project [23]. The existing research results still lack studies on the comprehensive benefits of all the receiving areas along the middle route project and the quantitative investigation of the correlation between water quantity and benefits. The main objective of this paper is to study the optimal water resource allocation combination for the receiving areas along the middle route, addressing the current issue of suboptimal water resource allocation in the middle route project, which only satisfies the supply demand without achieving the optimal allocation of water resources.Therefore, in this paper, an improved Markowitz model that fits the characteristics of water conservancy projects is built based on the Markowitz theory. Then this model is used to comprehensively analyze the economic, ecological, and social benefits of the four provinces and municipalities along the middle route project to obtain the optimal water allocation combination. By doing so, the original goal of achieving maximum comprehensive benefits with minimal investment has been achieved.

2. Materials and Methods

2.1. Profile of the Target Research Areas

The Middle Route of South-to-North Water Diversion Project runs 1432 km from Taocha in Henan Province to Beijing and Tianjin, passing through four provinces and municipalities of Beijing, Tianjin, Hebei, and Henan. Among which, the Henan section is 731 km, the Hebei section is 465.92 km, the Beijing section is 79.84 km, and the Tianjin section is 156 km. The schematic diagram of the project is shown in Figure 1.

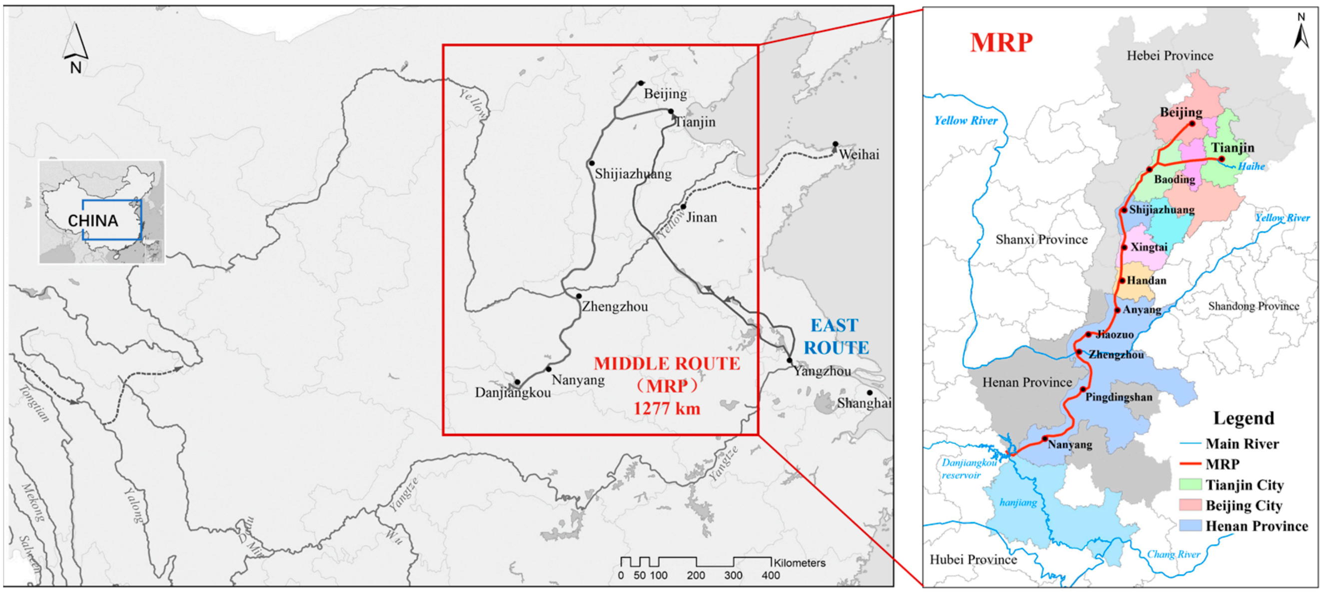

Figure 1. Schematic diagram of the middle route of the South-to-North Water Diversion Project.

The project was officially put into operation on 12 December 2014, and has supplied over 40 billion cubic meters of water to the north, benefiting 79 million people. After reaching the design conditions, the project has kept an average annual water transfer volume of 9.5 billion cubic meters for many years [24], providing water for more than 190 counties (or cities and districts) in 24 large and medium-sized cities in Beijing, Tianjin, Hebei, and Henan, for domestic, industrial, agricultural, and ecological use. During the water transfer process of the project, attention should be paid to the following aspects: (1) safety risks of the project. The water diversion project will affect the water level and water surface line of the adjacent canal section when supplying water to the receiving area [25], and in extreme cases, the sudden great change of water level and the upwelling of groundwater may cause canal damage [26,27]. (2) Risks of emergencies. Within two years of operation, some sections of the main canal of the project experienced rapid growth of algae with a high density of up to 10^7 cells/L in certain times. In 2016, the main canal had the phenomenon of prophetic algae aging, falling off, and floating up. The accumulated algae deposited 3–5 m at the inlet of the backflow gate, bringing certain risks to the operation and water supply safety of the project [28–30]. (3) Economic benefits. Currently, the price of ecological water replenishment and compensation costs are not clear, which will inevitably affect the sustainability of ecological water replenishment in the middle route project. It is necessary for stakeholders to negotiate and solve the problem. (4) Implementation efficiency. Due to the fact that most of the natural river channels in the water receiving area are dry, many people plant crops, build breeding farms and houses in the river channels, and many river channels are severely damaged, with many illegal sand mining pits and buildings, which reduces the efficiency of ecological water replenishment.

2.2. Model Framework

The comprehensive benefit assessment process of the middle route project based on the Markowitz theory mainly includes selecting model indicators, determining the annual values of each indicator and the risk-free rate of return of the project, calculating the annual rate of return and expected rate of return of each indicator, calculating the covariance matrix between indicators, calculating the efficient frontier, calculating and optimizing the global minimum variance combination, and obtaining the weight allocation combination that maximizes the comprehensive benefit of the project. The details are shown on Figure 2.

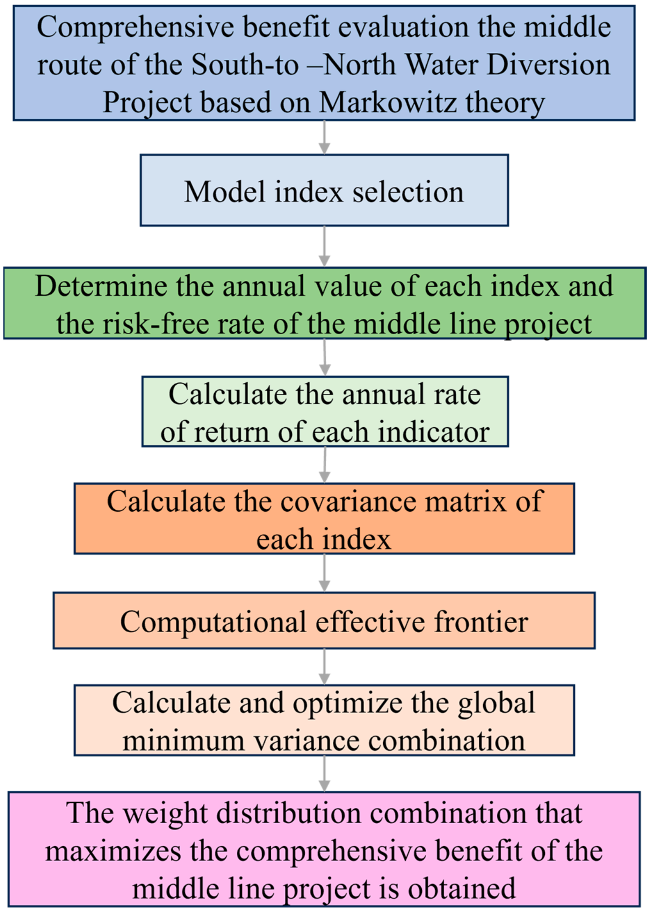

Figure 2. Flow chart of comprehensive benefit evaluation for the middle route of the South-to-North Water Diversion Project based on Markowitz theory.

2.3. Theoretical Basis

The Markowitz theory refers to the investment portfolio theory first proposed by famous American economist Markowitz in his paper "Portfolio Selection" in 1952, This theory includes two important parts: mean-variance analysis method and investment portfolio efficient frontier model. Markowitz won the Nobel Prize in Economics with this theory. In this theory, Markowitz uses the mean of risk assets to represent the expected rate of return, and uses the variance or standard deviation to represent the risk level, and based on this, issues of asset portfolio and selection are further studied. The key role of this theory is to help investors invest funds in various securities according to a certain proportion, so as to achieve the goal of minimizing risk when expected returns are given, or maximizing returns when risk is given [31].

In this paper the Markowitz theory is introduced into the field of water conservancy projects, and the asset investment issue in economics are transformed into water allocation subject in water conservancy projects. On this basis, a comprehensive benefit assessment model for the middle route project is constructed and analyzed to explore the weight allocation combination that maximizes the economic, ecological, and social comprehensive benefits of the project under normal operating conditions.

2.4. Model Building

2.4.1. Selection of Model Indicators

The selection of indicators for the comprehensive benefit assessment model of the project should follow the principles of system, representativeness, independence, and objectivity [32].

Under normal operation, the major goal of the project is to achieve the maximum comprehensive benefits with minimal risk by allocating different weights to different indicators, while considering the benefits of economy, society, and ecology. Based on the theories mentioned above and the actual operational needs of the project, nine indicators are selected in this model, including three indicators reflecting economic benefits B1—per capita GDP C1, water consumption per 10,000 yuan of industrial added value C2, and per m3 water GDP C3; three indicators reflecting ecological benefits B2—groundwater supply C4, ecological water consumption C5, and urban greening coverage C6; and three indicators reflecting social benefits B3—per capita water consumption C7, registered urban unemployment rate C8, and urbanization rate of permanent resident C9. The evaluation indicator system is shown in Figure 3.

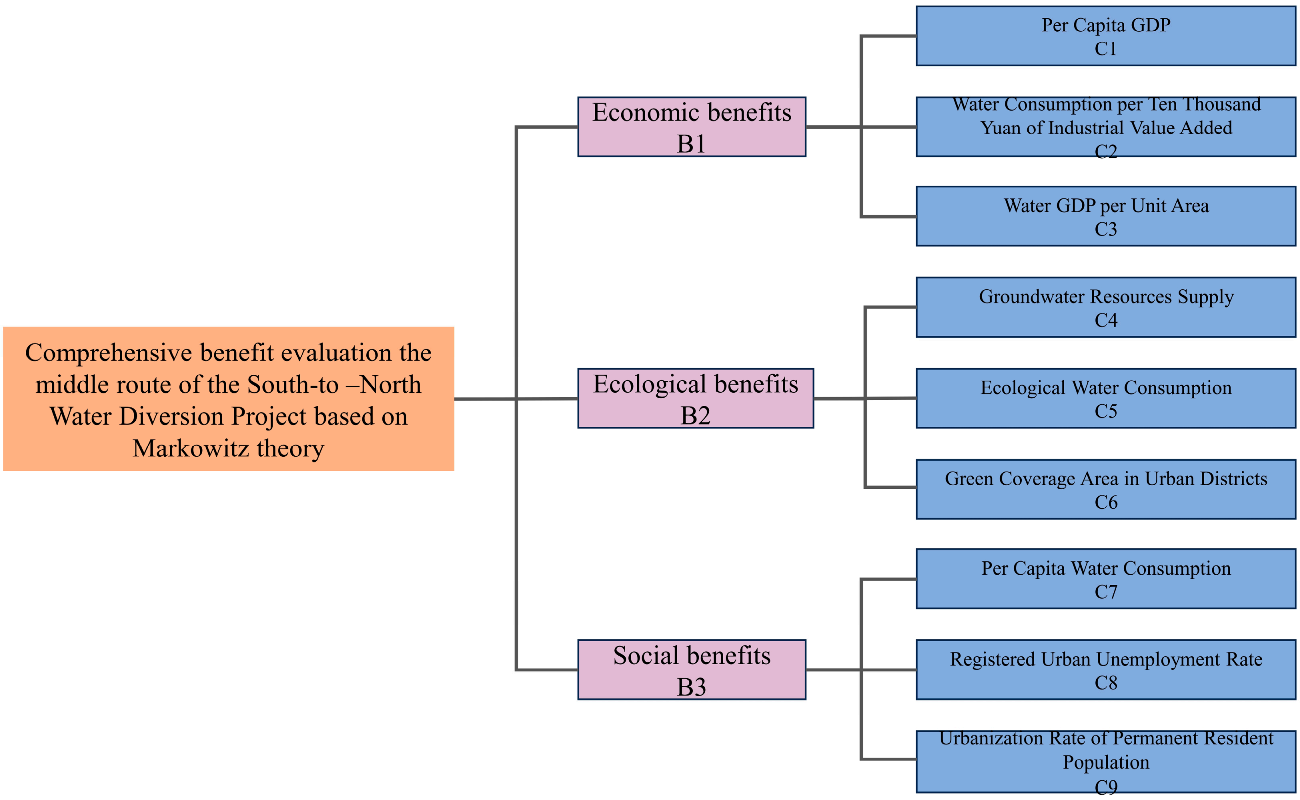

Figure 3. Evaluation index system diagram.

2.4.2. Model Running

The data in this paper comes from the Water Resources Bulletin (2015~2020) of four provinces and municipalities including provinces of Henan and Hebei, and municipalities of Beijing and Tianjin; the Water Resources Bulletin (2015~2021) of Tianjin, Hebei, and Henan; the China Water Resources Bulletin (2021); and the Annual Statistical Report on Environment in China (2015~2021). The sources are authoritative and reliable, ensuring the authenticity of the data, which provides a basis for further modeling analysis, and a guarantee for the value of subsequent analysis and results.

Modeling Method

Step 1: Determine the annual values for sub-indicators

Take the arithmetic mean value of each indicator's data in Beijing, Tianjin, Hebei, and Henan as its value. That is:

$$xi_j = \frac{\sum aij_k}{4} \quad (1)$$

where xi_j represents the value of an indicator for a certain year; aij_k represents the value of an indicator for a province (or municipality) in a certain year; i represents an indicator; j represents a year; and k represents a province (or municipality).

Step 2: Calculate the annual rate of return of the indicators

A concept in economics is introduced here, that is continuous compounding [33]. Compounding refers to the method of calculating interest where the interest for a certain interest period is the principal plus the total accumulated interest from previous periods, also known as "interest on interest". In the financial market, continuous compounding refers to the interest rate obtained in the extreme case as the number of periods approaches infinity, where the intervals between different periods are very short and can be considered as infinitesimal [34].

Since the middle route project operates continuously throughout a year, the benefits generated by the annual allocation of water to various regions continue to accumulate, and the benefits generated in the previous year will also affect the benefits of the second year, the concept of "continuous compounding" is applicable to water conservancy projects. When calculating the annual rate of return of the sub-indicators in the comprehensive benefit assessment model of the project, the formula for calculating continuous compound interest in economics is used [33].

$$rit = \ln(\frac{xi_{j-1}}{xi_j}) \tag{2}$$

where rit represents the rate of return of an indicator for a given year; xi_j represents the value of an indicator calculated above for the current calculation year; xi_{j-1} represents the value of an indicator for the previous year of the calculation year; i represents an indicator; and t represents a calculation year.

Step 3: Calculate the covariance matrix among the indicators

Calculation methods for variance and covariance in mathematics as well as matrix multiplication in linear algebra are applied [35] to obtain the formula for the covariance matrix:

$$S = [\sigma ij] = \frac{A^T \cdot A}{M-1} \tag{3}$$

where the matrix A is defined as:

$$A = \begin{pmatrix} r_{11} - \overline{r_1} & \cdots & r_{N1} - \overline{r_N} \\ \vdots & \ddots & \vdots \\ r_{1M} - \overline{r_1} & \cdots & r_{NM} - \overline{r_N} \end{pmatrix} \tag{4}$$

then the matrix A^T is:

$$A^T = \begin{pmatrix} r_{11} - \overline{r_1} & \cdots & r_{1M} - \overline{r_1} \\ \vdots & \ddots & \vdots \\ r_{N1} - \overline{r_N} & \cdots & r_{NM} - \overline{r_N} \end{pmatrix} \tag{5}$$

where S represents the covariance matrix; r_{NM} represents the rate of return of an indicator for a given year; $\overline{r_N}$ represents the arithmetic mean of annual rate of return for a certain indicator; N represents the number of indicators; and M represents the number of years for calculation.

The covariance is usually used to measure the linear relationship between two variables. When the Markowitz theory is applied to build investment portfolio, it is important to balance the expected return and risk of the asset, and make supplement and coordination between different assets to find the optimal investment portfolio. If there is a high relevance between different assets, their risks will be superimposed, which in turn increases the risk of the entire portfolio; if there is no relevance or there is negative correlation between different assets, their risks can be offset, and the risks of the entire portfolio are reduced.

Therefore, calculating the covariance matrix between different assets can clearly present the correlation between them, and help decision-makers fully consider the impact of correlation between different assets on portfolio risk when constructing investment portfolios, so as to obtain the optimal investment portfolio.

Step 4: Calculate the expected rate of return of the indicator

The arithmetic mean of the annual rate of return of the indicators is used as the expected rate of return for each indicator, i.e.,:

$$E(r_i) = \frac{\sum r_{it}}{6} \tag{6}$$

where $E(r_i)$ represents the expected rate of return for an indicator, and r_{it} represents the rate of return for an indicator calculated above for a given year.

Step 5: Risk-free rate of return

The economic internal rate of return of 23.14% [36] of the project is used as the risk-free rate of return for the model calculation, i.e.,:

$$C = 23.14\% \tag{7}$$

Step 6: Effective Frontier

In the field of financial investment, when the types of securities or stocks have been determined, investors can obtain an infinite number of portfolios with different risks and returns as the investment proportion changes, which is called feasible sets. In a feasible set, the frontier consisting of portfolios with higher return for the same risk or lower risk for the same return is the efficient frontier [37]. This theory can be applied to the constructed model. Under the premise that indicators are determined, the amount of water allocated to different indicators is different, and the comprehensive benefits of the project are also different. Therefore, a feasible set can be constituted, and the effective frontier of the model can also be found.

In this paper the effective frontier is constructed based on the following theory [38].

If there is a risk-free rate of return C, meaning there is a risk-free investment option, then C cannot be an efficient portfolio with any risk portfolio q inside the efficient frontier, because there is always another risk portfolio that is more beneficial or less risky than C, and still remains inside the efficient frontier until it reaches the portfolio T that connects C to the tangential point of the efficient frontier, where there is no longer a risk portfolio with C that has a higher return or lower risk. When two portfolios are known to be on the efficient frontier, an entire efficient frontier curve can be formed by a linear combination of these two portfolios.

The calculation is as follows:

$$E(r) - C = \begin{bmatrix} E(r_1) - C \\ E(r_2) - C \\ \vdots \\ E(r_N) - C \end{bmatrix} \tag{8}$$

Let

$$z = S^{-1}[E(r) - C] \tag{9}$$

Then

$$x_i = \frac{z_i}{\sum_{j=1}^{N} z_j}, x = \{x_1, \cdots x_N\} \tag{10}$$

where x_i represents the weight allocation of the tangential point combination; S^{-1} represents the inverse matrix of the covariance matrix; and $E(r)$ represents the expected rate of return for the indicators calculated above.

Calculate the weight allocation of the tangential point without risk-free rate of return and with risk-free rate of return respectively, and calculate the relevant mathematical and statistical indicators of the two tangential point combinations. Then the "simulation table" function in Excel is used to construct a linear combination of the two points to finally form an effective frontier.

Step 7: Global minimum variance combination

The leftmost point on the efficient frontier curve is *GMVP*, the portfolio with the lowest variance among all portfolios consisting of risk assets, i.e., the portfolio has the lowest risk. The calculation is as follows [39].

$$x_{GMVP} = \left\{ \begin{array}{l} x_{GMVP,1} \\ x_{GMVP,2} \\ \vdots \\ x_{GMVP,N} \end{array} \right\} = \frac{S^{-1} \cdot 1_{column}}{{1_{column}}^{T} \cdot S^{-1} \cdot 1_{column}} \tag{11}$$

Let

$$1_{column} = \left\{ \begin{array}{c} 1 \\ 1 \\ \vdots \\ 1 \end{array} \right\}, N\ in\ total \tag{12}$$

where, x_{GMVP} represents the weights of the indicators in the minimum variance combination; S^{-1} represents the inverse matrix of the covariance matrix; and N represents the number of indicators.

Step 8: Optimize the global minimum variance combination

The method introduced earlier calculates the vertex of the efficient frontier curve, which is the theoretically optimal combination. However, in the real financial market, it is very likely that there are restrictions on short selling of certain stocks. This restriction is even more important when applied to water conservancy projects. This paper focuses on the water allocation of the middle route project, so it is impossible to have phenomena such as short selling and leverage that may occur in financial market transactions, nor can there be a weight of 0, because in actual projects, the water obtained from any indicator cannot be 0. Therefore, in the model constructed in this paper, a global minimum variance combination with constraints is needed, that is, eliminating short selling, which requires an added constraint of "each weight is more than 0" in the solution process. Only when the additional conditions are met can the result be obtained by this model.

In the field of finance, for any investment portfolio composed of risk-free investment and risk investment, when the standard deviation of the portfolio's rate of return is used as a measure of its risk, the difference between the portfolio's rate of return and the risk-free rate of return is called its risk premium, and the risk premium per unit of risk is the Sharpe ratio [38].

When the concept of Sharpe ratio is introduced in the Markowitz model, it shows that investors always prefer portfolios with the highest Sharpe Ratio when there is a risk-free investment, because such portfolios offer the highest risk premium. Among all the intersection points on the lines that is derived from the risk-free rate of return and intersect with the efficient frontier, only the tangential point is the portfolio with the highest Sharpe ratio among all risk portfolios.

Based on the aforementioned theory, in the comprehensive benefit assessment of the project, we consider additional constraint conditions while optimizing the global minimum variance combination of the Markowitz model. The objective is to find the combination that can achieve the maximum Sharpe ratio.

$$\max(\theta) = \frac{E(r_{GMVP}) - C}{\sigma_{GMVP}} \tag{13}$$

$$s.t.\ \begin{cases} x_{GMVP,i} > 0 \\ \sum x_{GMVP,i} = 1 \end{cases}, where\ i = 1, \ldots N \quad (14)$$

where represents the mean of the returns of the global minimum variance portfolio; C represents the risk-free rate of return; represents the standard deviation of the returns of the global minimum variance portfolio; and represents the proportion of each risk investment in the global minimum variance portfolio.

Formulas (13) and (14) belong to the quadratic planning problem. The “planning solution” tool in the Excel is chosen to get the solution.

3. Results

Find the data of each indicator for each year according to Water Resources Bulletin (2015–2020) of Beijing; the Water Resources Bulletin (2015–2021) of Tianjin, Hebei and Henan; the China Water Resources Bulletin (2021) and the Annual Statistical Report on Environment in China (2015–2021). Then the year-by-year rate of return for each indicator is calculated according to Formula (2). The calculation results are shown in Table 1.

Table 1. The annual rate of return of each index. (Units: %).

Year	C1	C2	C3	C4	C5	C6	C7	C8	C9
2016	6.99	−4.79	5.10	−3.80	24.08	5.86	0.63	1.22	1.63
2017	9.34	−11.47	7.82	−5.53	27.40	6.64	0.86	−1.92	1.50
2018	9.36	−3.82	8.20	−4.00	21.83	4.11	0.63	−1.24	1.37
2019	6.69	5.30	3.39	−6.33	25.25	3.43	1.46	−0.98	1.36
2020	0.95	−13.45	2.93	−7.94	18.57	4.56	0.79	14.69	1.16
2021	11.04	−18.87	10.98	−7.89	19.44	4.59	1.53	16.50	0.77

As can be seen from Table 1, the rates of return for some indicators are negative. That is because after years of continuous water diversion and adjustments to the water supply pattern by the water receiving areas along the route, the arithmetic averages of “water consumption per 10,000 yuan of industrial added value” and “groundwater supply” in Beijing, Tianjin, Hebei, and Henan along the project have shown a decreasing trend year by year, but the logarithm of the ratio of the latter year to that in the previous year is used to calculate the rate of return in Formula (2), leading to negative values for indicators with a decreasing trend. The negative value in the “registered urban unemployment rate” is also due to the same reason. In 2017, 2018, and 2019, the registered urban unemployment rate in Beijing, Tianjin, Hebei, and Henan decreased year by year, resulting in negative results of these three years calculated by Formula (2).

The covariance matrix among the nine indicators was calculated according to Formulas (3)–(5), and the results are shown in Table 2.

Table 2. Covariance matrix. (Units: %).

	C1	C2	C3	C4	C5	C6	C7	C8	C9
C1	0.1262	−0.0276	0.0961	0.0196	0.0395	0.0071	0.0042	−0.0809	−0.0013
C2	−0.0276	0.7289	−0.1450	0.0808	0.1525	−0.0412	−0.0013	−0.5426	0.0159
C3	0.0961	−0.1450	0.0981	0.0010	−0.0099	0.0080	0.0027	0.0418	−0.0043
C4	0.0196	0.0808	0.0010	0.0330	0.0337	0.0062	−0.0047	−0.1250	0.0044
C5	0.0395	0.1525	−0.0099	0.0337	0.1178	0.0177	−0.0011	−0.2499	0.0076
C6	0.0071	−0.0412	0.0080	0.0062	0.0177	0.0139	−0.0022	−0.0176	0.0015
C7	0.0042	−0.0013	0.0027	−0.0047	−0.0011	−0.0022	0.0017	0.0119	−0.0008
C8	−0.0809	−0.5426	0.0418	−0.1250	−0.2499	−0.0176	0.0119	0.7250	−0.0217
C9	−0.0013	0.0159	−0.0043	0.0044	0.0076	0.0015	−0.0008	−0.0217	0.0009

The effective frontier is calculated according to Formulas (8)–(10), and the results are shown in Figure 4.

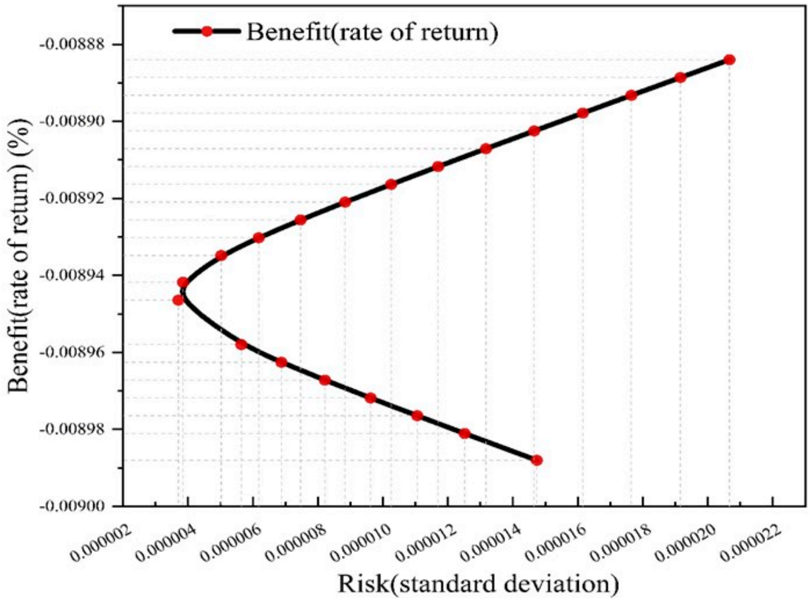

Figure 4. Effective frontier calculation result graph.

After the calculation of the effective frontier, the global minimum variance combination, which is the leftmost vertex of the effective frontier curve and also the theoretically optimal weight allocation combination, can be solved according to Formulas (11) and (12). The results are shown in Table 3.

Table 3. Global minimum variance combination.

Benefit Classification	Benefit Weight	Index	Index Weight
B1	−0.005	C1 C2 C3	−0.093 0.007 0.081
B2	0.108	C4 C5 C6	0.020 −0.110 0.198
B3	0.897	C7 C8 C9	0.772 −0.047 0.172
Aggregate			1.000

Some of the theoretical optimal weights calculated in Table 3 are negative, which in the financial world means that it is necessary to "short" these assets with negative weights, i.e., to borrow the asset without holding it and sell it immediately in the hope of buying it back when the price falls in the future, thus making a profit [40]. If there is no weight optimization, it means instead of supplying the required water to the indicators corresponding to negative weights, the water corresponding to the weights needs to be drawn from the water already in these indicators to replenish other indicators, which is obviously impossible in the actual operation of the project. Therefore, in accordance with the optimization theory mentioned above, there will be no shorting and leverage in water conservancy projects. Formulas (13) and (14) must be used to eliminate negative indicator weights appearing in Table 3 to optimize the calculation of the global minimum variance combination.

The optimized global minimum variance combination is shown on Table 4.

Table 4. The weight of each index after optimization.

Benefit Classification	Benefit Weight	Index	Index Weight
B1	0.045	C1 C2 C3	0.022 0.022 0.001
B2	0.158	C4 C5 C6	0.022 0.022 0.114
B3	0.797	C7 C8 C9	0.687 0.022 0.088

The Markowitz model constructed considering the characteristics of water conservancy engineering calculates the weight combination of water resource allocation to maximize comprehensive benefits, as shown in Table 4. When the water volume that can generate social benefits accounts for 79.7% of the total water volume, the maximum comprehensive benefits can be achieved. Secondly, the amount of water that can generate ecological benefits accounts for 15.8% of the total water volume, while the amount of water that can generate economic benefits accounts for 4.5% of the total water volume. This conclusion is based on the results of data statistics. As the basic information changes, this method can continue to provide corresponding decision-making references with subsequent content.

According to the results in Table 4, in the optimized final weight allocation combination, the weight of "per capita water consumption" is the largest, at 0.687, and the weight of "per m^3 water GDP" is the smallest, at 0.001. This is related to the utility and actual operation of the middle route project. China's basic water conditions have always been characterized by summer floods and winter droughts, and a lack of water in the north and abundance in the south. Both the spatial and temporal distribution of water resources are extremely unbalanced. The first major purpose of the South-North Water Diversion Project is to achieve optimal allocation of water resources, firstly ensuring daily water supply for urban and rural residents in the water receiving areas, and secondly providing ecological water for cities along the route and restoring the ecological conditions in the northern water-deficient areas. The focus of the project is not on obtaining economic benefits, so the calculation results in this paper are reasonable and consistent with the actual operation of the project.

4. Conclusions

Based on the comprehensive consideration of the economic, ecological and social impacts of the Middle Route of South-to-North Water Diversion Project on the four provinces and municipalities of the water receiving areas, nine indicators representing three aspects of benefits are selected for analysis. By applying the Markowitz theory of calculating the optimal investment portfolio of securities and stocks in economics, and optimizing the modeling process according to the characteristics of water conservancy projects, a Markowitz model suitable for calculating the optimal water allocation of water conservancy projects is finally constructed. Based on the actual data of the four provinces and municipalities in the water receiving areas from 2015 to 2021, the model was used to calculate the water allocation combination that maximizes the comprehensive benefits of the middle route project.

The results show that under the normal operation of the project, when the water allocated to produce economic benefits accounts for 4.5% of the total transferred water, the water allocated to produce ecological benefits accounts for 15.8% of the total transferred water, and the water allocated to produce social benefits accounts for 79.7% of the total transferred water, the project obtains the highest comprehensive benefits. Among the allocation combinations that can obtain the highest comprehensive benefits of the project, the water that can produce social benefits occupies the highest proportion, which is consistent with the current operation situation and shows the reasonableness of the model's calculation results.

The current research methodology involves using the Markowitz theory as the theoretical foundation. Drawing inspiration from the application of this theory in studying investment approaches for multiple stocks, the methodology is applied to investigate water resource allocation in the social, ecological, and economic aspects of the receiving areas along the middle route. The objective is to determine the optimal allocation of water resources that can maximize comprehensive benefits.

Based on the calculations mentioned above, the efficient frontier model from economics is utilized. It calculates different investment portfolios of water quantity and comprehensive benefit returns under varying proportions of water resource allocation. Through this analysis, the optimal solution is derived, which represents the globally optimal combination of water resource allocation and comprehensive benefits.

Since this method has been validated in the middle route, it can also be applied to similar long-distance water transfer projects to improve the comprehensive benefits of water allocation. Moreover, this method may have even better application prospects in the future.

This article only discusses the distribution of the highest comprehensive benefit water quantity under normal operation of the Central Route of the South-to-North Water Diversion Project. However, as one of the world's largest inter-basin water transfer projects, the Central Route crosses basins and provinces (municipalities), has a long total length, and includes complex hydraulic structures. It also faces various complex working conditions and is affected by various complex weather conditions. Therefore, this study can provide water transfer ideas for various long-distance water transfers in the world and provide the optimal water resource allocation method for most complex water transfer situations, in order to maximize the benefits of water transfer. However, at the same time, this study has not considered the impact of extreme weather conditions. Therefore, how to balance the safety and efficiency of the operation of the project in extreme emergency situations will be the further research direction in the future.

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