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A multi-objective water trading optimization model for Henan Province's water-receiving area in the Middle Route of China's South-to-North Water Diversion Project

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Abstract

Water trading is an effective method for solving regional water shortage problems and addressing the uneven spatiotemporal distribution of water resources. Therefore, taking the Middle Route of China's South-to-North Water Diversion Project (MR-SNWDP) as the research object, we present a study on a feasible water trading scheme in the water-receiving area of Henan Province. First, the tradable water of each calculation unit in the water-receiving area was calculated by analyzing the water-saving potential of different industries. Second, a multi-objective optimization model for trading water between different regions was developed, taking the largest social and economic benefits of the water-receiving area as the objective function. Finally, non-dominated sorting genetic algorithms were used to solve this optimization model, and an optimal scheme for water trading was proposed. The simulated results of the optimal scheme indicate that the total water shortage of the water-receiving areas will decrease by 650.69 million m^3, and there will be a surplus of 14.98 million m^3 of water, and the gross national product will increase by RMB 130.5 billion at a rate of 5.2%. This demonstrates that the water-receiving areas of Henan Province can effectively alleviate local water shortages by trading water without increasing external water supplies.

Keywords: Middle route of China's South-to-North Water Diversion Project; Multi-objective optimization; Non-dominated sorting genetic algorithms; Water trading

Introduction

China endures water shortages caused by inconsistencies in the spatiotemporal distribution and low utilization efficiency of water resources, which currently influence sustainable socioeconomic development. Water trading is an effective method for improving the utilization efficiency of water resources,

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optimizing the water use structure, and reasonably allocating water resources between different regions. Water trading first occurred in the western United States, which granted the owners of water resources priority occupancy to sell surplus water in the market, i.e., trading water rights (Chen & Xu, 2006). After decades of practice and exploration, two types of water markets have been established: the informal and the regular water markets. In some countries that experience water shortages, such as India and Mexico, the government could not control the changes in water demand and formed spontaneous local water markets before developing formal water trading. However, after developing formal water trading, Chile and Mexico have established regular water trading markets across their respective countries. Many states in the western United States and some in Australia have established similar water trading systems. Since July 2014, China has launched pilot water trading systems in seven provinces, i.e., Ningxia, Jiangxi, Hubei, Inner Mongolia, Henan, Gansu, and Guangdong, and has obtained some results.

Before the large-scale promotion of water trading, it is necessary to recognize its driving force and the operation mechanism of the water market, which is the basis for the trading of water rights. Many scholars have recently researched theories and methods for water trading. For example, Hahn (1986) researched the moving and trading process of water rights in the water market and combined water rights with their corresponding markets, while Colby *et al.* (1993) studied the role of market prices and value laws in water trading. Egteren & Weber (1996) proposed that tradable water rights can follow the trends of supply and demand through the role of the market and efficiently allocate water resources. Becker *et al.* (1996) found that the redistribution of water rights could be accomplished through the operation mechanism of water trading. Ermoliev *et al.* (2000) proposed that, as the market changes due to the relationship between supply and demand, water trading also exhibits dynamic changes in water markets. In another study, Luo *et al.* (2003) developed a water trading model through the uncertainty planning method, and found that the efficiency of water allocation could be improved through trading. Heaney *et al.* (2004) constructed a trans-regional water trading pattern, and applied it to the Murray Darling River Basin in Australia. Calatrava & Garrido (2005) analyzed the risks of water rights spots during trading on the market.

The selection and construction of a water trading model is central to obtaining an applicable water trading scheme as it determines the operating efficiency of the water rights market and water trading costs, thereby affecting the benefits of the water rights' parties. Most research on water trading has focused on the application of the game, auction, and complex adaptive systems (CAS) theories (Lu, 2007; Wang *et al.*, 2007; Deng & Xu, 2012). Based on this, several scholars have proposed water trading models from different perspectives, such as mathematics and economics, and have made important contributions to the development of water trading in different regions. For example, Thoyer *et al.* (2001) established a multi-variable negotiated bargaining model based on each water trading party, including agricultural and environmental water users, water resource managers, and taxpayers in the southwestern region of France. Gomez-Limon & Martinez (2006) developed a multi-criteria optimization model for irrigation area water markets, taking Spain as an example. Zhao *et al.* (2016) constructed a two-level water trading model based on Shayinghe River Basin, which considered local water users and administrative regions. The above studies provide good references for water resource management and the construction of a water trading market; however, few studies on water trading have focused on trans-basin cities. After the completion of China's Middle Route of the South-to-North Water Diversion Project (MR-SNWDP), the distribution of transferred water quantity between cities along the route was also completed. However, owing to differences in economic and social development between regions, contradictions caused by the imbalance of supply and demand of water resources are gradually emerging. Therefore, we analyzed the water-saving potential of water trading in various regions by referring to existing achievements and considering the actual demands of water trading in the water-receiving area of Henan Province along the MR-SNWDP. A multi-objective optimization model of water trading was then constructed using the cities in the water-receiving area of Henan Province to solve the imbalance of water supply and demand in the area along the route.

Methods

Based on analysis of the water use efficiency and exploitation of the local water-saving potential of the water-receiving area, we calculated the number of tradable water rights and proposed an optimization scheme for water trading between the cities in the water-receiving area. The main components of this research are as follows. First, we determined the water saving potential of various industries by comparing the water consumption quotas in high-efficiency water-saving areas. Second, the tradable water rights for each city in the water-receiving area were calculated by analyzing the influence factors of water supply and demand, including the decrease in the scale of groundwater exploitation, the quantity of water reserved by administrative measures, and the quantity of idle water due to other reasons. Based on this, the buyers and suppliers of water rights were determined. Third, a water trading model between the buyers and suppliers was developed, taking the largest social and economic benefits of the water-receiving area as the objective function and the water quantity balance, total maximum water use, and benefits priority restrictions as the constraints. Finally, an optimal cross-regional scheme of water trading in the water-receiving area was proposed according to the tradable water rights of each city and the relationship of water resource supply and demand.

There are two forms of water trading based on differences in the trading scope and object (Dou *et al.*, 2014): one is the exchange of water rights between different water users in the same area through a completely open water market, and the other is the redistribution of water rights between different regions through an incomplete market with administrative intervention. This study mainly focuses on the latter. As the water users in the MR-SNWDP are mainly urban domestic, service industries, and industrial enterprises with high water quality requirements, agricultural water users were not considered during the water trading calculation process. Therefore, the accounting and trading of water rights were only determined for water users in the industry and service industries. From combining the actual conditions of the regions and simplifying the calculations, the service industry's water use also includes the domestic water usage of residents. As industry and service industry water users in the same city share the same water supply lines, we will no longer discuss water trading between them as we assume that the first type of trading was completed in the urban water supply system. We will then focus on the second type of water trading behavior across regions.

Method of accounting tradable water rights

The tradable water right is the surplus of water resources that can be used for sale in the region. It is based on the district water saving calculation, and includes the water saving rights of water users such as industry, service industry, and urban residents. The quantitative calculation of tradable water rights follows certain procedures and principles: first, the water-use quota of each water user in each calculation unit was calculated from the water demand before the implementation of water-saving measures by users and socioeconomic indices according to water resources' bulletins and other related information. Second, the water quota reduction indicators for different water users were formulated considering water-saving potential and combined with the usage quota of high-efficiency water use areas, and the water demand after implementing the water saving measures was also calculated. Third, the quantity of water available for different water users was calculated considering the conditions of local water resources and the water allocation index of the MR-SNWDP for each city, and the total quantity of water saved in each calculation unit was obtained from the available water quantity and demand of water users. Finally, the total quantity of tradable water rights on the unit was determined on the basis of the water use savings of each user in the calculation unit.

As we only studied water trading in the water-receiving cities of the MR-SNWDP, the main object of trading was urban water users, including industry, service industry, and urban residents. Assuming that there were m water users in the water-receiving city participating in water trading, the tradable water rights Qit in the ith city could be expressed as:

$$Q_{it} = \sum_{j=1}^{m} Q_{\mathrm{js}} \tag{1}$$

where Q_{js} is the completed quantity of water savings for the jth user and its expression is:

$$Q_{js} = Q_{ja} - Q_{jx} \tag{2}$$

where Q_{ja} is the quantity of water available to the user before saving water, and Q_{jx} is the quantity of water required by the water user after saving water. When Q_{js} is a negative value, under current water demand and water saving level, this water user can use less water than required, and needs to purchase certain water rights to meet the demand. When Q_{js} is a positive value, under current water demand and water saving level, this water user can use more water than required, and can save certain water rights for trading.

The following principles should be followed during the calculation of tradable water rights. (1) To meet the local governments' requirements for water use efficiency (Li *et al.*, 2014). The water use efficiency of each industry in each city cannot be lower than that set by the local government. (2) To pursue high-efficiency water saving. The water-use quota of each industry should be as close as possible to the advanced water saving level set at home and overseas in the range of regional economic sustainability. (3) To guarantee basic water consumption. The tradable water rights must be the water-saving rights of users and ensure that their basic water demands are not impacted. For example, a certain quantity of water rights must be reserved to meet the basic residential and domestic, and ecological water need (Hu *et al.*, 2014).

Multi-objective optimization model of water trading

Based on obtaining the number of tradable water rights in each city of the water-receiving area, a multi-objective optimization model containing objective functions and constraints was developed to solve the optimal water trading scheme. The construction principle of the model is the quantitative balance of water supply, use and consumption, and drainage of each calculation unit in the water-receiving area. The water supply is sourced from local available groundwater, surface water, and external water transferred through water trading. As the water resources in the MR-SNWDP are the focus of this study, only urban residents, industry, and service industries are defined as water users that trade water rights. Water usage would consume some of the water and generate wastewater. This wastewater needs to be collected and disposed of after centralized treatment. To ensure that the ecological and environmental burdens within the unit are not increased, the sewage treatment capacity in the calculation unit should be considered.

Development of the water trading model. Objective function. When the water rights are traded, social efficiency should be considered first, water rights trading should solve water use conflicts in water-deficient areas. At the same time, economic efficiency and the ecological impact caused by discharge after water use must also be considered. The ecological impact of water trading represents the cost of wastewater treatment, which is a negative economic benefit. When calculating the economic benefits of water trading, negative economic benefits generated by ecological benefits need to be deducted. Therefore, taking the largest social and economic benefits of the entire water-receiving area as the objective function, we developed a multi-objective optimization model for water trading.

1. The social benefits should take into account water demand and shortage in different regions of the water-receiving area, and solve the water use contradiction in the water-scarce areas. Therefore, we took the minimum water shortage of the entire water-receiving area as a social benefit objective function. This social benefit objective function can be expressed as:

$$f_1(x) = Q_{zq} = \min\left[-\sum_{i=1}^{n}\left(\sum_{j=1}^{m} Q_{ja} + x_{it} - \sum_{j=1}^{m} Q_{jx}\right)\right] \tag{3}$$

   where Q_{zq} is the total water shortage of the water-receiving area. When it is positive, it means that the water-receiving area is still short of water after water trading, and a negative value means that water demand can be met. Q_{ja} is the available water quantity of the jth water user before water trading. x_{it} is the completed-trading water rights of the ith calculation unit; a positive value indicates the purchase of water rights, and a negative value indicates the sale of water rights.
2. The economic benefit is expressed as the sum of the positive and negative benefits in the water-receiving area. Assuming there were n calculation units in the water-receiving area, the economic objective function of water trading can be expressed as:

$$f_2(x) = TEB = \max\sum_{i=1}^{n}(puG_i - cbG_i \bullet \lambda_i) \bullet (Q_{ia} + x_{it}) \tag{4}$$

   where TEB is the total economic benefit of the water-receiving area in Henan Province; Q_{ia} is the available water quantity before the trading of the ith calculation unit; puG_i is the average gross national product (GDP) per cubic meter of water of the ith calculation unit; cbG_i is the average sewage treatment cost per cubic meter of the ith calculation unit; λ_i is the pollution discharge coefficient of the ith calculation unit.

The constraint conditions.

1. Water quantity balance constraint: Water supply, use, consumption, and discharge processes and water trading in each calculation unit must comply with the water balance principle, i.e.:

$$Q_{\mathrm{isg}} = Q_{isy} = Q_{isp} + Q_{ish} + Q_{iss} \tag{5}$$

   where Q_{isg} is the water supply quantity after the trading of the ith calculation unit; Q_{isy} is the water use quantity after the trading of the ith calculation unit; Q_{isp} is the discharge quantity after the trading of the ith calculation unit; Q_{ish} is the water consumption quantity after the trading of the ith calculation unit. Q_{iss} is the quantity of water loss in the ith calculation unit water trading process.
2. Maximum constraint of total water use: Each calculation unit (including transferred water quantity) cannot be higher than 1.2 times total water use quantity red line designed by the local government; at the same time, the total water use of the entire water-receiving area cannot be higher than the sum of total water use quantity red line designed by the local government, i.e.:

$$\begin{cases} \sum\limits_{j=1}^{m} (Q_{ja} + Q_{js}) + Q_{i1} \leq 1.2W_i \\ \sum\limits_{i=1}^{n} (Q_{ia} + x_{it} + Q_{i1} \leq W \\ W > 0 \\ Wi > 0 \end{cases} \tag{6}$$

   where Q_{i1} is the water consumption of the agriculture of the ith calculation unit after water users begin to save water; W_i is the quantity of the red line of water use regulated by local government of the ith calculation unit; Q_{ia} is the quantity of water available for the ith calculation unit; W is the sum of quantity of the red line for all calculation units in the water-receiving area in Henan Province.
3. Trading volume constraint: The water rights used for trading of each calculation unit cannot be greater than its tradable water rights calculated by the formula (1), i.e.:

$$x_{it} \leq Q_{it} \tag{7}$$

   where q_{ijy} is the maximum flow of trading water volume of the ith calculation unit; q_{isj} is the designed water delivery capacity of the trunk or branch canals of the MR-SNWDP.
4. Benefits priority constraint: The value of GDP per cubic meter of water is used as a criterion for the evaluation of the sequence of water trading of each calculation unit. The units with higher GDP per cubic meter of water will have priority in obtaining water rights' purchase opportunities, while the units with smaller GDP per cubic meter of water will have priority in obtaining water rights' sales opportunities.
5. Water loss constraint: When making a water rights scheme, it is essential to consider the water loss due to factors such as long distances for water delivery. When the upstream surplus water rights are

traded downstream, the trading water volume should include the loss of water to ensure that the water demand of the water-requiring party is satisfied.

Solution of the water trading model. A genetic algorithm is a random search algorithm that simulates natural selection and evolution of organisms, and they are widely used to solve highly complex, non-linear optimization problems. The non-dominated sorting genetic algorithm method (NSGA-II) with an elite strategy is an improvement on the traditional genetic algorithm, which can reduce the computational complexity of the algorithm and ensure that the global optimal solution is evenly distributed on the solution set domain, guaranteeing the diversity of the population (Liu & Yu, 2013).

To solve the multi-objective water trading model, NSGA-II is applied. There can be no solution in the solution process, so that each objective function can reach the optimal solution. Therefore, the solution should be a set of non-inferior solutions. The advantages need to be optimized according to the actual requirements. The solution steps in this study are as follows: (1) a solution set that satisfies the water trading constraint requirements is obtained according to the NSGA-II method; (2) the Young Conflict Resolution Theory (YCRT) method, also written as Young's Bargaining Method or the Young Bargaining Theory (Fallah-Mehdipour *et al.*, 2011), is then used to optimize the emissions trading plan.

The NSGA-II is calculated as follows:

Step 1: Initialize the population, i.e., randomly generate the parent population P_t (population size N).

Step 2: Non-dominated classification, i.e., classification according to the dominated and non-dominated relationships between individual populations. In this step, the progeny population Q_t (population size N) should be generated from the parent population P_t, and the two populations should be combined into R_t (population size $2N$); Z_i then forms according to R_t non-dominated sorting and Z_1 is set as the non-dominated set of the first level. In this set, all individuals with optimal solutions are independent of any other individual, and the larger the value of i, the poorer the superiority.

Step 3: Fast non-dominated sorting. This step first imposes constraints on the individuals in non-dominant set Z_i. If an individual can meet the corresponding constraints, Z_i is inserted into the newly generated population P_{t+1}; otherwise, it is discarded. Therefore, there is no limit to the number of non-dominated elements in this operation. If the number of population P_{t+1} is not N, a new population P_{t+1} needs to be formed by selecting appropriate individuals based on the non-dominated relationships between them and the degrees of congestion. If the number of population P_{t+1} is less than N after the non-dominated set Z_1 is added to P_{t+1}, it is necessary to continue adding the next-level non-dominated set Z_2 to the population P_{t+1} until the non-dominated set Z_n is added. The number of population P_{t+1} is equal to or greater than N. In this case, it is necessary to calculate the crowding degree of individuals in non-dominated Z_n. As individuals are on the same non-dominated layer, individuals with larger crowding distances will be better than those with smaller crowding distances, so all individuals in this tier can be sorted. The calculation principle of crowdedness operators can be found in Gao (2006). When an individual is not in the same non-dominating layer, the smaller the i, the better the individual. After the individual's congestion degree is calculated, some individuals in front of it are added to P_{t+1} so that the number of P_{t+1} is equal to N, and the number of selected individuals is $\{\mathrm{num}(Z_n) - [\mathrm{num}(P_{t+1}) - N]\}$. The traditional crossover and mutation are then performed to generate a new offspring population Q_{t+1}.

Step 4: Perform crossover and mutation operators to generate offspring population Q_{t+1} (population size N).

Step 5: Execute the loop. If $Gen = 1{,}000$, stop the calculations and output the water trading plan set. Otherwise, repeat steps 2 to 4 until the requirements are met and the iteration ends.

A set of solutions satisfying the constraint conditions can be obtained according to the above steps, and the YCRT method is then used to optimize the solution set. Considering that different objective functions represent different interest subjects, utility functions are used to reflect the degree of preference of the two and identify the better points. This method seeks the maximum value of $R(x)$, which is calculated as follows (Fallah-Mehdipour *et al.*, 2011):

$$Max\ R(x) = \min\left\{ \min_{j\in I_1} \frac{\frac{\partial u_j(x_1)}{\partial x_1}}{u_j(x_1)},\ \min_{k\in I_2} \frac{\frac{\partial v_k(x_2)}{\partial x_2}}{v_k(x_2)} \right\} \tag{8}$$

where u_j and v_k are utility functions of two interest subjects; I_1 and I_2 are interest subjects, respectively; x_1 and x_2 are two objective function values (dimensionless), and $x_1 + x_2 = 1$.

$$\begin{cases} x_1 = \dfrac{l_2}{l_1 + l_2} \\ x_2 = \dfrac{l_1}{l_1 + l_2} \end{cases} \tag{9}$$

where l_1 and l_2 are objective function values with different dimensions, respectively. In order to facilitate the calculation, the two objective function values need to be normalized. Therefore, l_1 and l_2 are transformed into values in the range [0, 1], and the following transformation is performed:

$$l_1 = \frac{f_1^{\max} - f_1}{f_1^{\max} - f_1^{\min}} \tag{10}$$

$$l_2 = \frac{f_2 - f_2^{\min}}{f_2^{\max} - f_2^{\min}} \tag{11}$$

where f_1 and f_2 represent the results of a certain trading scheme of two objective functions, and $f_1^{\max}$ and $f_2^{\max}$ represent the maximum of the results of two objective functions in all trading schemes, $f_1^{\min}$ and $f_2^{\min}$ represent the minimum of the results of the two objective functions in all trading scenarios, respectively.

Results and discussion

Study area

The MR-SNWDP mainly provides domestic and industrial water to 19 large and medium-sized cities and more than 100 counties in the Beijing, Tianjin, Henan, and Hebei Provinces or Municipalities, and the total water-receiving area is approximately 155,000 km^2. The water-receiving area of Henan Province consists of 11 cities with a total population of 62.1347 million and total area of 87,740 km^2. Some specific situations for the water-receiving area of Henan Province are shown in Table 1. The average annual total water resources in Henan Province are 41.4 billion m^3, and surface water resources constitute 31.3 billion m^3, shallow groundwater resources constitute 20.47 billion m^3, and of this, water resource modules constitute 248,000 m^3/(a•km^2). The total quantity of water resources in the province ranks 19th in the country, with a per capita occupancy of 445 m^3 and an average cultivated area of 407 m^3.

The total length of the trunk canal of the MR-SNWDP is 1,431 km, and 730 km of this is in Henan province. It spans four river basins in China, i.e., the Yangtze, Huaihe, Yellow, and Haihe River Basins. The water-receiving area of Henan Province has the longest trunk canal, the largest investment, and the most complex geological conditions of the four provinces. Almost 1,000 km of supporting water delivery pipes have been built along the trunk canal in Henan Province to ensure safe water supply from the 39 water-diverting outlets along the line to the 83 supporting water plants in 11 water-receiving cities, as shown in Figure 1 (U1–U11 are used to number these cities in order from south to north). After deducting the water loss from the total trunk canal and the quantity of irrigation water for the Danjiangkou Irrigation District, 2.994 billion m^3 of water is allocated to all outlets (Wang *et al.*, 2014).

Quantification of tradable water rights

Taking the urban area of each prefecture-level city in the water-receiving area as the calculation unit, we calculated the tradable water rights according to the quantitative principles and calculation methods given above.

Table 1. Basic situations of the water-receiving area of Henan Province in 2015.

Number	Corresponding city	Urban population/10^4 capita	Area/km^2	*GDP*/10^8 RMB	Industrial added value/ 10^8 RMB	Service industrial added value/10^8 RMB	Allocated water by the MR-SNWDP/10^8 m^3
U1	Nanyang	397	26,600	2,875.02	1,525.71	997.19	4.91
U2	Pingdingshan	245	7,882	1,705.78	889.48	646.94	2.50
U3	Luohe	125	2,617	992.85	624.75	261.58	1.06
U4	Zhoukou	319	11,959	2,082.38	964.39	663.97	1.03
U5	Xuchang	207	4,996	2,170.6	1,281.80	719.27	2.26
U6	Zhengzhou	667	7,446	7,315.19	3,625.52	3,528.72	5.40
U7	Jiaozuo	194	4,071	1,943.37	1,182.93	623.71	2.69
U8	Xinxiang	280	8,269	1,982.25	1,006.73	754.64	3.92
U9	Hebi	89	2,299	713.23	471.41	179.97	1.64
U10	Puyang	146	4,188	1,333.64	754.49	421.65	1.19
U11	Anyang	246	7,413	1,884.48	952.67	727.23	3.34
Total	2,915	87,740	24,998.79	13,279.88	9,524.87	29.94	

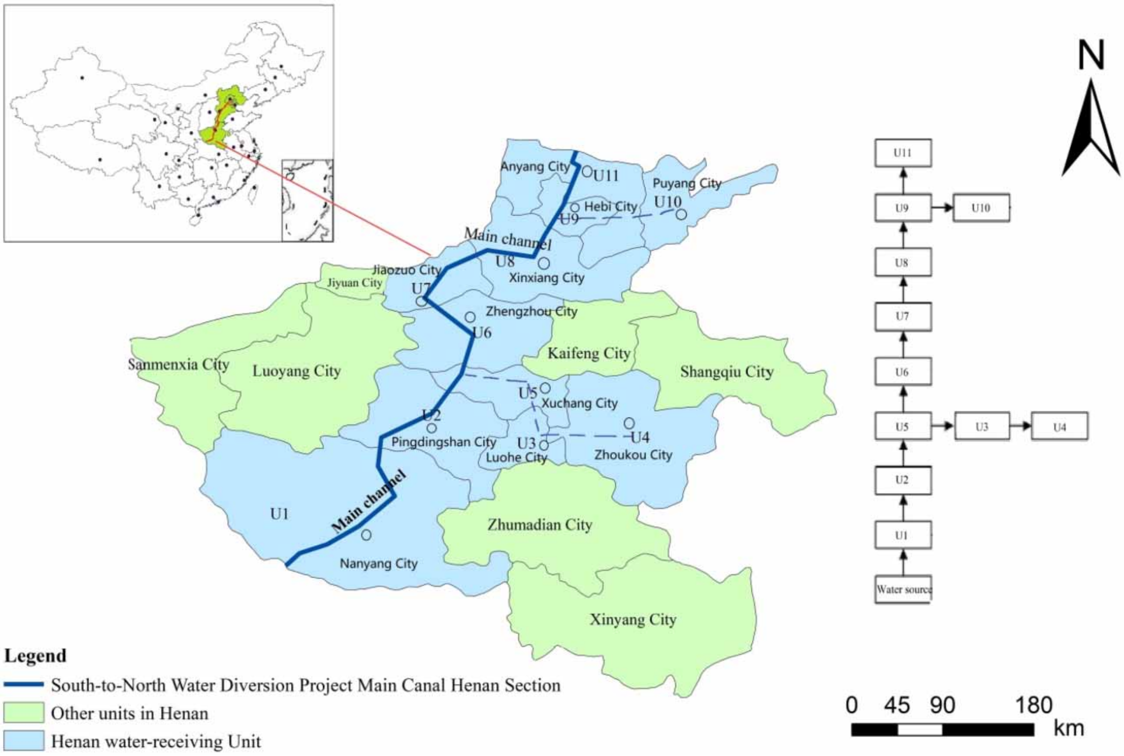

Fig. 1. Schematic diagram of trunk canal of the MR-SNWDP and water-receiving area of Henan Province.

By referencing literature such as the *Henan Water Resources Bulletin* in 2015, the *Water Resources Management Indicators Plan of Henan Province*, and the *Local Standards of Henan Province*: *Industrial and Urban Life Water Quota (DB41T385-2014)*, we calculated the water-saving goals of the cities in the water-receiving area by combining advanced global water-saving levels. By calculating the available water volume of various industries in the water-receiving areas in 2015 and the water demand after water saving, the final tradable water rights of each calculation unit can be calculated. For the convenience of calculation, the water users in one calculation unit are simplified into two water users: industry and service industries (including urban domestic). The accounting results of tradable water rights are shown in Table 2.

Negative values in Table 2 indicate water shortages at the current water saving level for the user or calculation unit, and positive values indicate the surplus water for the user or calculation unit at the current water saving level. Table 2 shows that water users in Nanyang (U1), Pingdingshan (U2), Luohe (U3), and Zhoukou City (U4) can meet their own water demands by adopting certain water saving measures. Under water-saving conditions, a large quantity of water rights can be saved for trading between regions. Nanyang City (U1) possesses the largest amount of tradable water rights at 195.03 million m^3, followed by Zhoukou City (U4) at 90.66 million m^3. Even if water users in other calculation units adopt certain water-saving measures and increase their water-saving levels, their water supply capacity cannot meet their own development needs, therefore, they need to obtain necessary water resources through water trading. Zhengzhou City (U6) faces the most serious water shortages of 140.54 million m^3. Table 2 also shows that water shortages in water-scarce cities are caused by industrial water

Table 2. The tradable water rights of each computing unit in the water-receiving area of the MR-SNWDP of Henan Province.

	Water supply before water rights trading		Water requirement after saving water (10^4 m^3)		
Computing unit	Industry	Service industry (including town life)	Industry	Service industry (including town life)	Tradable water rights (10^4 m^3)
U1	55,529	23,795	38,617	21,204	19,503
U2	38,022	8,442	35,971	7,690	2,803
U3	15,742	4,357	13,057	3,969	3,073
U4	33,211	16,452	25,937	14,660	9,066
U5	21,559	11,589	25,955	10,671	−3,478
U6	36,799	48,720	54,230	45,343	−14,054
U7	28,242	10,280	32,492	9,262	−3,232
U8	19,503	23,459	24,906	21,369	−3,313
U9	5,724	5,479	7,239	5,125	−1,161
U10	24,991	11,149	29,075	10,050	−2,985
U11	14,779	13,125	19,873	11,915	−3,884
Total	294,100	176,848	307,352	161,258	2,338

shortages. Zhengzhou City (U6) also faces the most serious industrial water shortages, amounting to 177.95 million m^3. Overall, with the fulfillment of their own water-saving potential and supplementing industrial water shortages, the water-receiving area still possesses a surplus of water rights, which is approximately 23.38 million m^3. The surplus water in the service industries (including urban domestic) is the most significant, accounting for approximately 75% of the total surplus; the surplus tradable reserved administrative and idle water rights accounted for 8.3% and 16.7%, respectively. Under the principle that the water sources of the MR-SNWDP will give priority to water for domestic use, there will be a surplus of water in the service industries (including urban domestic) of each city in the water-receiving area. In some northern cities, there is a shortage of industrial water that needs to be met through water trading. This is consistent with the high development of industry in northern China, but insufficient water supply.

Water trading scheme selection and analysis

The GDP per cubic meter of water of local cities (according to the Henan Province statistical data), the city's pollutant discharge coefficient, and other relevant data were calculated by consulting the *Statistical Yearbook of Henan Province in 2015*. The NSGA-II algorithm was then used to solve the water trading multi-objective optimization model. The parameters were set as follows: population size $N = 500$; maximum number of iterations $Gen = 1{,}000$, hybrid probability $P_c = 0.9$, and mutation probability $P_m = 0.033$, and non-inferior solution sets were obtained through iterative calculation.

In conjunction with relevant references, the utility functions $u(x_1)$ and $v(x_2)$ of the two subjects of economic and social benefits are set to curves (a) and (b), and du/dx_1, dv/dx_2, and $R(x)$ are then obtained, respectively. When $x_1 = 0.6$ and $x_2 = 0.4$, $R(x)$ has a maximum value of 2.68. At this time, $l_2 = 1.5l_1$, and a better solution can be obtained (A). $R(x)$ reaches its maximum value, and the corresponding trading scheme is shown in Table 3 and Figure 2. At the same time, the remaining tradable water in each city after trading was also calculated.

Table 3. Water trading results in each calculation unit of the water-receiving area of Henan Province.

Water-seller units	Water-buyer units	Sold water rights amount/10^4 m^3	Purchased water rights amount/10^4 m^3	Surplused tradable water rights of the water-seller/10^4 m^3
U1	U5	3,548	3,478	15,955
	U6	14,445	14,054	1,510
	U7	1,510	1,475	0
U2	U7	1,795	1,757	1,008
	U8	1,008	978	0
U3	U8	2,385	2,335	688
	U9	688	669	0
U4	U9	517	492	8,549
	U10	3,055	2,985	5,494
	U11	3,996	3,884	1,498

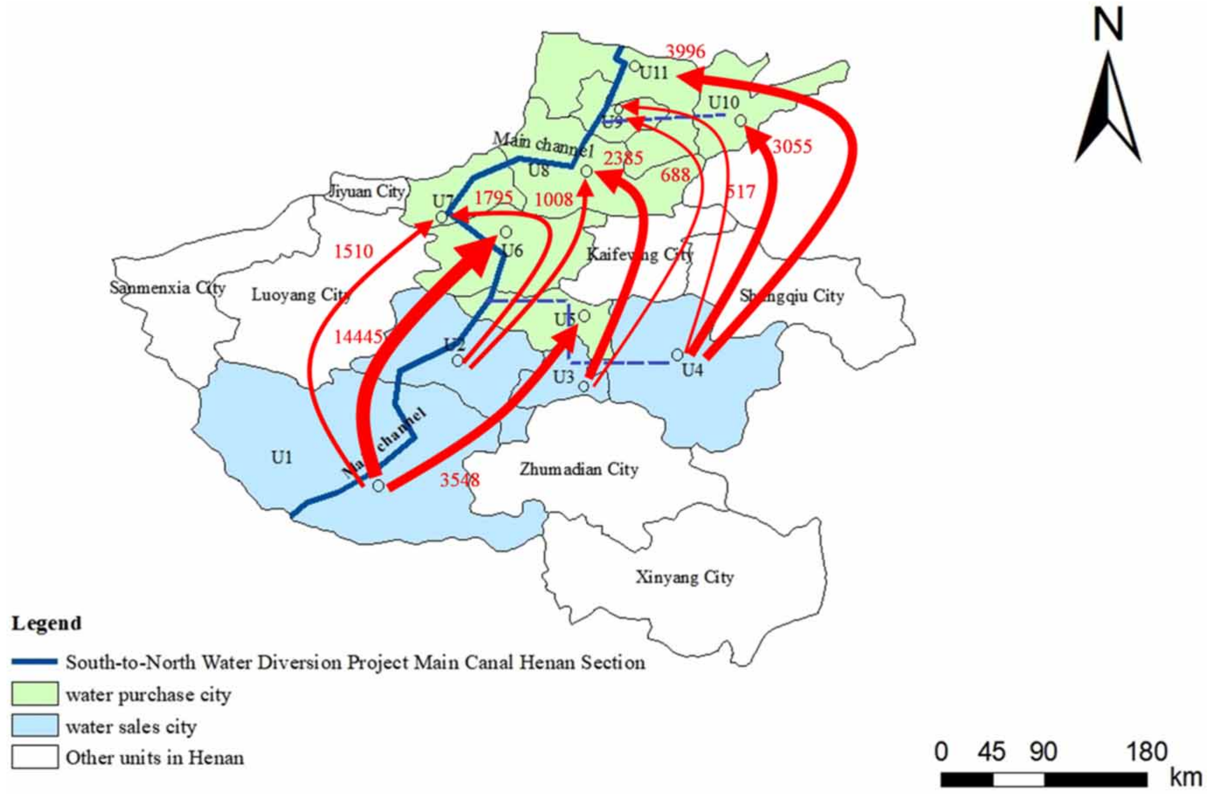

Fig. 2. Water trading results in each calculation unit of the water-receiving area of Henan Province.

Table 3 shows the water trading process and volume between the units in the water-receiving area. As water loss during the water transfer process is unavoidable, the water purchaser needs to purchase more water rights than required to meet the demand. We used a percentage of 0.01% of water loss per kilometer to calculate the water trading. As shown in Table 3, there were four water sales units: U1, U2, U3, and U4. U1 sold water rights to U5, U6, and U7, with trading volumes of 35.48 million, 144.45 million, and 15.1 million m^3, respectively, constituting all of U1's tradable water rights. U2 sold the rights to take water to U7 and U8. The trading volumes were 17.95 million and 10.08 million m^3, respectively, and there were no remaining tradable water rights in U2. U3 sold water rights to U8 and U9, with trading volumes of 23.85 million and 6.88 million m^3, respectively, and all the tradable water rights of U3 were sold. U4 sold water rights to U9, U10, and U11, with trading volumes of 5.17 million, 30.55 million, and 39.96 million m^3, respectively. U4's remaining tradable water rights amounted to 14.98 million m^3. The water shortage situation of the seven water-purchasing cities was improved through water trading, and the normal water demand of the four water-selling cities was not significantly affected, and there were still 14.98 million m^3 of tradable water rights remaining in U4.

Under the water trading results of the optimal scheme, the water usage of each calculation unit in the water-receiving area changed. As shown in Table 4, the social water shortages are negative in units U1, U3, and U4 before the implementation of trading, indicating that the water supply of these three units is sufficient for meeting their own water demand and there is a certain quantity of surplus water. The remaining water in U1 reaches 11.052 million m^3, while other units are short of water. U6 faces the most serious water shortage of 287.23 million m^3, and the total social water shortage in the water-receiving area is 635.71 million m^3. After water saving and trading, all calculation units can meet their water demand and U4 has 14.98 million m^3 of remaining water rights; other units have no residual water rights. The total water remaining in the water-receiving area reached 14.98 million m^3, which is a decrease of 650.69 million m^3 from the pre-trading social water shortage. This indicates the remarkable social effect of water trading.

The economic benefits of the water trading results are also significant, as shown in Table 4. If the *GDP* per cubic meter of water is constant, the four water-selling cities sell part of their surplus water rights while meeting their normal water demands, and water use declines. Therefore, the value of economic benefits *TEB* decreases relative to the original *GDP*. The economic benefits of U1 exhibited the most notable decline, with a drop of RMB 41.2 billion, which is a decrease rate of 14.3%. The

Table 4. Comparison of target benefits before and after water trading among various calculation units in water-receiving area of the MR-SNWDP of Henan Province.

	Comparison of economic benefits/10^8 RMB			Comparison of social benefit/10^4 m^3		
Calculation units	Pre-trading *GDP*	Post-trading *TEB*	Economic growth	Pre-trading water shortage	Post-trading Water shortage	Reduction of water shortage
U1	2,875	2,463	−412	−11,052	0	−11,052
U2	1,706	1,643	−63	2,898	0	2,898
U3	993	888	−105	−792	0	−792
U4	2,082	1,899	−183	−3,315	−1,498	−1,817
U5	2,171	2,381	210	8,513	0	8,513
U6	7,315	8,491	1,176	28,723	0	28,723
U7	1,943	2,095	152	8,798	0	8,798
U8	1,982	2,118	136	10,148	0	10,148
U9	713	779	66	2,952	0	2,952
U10	1,334	1,430	96	8,283	0	8,283
U11	1,884	2,117	232	8,413	0	8,413
Total	24,999	26,304	1,305	63,571	−1,498	65,069

economic benefits of U2 decreased the least, with a drop of RMB 6.3 billion and a decrease rate of 3.7%. After acquiring the corresponding water rights in the seven water-purchasing cities, economic benefits increased significantly due to the increase in water usage at the same *GDP* per cubic meter of water. The economic benefits *TEB* of U6 increased the most by RMB 117.6 billion from the original *GDP*, with the largest growth rate of 16.1%. The economic benefits *TEB* of U8 increased by RMB 13.6 billion at a growth rate of 6.9%, which is the lowest growth rate among the cities. The economic benefits *TEB* of U9 were 6.6% higher than the original *GDP*, with a growth rate of 9.2%, which is the lowest increase in value among the cities. Overall, although the economic benefits *TEB* of water-selling cities declined, the total economic benefits *TEB* of the 11 cities increased by RMB 130.5 billion from the initial *GDP*, with a growth rate of 5.2%. In summary, the water trading through the trunk canal can solve the conflict between regional water supply and demand, and promote economic growth.

Conclusion

We established a multi-objective optimization model for water trading considering social and economic benefits in the water-receiving area of the MR-SNWDP in Henan Province. The actual water usage situation in the water-receiving area in 2015 was used as an example to calculate the optimal trading scheme. The results of trading show that after the water-receiving area increases its water level through water saving, cities with abundant water resources are able to sell water rights to water-scarce areas while meeting local water demand, helping to solve the water shortage problem in water-scarce areas, and the entire water-receiving area is no longer lacking water. In the case of constant *GDP* per cubic meter of water, the economic development of water-selling cities has been affected to a certain extent, but the water-scarce cities have achieved significant economic growth after purchasing water, and thus the overall economy of the water-receiving area has achieved significant growth. Overall, the social and economic benefits of this model are significant. This demonstrates that this trading model can promote the optimal allocation of water resources in the water-receiving area and improve the utilization of water resources. The trading of water rights will also help in easing the current water shortages in some areas. Additionally, the role of the MR-SNWDP will also be maximized.

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