Research on the potential of water resources utilization efficiency in the North Canal Basin to improve environmental flow guarantee degree

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Abstract. North Canal is one of the important tributaries of Haihe River, however, it can’t meet the requirement of environmental flow. Improving water resources utilization efficiency is one significance way to enhance the environmental flow guarantee degree, Hence, it’s significant to study the potential of improving water use efficiency of the North Canal Basin. Based on the Analytic Hierarchy Process, this paper comprehensively evaluates the water use efficiency of the North Canal Basin from 2016 to 2019, and analyse the water use efficiency improvement potential. The results show that the water use efficiency of the North Canal Basin is high compared to the national average level, and the water use efficiency of the basin is increasing from 2016 to 2019, and the comprehensive score of water use efficiency in 2019 is the highest at 0.927, and lowest in 2016 at 0.896. The water use efficiency of the North Canal Basin still has the potential to be improved, and with the promotion of ecological civilization construction in China, the environment water consumption in the North Canal Basin is increasing year by year, and the environmental flow guarantee degree of the North Canal Basin will be gradually improved.

1. Introduction

With the rapid growth of economy and population, the contradiction caused by insufficient water resources in China has been continuously serious. With the promotion of ecological civilization construction, the demand for ecological water has gradually increased, and the contradiction has become increasingly prominent. North Canal, one of the important tributaries of Haihe River, originated in Beijing and passed through Hebei Province and Tianjin City from upstream to downstream. The environmental flow guarantee rate of the basin gradually decreased, especially Tianjin, in which could hardly meet the demand. With the limited water resources, improving the utilization efficiency of water resources is one important way to effectively alleviate the contradiction of water resources and improve the guarantee rate of environmental flow. Since 1980s, more and more attention has been paid to the research of water use efficiency in the world. However, most of the researches focus on agricultural water use efficiency [1-6], but few attention on the ecological water use. In the related researches, Zhang et al.[7] studied the water resources utilization efficiency of Huaihe River Basin, evaluated the water resources utilization efficiency of the main cities in the upper, middle and lower reaches of Huaihe River.
by using AHP and DEA, and found that the scores of all six cities were high. However, in this study, the weight of ecological benefit index is minimum, which is not applicable to the watersheds with large ecological requirements. Gao\cite{9} evaluated the water use efficiency of 31 provinces in China by combining the AHP model improved by the traditional 1-9 scale method with the sum of squares deviation method, genetic algorithm and projection pursuit model. It was found that the water use efficiency of the economically developed areas in North China, such as Beijing and Tianjin, was higher than that of the economically underdeveloped areas with poor natural conditions, but the ecological environment water consumption index was not involved in this paper. Most of the North Canal Basin is located in Beijing, and ecological benefits have not been taken as the key research object in the existing studies\cite{11,12}. However, the Planning Outline of Cultural Protection, Inheritance and Utilization of the Grand Canal issued by the State Council (hereinafter referred to as the Planning Outline) clearly points out that we must build a green ecological corridor of the Grand Canal, it is required that there is water in the whole main river course and the ecological environment is fundamentally improved. Therefore, the comprehensive evaluation of water use efficiency in the North Canal Basin should put ecological benefits first, and the evaluation results are more suitable for the current development goals of Beijing.

In this paper, according to the characteristics of the North Canal Basin, three criteria indicators (i.e., economic benefit indicators, ecological benefit indicators and social benefit indicators) and eight secondary indicators (i.e., water consumption per 10 thousand RMB of GDP, water consumption per 10 thousand RMB of industrial added value, utilization ratio of reclaimed water, COD emission per capita, environment water consumption, domestic water consumption per capita and utilization coefficient of irrigation water) are selected for comprehensive evaluation of water use efficiency, focusing on the ecological benefit indicators of the North Canal Basin. Based on the data of North Canal Basin from 2016 to 2019, this paper constructs the evaluation model of water resources utilization efficiency of the North Canal by AHP, evaluates the water use efficiency from 2016 to 2019, and analyses the potential of rising water use efficiency of the North Canal Basin, which can give some reference for improving the environmental flow guarantee degree of the North Canal Basin.

2. Overview of study area
The North Canal belongs to the Haihe River system, which rises in the south of Yanshan Mountain in Beijing and lies in the middle zone between Chaobai River and Yongding River. Its upstream is Wenyu River, which runs from northwest to southeast, and changed the name to North Canal after the confluence of Tongzhou Beiguan and Tonghui River. Then it flows through Xianghe County of Hebei Province, wuqing district of Tianjin, and joins Haihe River at Dahongqiao in Tianjin. The North Canal Basin includes the central city of Beijing and Tongzhou New City, and it has taken over most of the sewage discharged from the urban areas and suburbs of Beijing, with remarkable urbanization characteristics.

3. Construction of evaluation index system of water resources utilization efficiency in North Canal Basin

3.1. Introduction of the evaluation index system
AHP model analysis method was put forward by T.L. Saaty in 1970s, which can be used to make decisions, which object is a multi-objective problem that needs both quantitative and qualitative analysis. AHP model consist of target layer, criterion layer and index layer. Evaluators should determine the criterion layer from the target layer according to the discussion and research of authoritative scholars, and then determine the index for each criterion layer. In addition, the evaluator needs to establish a judgment matrix among three layers and check the consistency of judgment results, and finally the weight of each index can be determined\cite{8}.

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3.2. Selection and construction of the model indicators

The purpose of this study is to evaluate the water use efficiency in the North Canal Basin, so the target layer of the model is water use efficiency evaluation. The determination of criterion layer takes into account the attribute of water resources, and selects economic benefit, social benefit and ecological benefit. Economic benefit indicators include water consumption per 10 thousand RMB of GDP and water consumption per 10 thousand RMB of industrial added value. Ecological benefit indexes include utilization ratio of reclaimed water, COD emission per capita and environment water consumption. The social benefit indexes include domestic water consumption per capita, utilization coefficient of irrigation water and water resource replacement rate of South-to-North Water Transfer Project. All above finally form a comprehensive evaluation index system of water use efficiency in the North Canal Basin, as shown in Figure 1. The indicators include benefit indicators and cost indicators, which have positive and negative impacts on water use efficiency respectively.

![Image](https://example.com/figure1.png)

**Figure 1** The evaluation index system of water resources utilization efficiency in North Canal Basin

Based on the above evaluation system model of water resources utilization efficiency, this paper evaluates the water resources utilization efficiency of the North Canal Basin from 2016 to 2019. The values of cost index and benefit index from 2016 to 2019 are shown in Tables 1 and 2.

| Table 1  | Cost index data of North Canal Basin |
|----------|-------------------------------------|
| Year     | 2016  | 2017  | 2018  | 2019  |
| COD emissions per capita (kg/person) | 5.15  | 5.38  | 3.71  | 2.82  |
| Water consumption of 10 thousand RMB GDP (m³) | 11.48 | 10.66 | 9.51  | 9.42  |
| Water consumption of 10 thousand RMB of industrial added value (m³) | 9.78  | 8.89  | 7.84  | 7.78  |
In order to ensure the consistency of data, it is necessary to standardize the indicators, in which the standardized formula of benefit indicators as follows:

$$r_{ij} = \frac{x_{ij}}{X_{maxj}}$$

Where $X_{ij}$ is the $i$th index parameter of the $j$th indicator group, $X_{maxj}$ is the maximum value of the corresponding index, and $r_{ij}$ is the relative evaluation coefficient. The standardized formula of cost index is:

$$r_{ij} = \frac{x_{minj}}{x_{ij}}$$

Where $X_{ij}$ is the $i$th index parameter of the $j$th indicator group, $X_{minj}$ is the minimum value of the corresponding index, and $r_{ij}$ is the relative evaluation coefficient.

3.3. Establishment of the model judgment evaluation matrix
The influence degree of each index on the water use efficiency of the North Canal Basin, that is, the weight of each index, should be judged according to its importance degree. This paper evaluates the importance degree of each index to the upper indicator by Delphi method and determines the influence ability of each index by comparing them one by one, which is, using 1-9 scale method to establish index contrast matrix $A_{n \times n}$, where $a_{ij}$ is the importance degree of index $i$ relative to index $j$. The values of the parameters of benefit indicators and cost indicators have different meanings. From one to nine, the benefit indicators become more important, while cost indicators become less important. See table 1 for the scaling method.

According to the requirements of Green Corridor construction put forward in the Planning Outline and the concept of green development first put forward in the Development Outline of Beijing's 14 th Five-Year Plan, this paper puts the importance of ecological benefits first. The North Canal Basin is densely populated, with a high level of urbanization and developed agriculture, so the importance of social benefits is placed second. Therefore, the importance of economic benefits is placed in the third place. The ecological benefit index in this paper is obviously important compared with the economic benefit index, while the ecological benefit index is slightly important compared with the social benefit index. Social benefit index is slightly more important than economic benefit index, while social benefit index is slightly less important than ecological benefit index. As for the economic benefit index, it is obviously unimportant relative to the ecological benefit index, but slightly unimportant to the social benefit index.
Table 3  Random consistency index

| Scale value | Connotation                                      |
|-------------|--------------------------------------------------|
| 1           | the two factors compared are equally important   |
| 3           | one is slightly more important in two compared factors |
| 5           | one is markedly more important in two compared factors |
| 7           | one is markedly more important in two compared factors |
| 9           | one is extremely more important in two compared factors |
| 2, 4, 6     | the degree between those above                   |

Reciprocal: If compared factor i with j before, then compare factor j with i by the same rule.

According to the above method, the weights of each index are calculated, and the four judgment matrices (criterion layer matrix, economic benefit matrix, ecological benefit matrix and social benefit matrix) used in this paper are constructed, as shown in Tables 4 to 7.

Table 4  Criterion level judgment matrix

| Economic Benefit | Ecological Benefit | Social Benefit | W_i |
|------------------|--------------------|----------------|-----|
| Economic Benefit | 1.00               | 0.20           | 0.33| 0.10 |
| Ecological Benefit | 5.00             | 1.00           | 3.00| 0.64 |
| Social Benefit | 3.00               | 0.33           | 1.00| 0.26 |

Table 5  Economic benefit judgment matrix

| Economic Benefit | Water consumption of 10 thousand RMB GDP | Water consumption of 10 thousand RMB of industrial added value | W_i |
|------------------|------------------------------------------|---------------------------------------------------------------|-----|
| Water consumption of 10 thousand RMB GDP | 1.00                                     | 5.00                                                          | 0.83 |
| Water consumption of 10 thousand RMB of industrial added value | 0.20                                     | 1.00                                                          | 0.17 |

Table 6  Ecological benefit judgment matrix

| Ecological Benefit | Utilization ratio of reclaimed water | COD emissions per capita | Environment water consumption | W_i |
|--------------------|------------------------------------|--------------------------|-------------------------------|-----|
| Utilization ratio of reclaimed water | 1.00                                | 5.00                     | 0.33                          | 0.66 |
| COD emissions per capita | 0.20                                | 1.00                     | 3.00                          | 0.16 |
| Environment water consumption | 0.33                                | 1.00                     | 1.00                          | 0.19 |

Table 7  Social benefit judgment matrix

| Social Benefit | Domestic water consumption per capita | Utilization coefficient of irrigation water in farmland | Replacement rate of water resources in South-to-North Water Transfer Project | W_i |
|---------------|--------------------------------------|--------------------------------------------------------|--------------------------------------------------------------------------|-----|
| Domestic water consumption per capita | 1.00                                 | 6.00                                                   | 4.00                                                                      | 0.71 |
| Utilization coefficient of irrigation water in farmland | 0.17                                 | 1.00                                                   | 0.00                                                                      | 0.14 |
| Replacement rate of water resources in South-to-North Water Transfer Project | 0.25                                 | 1.00                                                   | 1.00                                                                      | 0.16 |

3.4. Consistency test of evaluation matrix

The establishment of evaluation matrix can simplify complex problems, and change many qualitative problems to be quantitative. However, the evaluation matrix requires the evaluators think in the same way in the evaluation process, that is, the evaluators' judgments should not be contradictory. Therefore,
in order to judge the degree that the evaluation matrix deviates from the consistency, the maximum eigenvalue $\lambda_{\text{max}}$, the consistency index $CI$ and the random consistency ratio $CR$ of the matrix need to be calculated.

According to the definition given by T.L. Saaty, the formula for calculating the random consistency ratio $CR$ is:

$$CR = \frac{CI}{RI}$$

The formula for calculating the consistency index $CI$ is:

$$CI = \frac{\lambda_{\text{max}} - n}{n-1}$$

Where $\lambda_{\text{max}}$ is the maximum eigenvalue of judgment matrix $a$, and $n$ is the number of indexes. See table 6 for the values of random consistency index $RI$.

| n | RI   |
|---|------|
| 1 | 0    |
| 2 | 0.58 |
| 3 | 0.90 |
| 4 | 1.12 |
| 5 | 1.32 |
| 6 | 1.41 |
| 7 | 1.45 |
| 8 | 1.49 |
| 9 | 1.51 |

When the random consistency ratio $CR$ is less than 0.10, the consistency of the evaluation matrix is satisfactory, and the logical error between the model and the evaluation matrix is acceptable; otherwise, the matrix must be modified until it can pass the consistency test.

The consistency ratios of criterion layer matrix, economic benefit matrix, ecological benefit matrix and social benefit matrix are calculated respectively, and the calculated results are 0.037, 0, 0.0272 and 0.0176, which all pass the consistency test and show that the weight distribution of each index is reasonable. Finally, the results of weight distribution scheme of water use efficiency evaluation index in North Canal Basin are shown in Table 9.

| Primary Indexes  | Relative weight | Rank | Secondary Indexes                                      | Relative weight | Rank |
|------------------|----------------|------|--------------------------------------------------------|----------------|------|
| Economic Benefit | 0.10           | 3    | Water consumption of 10 thousand RMB GDP                | 0.09           | 5    |
|                  |                |      | Water consumption of 10 thousand RMB of industrial added value | 0.02           | 8    |
|                  |                |      | Utilization ratio of reclaimed water                     | 0.42           | 1    |
| Ecological Benefit| 0.64           | 1    | COD emissions per capita                                | 0.10           | 4    |
|                  |                |      | Environment water consumption                           | 0.12           | 3    |
|                  |                |      | Domestic water consumption per capita                   | 0.18           | 2    |
| Social Benefit   | 0.26           | 2    | Utilization coefficient of irrigation water in farmland | 0.04           | 6    |
|                  |                |      | Replacement rate of water resources in South-to-North Water Transfer Project | 0.04           | 7    |

4. Results and analysis
According to the index system established above, the comprehensive score of water use efficiency in North Canal Basin from 2016 to 2019 is calculated, and the results are shown in Table 10. In 2019, the water consumption efficiency in the North Canal Basin was the highest, at 3.46% higher than that in 2016. Through the analysis of each index data, the improvement of water use efficiency in the North Canal Basin is mainly due to: 1) The unconventional water sources, such as water source of South-to-North Water Transfer Project and reclaimed water, are introduced, and the increase of unconventional water resources greatly reduces the consumption of groundwater resources in this basin. 2) Upgrade and optimize the industrial structure, which is, while maintaining economic growth, strictly controlling the water consumption for production. In 2019, the water consumption of 10 thousand RMB GDP in the
North Canal Basin decreased by 17.94% compared with 2016, and the water consumption of 10 thousand RMB of industrial added value decreased by 20.45%. The irrigation water utilization coefficient and the economic water use efficiency was greatly improved. 3) The environmental protection has been increasingly emphasized, and the environmental water consumption has increased significantly. From 2016 to 2019, the environment water consumption in the North Canal Basin has increased year by year. In 2019, the environmental water consumption in the North Canal Basin was 210 million m³ higher than that in 2016; 4) The rate of sewage collection and treatment has been greatly improved. From 2016 to 2019, the COD emission per capita in the North Canal Basin decreased significantly, which was 45.24% lower than that in 2016, and the water quality in the basin improved significantly.

Table 10 Score table of water use efficiency evaluation in North Canal Basin

| Year | Score of water use efficiency |
|------|------------------------------|
| 2016 | 0.896                        |
| 2017 | 0.922                        |
| 2018 | 0.902                        |
| 2019 | 0.927                        |

The trend of water use efficiency in the North Canal Basin from 2016 to 2019 was analyzed (Figure 2). The water use efficiency score of the North Canal Basin increased from 2016 to 2019, indicating that the water use efficiency in the North Canal Basin was on the rise, and the water resources management and utilization policies played a positive role. Gao etc. found that the water use efficiency of Beijing, Tianjin and other economically developed areas is higher than the national average level[9, 15], but compared with Israel, Singapore, Hong Kong and other countries with high water use efficiency, there is still a big gap. According to statistics, the water consumption of 10 thousand RMB GDP in Singapore and Hong Kong is 21.37% and 41.51% of that in Beijing respectively. In 2012, Israel has reached 93% sewage treatment rate and 85% recycled water utilization rate, which is much higher than that in the North Canal Basin (21%). Therefore, there is still much room for improvement in water resources utilization efficiency in the North Canal Basin. With the gradual improvement of water resources utilization efficiency, ecological water consumption and water quality in the North Canal Basin, the guarantee of ecological flow in the North Canal Basin will be gradually improved.

Figure 2 The evaluation index system of water resources utilization efficiency in North Canal Basin

5. Conclusion
Based on the analytic hierarchy process (AHP), considered the characteristics of the North Canal Basin and the importance of ecological indicators, the evaluation index system of water use efficiency in the North Canal Basin was constructed. The results showed that the comprehensive score of water use
efficiency in the North Canal Basin increased gradually from 2016 to 2019. Compared with the national water use efficiency, the overall water use efficiency of the North Canal Basin is higher, but it still has a certain potential for improvement. With the improvement of water use efficiency in the North Canal Basin, the ecological environmental water consumption in the North Canal Basin is increasing year by year, and the ecological flow guarantee situation in the North Canal Basin will be gradually improved.

Acknowledgements
The authors thank the anonymous reviewers for their valuable comments. This work was jointly supported by the National Major Science and Technology Program for Water Pollution Control and Treatment of China (2018ZX07111003), National Key Research and Development Program of China (2018YFE0206400), and the National Natural Science Foundation of China (Grant No. 51879278, 51879279).

References
[1] Ze-di Zhang, Dong Liu, Haoran Zhang, etc. Water Saving Irrigation, 10, 59-63(2018).
[2] Yan Song, Qunchang Liu, Peifu Jiang, etc. Yangtze River, 44, 30-33(2013).
[3] Junshi He, He Zhang, Yujuan Fu, etc. Water Resources and Power, 31, 125-128(2013).
[4] Haoxin Li, Dongguo Shao, Xi Yin, etc. Agr. Eng. and Sustainability, 31, 96-102(2015).
[5] Xiaohui Yang, Xiuqiao Huang, Zhen Chen, etc. Agr. Eng. and Sustainability, 31, 95-100(2015).
[6] Shaofei Li. J Arid Land Resour Environ, 25,175-181(2011).
[7] Lei Zhang, Bingqing Tan, Xiangdong Ma, etc. Environ Protection and Sci.39, 23-28(2013).
[8] Hongbo Ling, Hailiang Xu, Qiao Mu, etc. J Desert Research, 30, 989-994(2010).
[9] Yuanyuan Gao, Xinyi Xu, Hongrui Wang, etc. System Eng Theor Prac, 33, 776-784(2013).
[10] Yanfei Zhu, Zhihe Chen, Yuanzheng Jin. Yangtze River, 47, 43-47(2016).
[11] Jing Xu, Lihui Gao. Inner Mongolia Water Conservancy, 10, 42-44(2019).
[12] Ruoxin Cao, Kexin Zhang, Weihua Zeng, etc. Acta Sci Circum, 41, 2005-2017(2021).
[13] Yong Luo, Lezhi Wang, Chun Fu, etc. Yangtze River, 50, 80-84(2019).
[14] Xiong Gao, Hongrui Wang, Yuanyuan Gao, etc. J Hydraul Eng, 44, 478-488(2013).
[15] Shixiang, Li, Jinhua Cheng, Qiaosheng Wu. Chinese Journal of Population Resources and Environment, 3, 215-220(2008).