Water supply eco-economic benefit evaluation of middle route of south-to-north water diversion project in Hebei Water-recipient Area

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Abstract. The Hebei water-recipient area of the middle route project of China’s South-to-North Water Diversion Project (SNWD Project) is located in the Haihe River Basin, which was arid and had higher utilization intensity than other regions in China. Surface water shortage and groundwater over-pumping caused the world’s largest underground water funnel group in the research area. Water supply from the middle route of the SNWD Project is of great significance to ease acute water shortage, alleviate groundwater over-pumping and improve groundwater quality in Hebei water-recipient area. The purpose of this article was to evaluate the eco-economic benefits of the delivered water from the middle route of SNWD Project to alleviate groundwater over-pumping in Hebei water-recipient area by means of reference model method, cost-benefit method and substitute cost method. The results of reference model method, cost-benefit method, and substitute cost method were 5.526, 10.770 and 9.831 billion Yuan per year. While, the cost of delivered water in Hebei water-recipient area was 6.592 billion Yuan per year. From this point of view, the middle route of SNWD Project is very profitable in alleviating groundwater over-pumping in Hebei Province.

1. Basic information of Hebei water-recipient area
The middle route of the South-to-North Water Diversion Project (SNWD Project for short) delivers water through canals and pipes from Danjiangkou reservoir in central China’s Hubei Province to the cities of Beijing and Tianjin, and the provinces of Hebei and Henan. The domestic and production water of more than twenty large and medium cities along the project will be supplied. The first phase of the SNWD Project was completed at December 12nd, 2014. According to the plan of the project, 3.47 billion m³ of water resource was allocated to Hebei every year in the first phase. The delivered water will be mainly used for industrial production and urban living. It will benefit the research area for alleviating groundwater over-pumping and providing more water supply to agriculture.

Hebei water-recipient area of the mid-route of the SNWD Project involves seven municipal administrative --Langfang, Shijiazhuang, Baoding, Hengshui, Cangzhou, Xingtai and Handan. The research area has a total of 91.80 million km² area and 55.81 million people in 2016. The GDP is 2.24 trillion Yuan in 2016. Its area, population and regional GDP account for 48.9%, 74.7% and 69.9% of the total in Hebei Province respectively.

The research area is located in Haihe river basin. Water resources of Haihe river basin were highly
developed and utilized. All of the surface water had been almost used. Most of the waste water discharged from urban living was used for agriculture or infiltrated into the ground [1]. For years, water supply was supported by massive groundwater over-pumping, which caused a continuous decline of groundwater level in the research area, with a groundwater funnel of more than 10,000 km², and a maximum groundwater depth of more than 100m.

2. The dynamic change of water supply-demand during 2000-2016

Based on the data of Hebei water resources bulletin (2000–2016 years) [2], the dynamic change of water resources, water supply and supply-demand balance of water resources in the research area in recent 17 years were analyzed.

2.1. The dynamic change of water resources

During 2000–2016, the total amount of water resources vibrated between 5.178 billion and 12.268 billion m³ in the research area as shown in figure 1. The average annual water resources were 8.183 billion m³, which including 2.449 billion m³ of surface water and 7.157 billion m³ of groundwater. The evolution trends of total water resources, surface water and ground water were relatively consistent. Whereas, the variation magnitude of total water resources and groundwater was significantly greater than that of surface water.

2.2. The dynamic change of water supply

The annual average water supply was 14.185 billion m³ in 2000 – 2016, with a decreasing trend. Of the total water supply, 15.8% was surface water, 83.3% was groundwater, and the rest was unconventional water resources. The annual average groundwater supply was 11.811 billion m³ with an average annual decrease of 212 million as shown in figure 2. The average annual surface water supply was 2.240 billion m³, with an average annual growth of 67 million m³, as shown in figure 2. In addition, the average annual supply of unconventional resources was 134 million m³, with an average annual growth of 29 million m³.
2.3. Analysis of water resources supply-demand balance
The main problem of water resource in the research area was serious groundwater over-pumping. The average amount of groundwater over-pumping in the past 17 years was 5 billion m³ per year. An excess of 2 billion m³ per year in wet years and 7 billion m³ per year in dry years has been taken. During 2000 ~ 2016, the amount of over-pumping groundwater was up to 78.650 billion m³. Under the premise of taking balance, according to the recovery period of 20 years, the annual recharge of groundwater needs to reach 3.933 billion m³. The 3.40 billion m³ water from the SNWD Project can barely make up for the deficit of groundwater over-pumping.

3. Assessment of eco-economic benefit
It was simple to calculate the increasing water cost caused by the higher water price of the delivered water. The total delivered water from SNWD Project reached Hebei was 3.04 billion m³. The average annual groundwater over-pumping in the Hebei water-recipient area was 4.6 billion m³ in the past 17 years. The delivered water all can be used to replace the over-pumping groundwater and restore the groundwater environment. According to the water price of 2.15 Yuan/m³ for the water inlet plant of the SNWD Project determined by the Hebei Provincial Price Bureau, the water cost for Hebei water-recipient area will increase 6.592 billion Yuan/year.

There were two main impacts of delivered water from SNDW Project to Hebei water-recipient area for groundwater over-pumping reduction. First, the high water price of SNDW Project, will lead to a rise of water cost. Second, the exploitation of groundwater will be reduced and the environment of groundwater will be improved. Therefore, the eco-economic benefits of delivered water from the SNWD Project include two parts: the increasing water costs caused by higher water price and the ecological benefits brought by groundwater environment improvement.

The eco-economic benefits of groundwater over-pumping reduction can be calculated using the avoid cost method. The loss brought by the groundwater over-pumping can be used as an alternative to the ecological benefits of groundwater over-pumping reduction. At present, as the seawater intrusion, land subsidence, well end-of-life scrapping, water quality deterioration caused by groundwater over-pumping cannot be accurately measured, the research on estimation of groundwater over-pumping losses is relatively lacking. It is difficult to establish a quantitative relationship between groundwater over-pumping quantity and its consequences such as land subsidence. Therefore, it is difficult to define the eco-economic benefits of groundwater over-pumping reduction. In this article,
the eco-economic benefit of groundwater over-pumping reduction was estimated by three methods: reference model method, cost-benefit method and substitute cost method.

3.1. Reference model method

At present, the eco-economic benefits of groundwater over-pumping reduction are mainly estimated by calculating disaster losses. There are reference model method and direct calculation method for calculating disaster losses. In view of the lack of data, the reference model method was chose in this article. The reference model uses statistical data to establish the average loss of ground fissures, land subsidence, ground subsidence, and seawater intrusion, as well as the relationship between population and regional GDP, and then estimates the economic loss of groundwater over-pumping as the eco-economic benefits of groundwater over-pumping reduction. In this article, the existing groundwater over-pumping economic loss model [3,4] was used to measure the ecological benefits of groundwater over-pumping reduction. The model is as follows:

\[ M = f(E_p) \times A \]  \hspace{1cm} (1)

In equation (1), \( M \) is the economic loss caused by groundwater over-pumping per year (10000 Yuan/year); \( f(E_p) \) is a function of economic loss per area (10000 Yuan/km\(^2\)); \( E_p \) is a composite parameter of economic loss; \( A \) is the area of groundwater over-pumping per year. Parameter \( E_p \) can be defined as:

\[ E_p = \frac{2G_{GDP} + P_s}{3} \]  \hspace{1cm} (2)

In equation (2), \( G_{GDP} \) is GDP per area (10000 Yuan/km\(^2\)); \( P_s \) is the density of population (person/km\(^2\)). Based on equations (1) and (2), the final model can be established as:

\[
M = \begin{cases} 
0.0067E_p + 0.5 & (30 \leq E_p \leq 180, \text{ for minor disaster areas}) \\
0.0075E_p + 1.13196 & (200 \leq E_p \leq 1400, \text{ for general disaster area}) \\
0.008E_p + 1.5168 & (100 \leq E_p \leq 600, \text{ for underdeveloped serious disaster area}) \\
0.0011E_p + 12.434 & (1000 \leq E_p \leq 6000, \text{ for developed serious disaster area}) 
\end{cases} \times A
\]  \hspace{1cm} (3)

According to 2017 Hebei Economic Yearbook [5], the density of GDP and population were calculated. Based on the calculated data, \( E_p \) is all between 1000 and 3000. So, equation (3) can be simplified as follows.

\[ M = (0.0011E_p + 12.434) \times A \]  \hspace{1cm} (4)

Based on Hebei Economic Yearbook [5] and the data announced by the government of Hebei province [6], benefit of groundwater over-pumping reduction was 8.361 billion Yuan/year.

3.2. Cost-benefit method

Delivered water from SNWD Project will be mainly used for two aspects: new additional water consumption in urban development and replacement of agriculture water use and ecological water use. Delivered water will increase available water resources, and reduce costs of drilling deep wells and well end-of-life scrapping brought by groundwater over-pumping, etc. Meanwhile, delivered water will improve water quality and reduce costs of residents in improving water quality and disease medical costs [7]. Therefore, the main benefits of delivered water for groundwater over-pumping reduction include the increase of agriculture output, the saving of domestic water costs, the saving of medical expenses and the cost saving of groundwater extraction.
3.2.1. The increase of agriculture output
It can be measured by comparing the irrigation benefits of surface water and groundwater. As it was verified in an experiment at Heilongjiang Jiangchuan farm [8], comparing to groundwater irrigation, surface water irrigation was more productive with higher yield, better quality and efficiency. Benefiting from the differences in water temperature and the nutrients carried by the water bodies, the yield of wheat irrigated by surface water were higher than that of groundwater irrigating wheat by 6000 Yuan/ha. As it was reported in Handan, wheat outputs irrigated by surface water and groundwater were 9000 kg/ha and 4500~5250 kg/ha respectively [9,10]. Comparing the two income data, the average income of wheat was calculated as 7500 Yuan/ha. According to the ratio of groundwater irrigated area, 30% of the groundwater agriculture used can be replaced. The formula is as follows:

\[ M_1 = M_A \times A \times a \]  

In equation (5), \( M_1 \) is the increase of agriculture output per year (Yuan/year); \( M_A \) is the increased benefit per hectare from irrigated water replacing (Yuan/ha); \( A \) is the effective irrigation area of food crop in the research area (ha/year); \( a \) is the area ratio which can be replaced by surface water irrigation (%). Based on the effective irrigation area of food crop from 2017 Hebei Rural Statistical Yearbook [11], the increase of agriculture output was calculated. The value of \( M_1 \) was 7.258 billion Yuan/year.

3.2.2. The saving of domestic water costs
Benefiting from the middle route of SNWD Project, water quality of water-recipient area was improved effectively. According to reports [12], after starting to supply water to Henan province, many households in urban of Henan water-recipient area have already abandoned household water purification appliances. According to this, urban residents in Hebei water-recipient area will no longer have to spend on water quality improvement. The reduction of the expenses for improving the water quality can be regarded as the saving of domestic water costs, which can be calculated as follows:

\[ M_2 = Q_{UP} \times p_a \times C \times 365 \]  

In equation (6), \( M_2 \) is the saving of domestic water costs per year (Yuan/year); \( Q_{UP} \) is the urban population of the research area (person); \( p_a \) is the proportion of urban residents will abandon water purification appliances in the urban residents (%); \( C \) is the costs of improving water quality per person per day (Yuan/ (person•day)).

According to 2017 Hebei Rural Statistical Yearbook [11], the urban population of the research area was 28.90 million people. It can be calculated roughly that 40% of urban households will abandon water purification equipment, and the costs on water quality improvement was 1 Yuan/day. It can be calculate that the saving of domestic water costs in the research area was 4.219 billion Yuan/year.

3.2.3. The saving of medical expenses
The residents in polluted areas will suffer from chronic diseases and epidemics by drinking contaminated groundwater. All of these will damage the health of residents and increase medical expenses. The delivered water can improve water quality and reduce medical expenses. According to statistical data, 1.5% of the total mortality and 3% of the total disease rates in China are related to water supply and sanitation [13]. With reference to the statistics, it was supposed that disease incidence will be reduced by 3% due to improved water quality by the SNWD Project.

The saving of medical expenses can be regarded as the loss of human health caused by groundwater pollution, as follows:

\[ M_3 = P \times p_r \times C_{MT} \]  

In equation (7), \( M_3 \) is the saving of medical expenses per year (Yuan/year); \( P \) is the population of the research area (person); \( p_r \) is the reduced disease incidence (%); and \( C_{MT} \) is the per capita health
care expenditures for urban residents (Yuan/(person•year)).

The data of population and per capita health expenditure of urban residents was supplied by 2017 Hebei Economic Yearbook. According to the Yearbook, the research area had a population of 55.81 million people. The per capita health care expenditure of urban residents was 1549.85 Yuan. According to calculations by equation (8), the saving of medical expenses was 2.595 billion Yuan/year.

3.2.4. The cost saving of groundwater extraction

Due to groundwater over-pumping, underground water level dropped dramatically. According to the research results of the Institute of Hydrogeology and Environmental Geology [14], average annual decline rate of underground water level in Shijiazhuang was 0.6m/a from 1985 to 2001. As a result of decline of groundwater level, some wells were in ruins and useless. The tracing investigation of 4000 deep wells in Hengshui found that the average annual scrap rate of wells was 3 to 4%, and the loss of each well was tens of thousands or even hundreds of thousands Yuan [15,16]. After the water supply of the middle route of the SNWD Project, some of the surface water can be replaced for agricultural production. In turn, by reducing groundwater use, the loss of well scrapping can be reduced. The loss of water cost can be regarded as the cost saving of groundwater extraction. It can be measured as follows.

\[
M_4 = WQ \times p_{sr} \times L_C
\]  

In equation (8), \(M_4\) is the cost saving of groundwater extraction per year (billion Yuan/year); \(WQ\) is the number of wells in the research area (ten thousand); \(p_{sr}\) is the average annual scrap rate of wells (%); \(L_C\) is the loss cost per well (ten thousand Yuan/well).

According to 2017 Hebei Rural Statistical Yearbook [11], there were a total of 741,800 agricultural wells in the research area. 3% for the average annual abandon rate of a well, 100,000 Yuan for the cost of each well, \(M_4\) can be estimated. As groundwater is replaced, the loss will no longer happen again. So it was calculated that the cost saving of groundwater extraction was 2.225 billion Yuan/year.

3.2.5. Evaluation of total benefits

The total benefits of delivered water for groundwater over-pumping reduction are the sum of above items. Based on the analysis, four kinds of economic benefit can be arranged in the order of amount: the increase of agriculture output, the saving of domestic water costs, and the saving of medical expenses, the cost saving of groundwater extraction. As it was showed in table 1, the increase of agriculture output accounted for 44.54% of the total benefits. Thus, if the agricultural groundwater can be fully replaced, then the benefit of agricultural production will be very impressive.

| Project                      | Increase of agriculture output (billion Yuan/year) | Saving of domestic water costs | Saving of medical expenses | Cost saving of groundwater extraction | Total benefit |
|------------------------------|---------------------------------------------------|--------------------------------|---------------------------|---------------------------------------|---------------|
| Economic benefit             | 7.258                                              | 4.219                          | 2.595                     | 2.225                                 | 16.297        |
| Ratio (%)                    | 44.54                                              | 25.89                          | 15.92                     | 13.65                                 | 100           |

3.3. Substitute cost method

Groundwater over-pumping causes groundwater environmental damage, which leads to significantly increasing costs of pollution treatment and environmental remediation. In this article, the cost for groundwater environment remediation will be used as the ecological benefit of groundwater over-pumping reduction.

According to the research results of the Hydrogeological and Environmental Geology of the Chinese Academy of Geological Sciences [17], of 245 monitoring sites in North China Plain, 49 sites
were extremely affected by fluorine, and organic carcinogens of 22 sites were in excess of the standard. Then the proportion of groundwater that needs to be defluorinated in the research area was 19.2%, and the proportion of groundwater that requires more complex repair techniques was 9.0%. Assuming that 10% of groundwater pollution was caused by groundwater over-pumping, then the groundwater remediation costs can be calculated as follows:

\[ M_4 = Q_g \cdot k \cdot \sum P_i \cdot C_i \]  

(9)

In equation (9), \( M_4 \) is the cost of groundwater environment remediation (Yuan/year); \( Q_g \) is the average annual amount of groundwater over-pumping (m\(^3\)/year); \( k \) is the ratio of polluted groundwater caused by over-pumping (%); \( P_i \) is the proportion of experimental sites of different pollution types in all experimental sites (%); \( C_i \) is the remediation costs of different types of pollution per unit volume (Yuan/m\(^3\)).

Due to very little groundwater environment restoration work carried out, groundwater remediation cost standard was difficult to measure. Calculation of this article depended on the data in the literature and network reports. Wei Xiaojun [18] mentioned that the cost of groundwater remediation would be 45-150$/t if using lower cost repair technology. Inquiring through the Baidu.com, the costs of biological ventilation technology and fluoride technology were 13~27 US dollars/t and 0.1~0.6 US dollars/t respectively. Finally, the median value of the three technical cost ranges was used as the standard in the calculation. The exchange rate was calculated at 1 U.S. dollar = 6.8 Yuan. According to the above formulas and data, the cost for groundwater environment remediation in the research area was 14.876 billion Yuan/year.

4. Analysis of calculation results

Comparing the results obtained by the three methods, as shown in table 2, the largest value was calculated by cost-benefit method, followed by the alternative engineering method. The value calculated by the reference model method was the lowest.

| Calculation methods | Reference model method | Cost-benefit method | Substitute cost method |
|---------------------|------------------------|--------------------|-----------------------|
| Benefits (billion Yuan/year) | 8.36 | 16.297 | 14.876 |

The benefit calculated by reference model method was smaller than the other two methods. This is mainly due to the fact that the model was based on statistics data. The reasons for the lower value mainly included two aspects. Firstly, due to the incompleteness of the types of disasters in the statistics, the data of disaster losses was scarce. Secondly, the statistical data of disaster losses were all direct economic losses, while the data of indirect losses was not included. In the economic loss of the ecological environment caused by groundwater pollution, direct loss was generally small, while the indirect loss was sometimes 10 to 1000 times of the direct loss [19]. According to Zeng et al [20], the ratio of indirect loss to direct loss was 14.5 times in Shanghai.

The cost-benefit method measured the four measurable direct loss of groundwater over-pumping that was currently concerned. In fact, this value represents the lowest economic benefit of delivered water from the middle route of the SNWD Project.

The substitute cost method calculated the cost based on the current restoration needs rather than the cost of repairing the overall groundwater environment. In fact, the cost of rehabilitating the groundwater environment overall was several times higher than the current result. At present, there is a lack of data on the costs of groundwater environmental rehabilitation and groundwater pollution control. If possible, evaluation of the economic loss of groundwater environment based on groundwater quality can be strengthened.
5. Conclusions

The calculation of the eco-economic benefits of groundwater over-pumping reduction was based on the assumption that the groundwater recovery and compensation balance was reached, which need 46 billion m$^3$ of water per year. However, there is only 30.4 billion m$^3$ water every year allocated to Hebei in the middle route of the SNWD Project Plan. The eco-economic benefits of groundwater over-pumping reduction of the middle line of the SNWD Project must be multiplied by a factor of 0.66. Therefore, the direct eco-economic benefits of groundwater over-pumping reduction measured by reference model method, cost-benefit method, and substitute cost method were 5.525 billion Yuan/year, 10.770 billion Yuan/year and 9.831 billion Yuan/year respectively. Meanwhile, the increased cost for the delivered water from the SNWD Project was 6.592 billion Yuan/year. It can be seen that the economic benefits of groundwater over-pumping reduction are substantially greater than the cost of water costs increased. The conclusion is that the unit directs eco-economic benefits generated by the delivered water are good, which is of great significance for alleviating groundwater over-exploitation in Hebei water-recipient area. As the indirect economic benefits of improving the ecological environment are often ten or even a thousand times more than direct economic benefits, the benefits of delivered water from the middle route of the SNWD Project is very significant for relieving groundwater over-pumping in Hebei Province.

However, during three years after water supply from the middle route of the SNWD Project, the biggest volume of delivered water to Hebei was 966 million m$^3$. There is still a large gap between that and the allocation indicators of 3.04 billion m$^3$. The huge investment in the SNWD Project impacted delivered water demand. The SNWD Project in Hebei Province includes the construction and transformation of four large-scale water mains, which length of water transmission pipelines above the waterworks is 2056 km. It has the largest scale, the longest pipeline and the largest number of newly built water plants in the four provinces and cities the middle route of the SNWD Project involved. It has a total investment of 60 billion Yuan.

According to report, up to now, Hebei province has the capacity of using 30.4 billion m$^3$ of allocated water. In the past three years, 7063 wells were closed in Hebei. In 2016, the shallow groundwater level increased by 0.58m and the deep groundwater level increased by 0.7 m than three years ago. In 2017, the agricultural groundwater over-pumping reduced 258 million m$^3$, which achieved remarkable results. There is still a big gap to 3.04 billion m$^3$. Groundwater over-pumping reduction is not a work that can be accomplished overnight. It requires a relatively long period of time. It involves the factors of the natural rules, the technical and engineering means, and financial support etc. While, with the increase of water inflow from the middle line of the SNWD Project, the benefits will increase prominently.

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