Optimal allocation of water resources through artificial fish swarm algorithm: A case study in Haixing, China

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Abstract. North China is a typical developing region where the conflict between large water demand and little natural water resources exist. Thus, scientifically optimizing the allocation of regional water resources is particularly significant in this area. In this study, Haixing County, China was selected as the research region. Then, regional optimization model of water resource allocation was established, of which the objective function aims at the maximum integrated benefit of regional social and economy. In this model, two forbidden red lines of water use amount and water use efficiency were considered as the constraints, and Artificial Fish Swarm Algorithm was applied to calculate the optimization of water resource allocation. In 2020, the p = 50% total water shortage is forecast as 0.747 × 10⁶ m³ or 2.1%. The results show that the efficiency and benefits have been improved, which illustrates that the optimization allocation of water resources through Artificial Fish Swarm Algorithm is reasonable. The research could provide a crucial technical support for regional water resource management.

1. Introduction

Water resources is indispensable natural resources for human survival and development. With the rapid development of economy and society of China, the problem of water shortage is becoming more and more serious. Especially in North China, the accelerated development resulted in groundwater over-pumping and the increasing of water conflict among different regions and water departments, which limits the regional economic now [1]. Therefore, the rational allocation of water resources is significant and also effective measure to solve water shortage.

Because the multi-objective problem of optimal allocation of water resources is hard to be solved through traditional planning methods [2-5], so, many scholars tried to solve this problem through sorts of intelligent optimization algorithms [6-10], which are Particle Swarm Optimization (PSO for short) [11], Genetic Algorithm (GA for short) [12-14], Ant Colony Optimization (ACO for short) algorithm [15] and Artificial Fish Swarm Algorithm (AFSA for short) [16] and so on. The AFSA has a parallel algorithm and no strict set of initial value [17]; and the process of searching objective is simple, overall and rapid. At present, there is no research on water resource allocation in Haixing County and it is a typical groundwater over-exploitation area in the North China. Therefore, the AFSA was selected in the optimal allocation model of water resources in Haixing County, i.e. a typical county in...
North China, aiming at providing reference for optimal allocation of local water resources.

2. Optimal water resource allocation model

2.1. Objective function
The objective function of the optimization of water resource allocation is aimed at minimizing regional water shortage and maximizing net benefit.

2.1.1. Optimal social benefits.

\[
\min f(X) = \min \left\{ \sum_{i=1}^{I} \sum_{j=1}^{J} \left( \phi_j - \sum_{k=1}^{K} X_{ij}^k \right) \right\}
\]

where \( f(X) \) is the total water shortage, \( I \), \( K \) and \( J \) represent the quantity of water supply, sub-region and water sector, respectively; \( \phi_j \) is water demand of user \( j \) in sub-region \( k \); and \( X_{ij}^k \) denote the water supply by source \( i \) to user \( j \) in sub-region \( k \).

2.1.2. Optimal economic benefits.

\[
\max f(X) = \max \left\{ \sum_{i=1}^{I} \sum_{j=1}^{J} \left( b_{ij} - c_{ij} \sum_{k=1}^{K} X_{ij}^k \lambda_j^k \right) \right\}
\]

where \( f(X) \) is the net benefit; \( b_{ij} \), \( c_{ij} \), and \( \lambda_j^k \) are the coefficients of efficiency, water supply cost and preferential water supply of user \( j \) in sub-region \( k \); and \( \alpha_i^j \) denote coefficient of water supply sequence by source \( i \) in sub-region \( k \).

2.2. Constraints
According to the regional actual water consumption and development planning, the following five constraints are confirmed, based on the two perspectives of total water consumption and efficiency red line.

2.2.1. Carrying capacity of water resources. The constrain of Carrying Capacity of Water Resources (CCWR for short) means that the sum of the water supplied to all users of a water source is less than or equal to the water supplied to the water source.

\[
\sum_{j=1}^{J} X_{ij}^k \leq p_i^k
\]

where \( p_i^k \) is the water supply by source \( i \) in sub-region \( k \).

2.2.2. Water demand. The amount of water dispensed by the user is between the upper and lower limits of water demand.

\[
D_{j\text{min}}^k \leq \sum_{i=1}^{I} X_{ij}^k \leq D_{j\text{max}}^k
\]

where \( D_{j\text{min}}^k \) and \( D_{j\text{max}}^k \) are the minimum and maximum water demands of user \( j \) in sub-region \( k \), respectively.

2.2.3. The capacity of water conveyance. Requiring the water supply is less than or equal to the maximum water delivery capacity.

\[
X_{ij}^k \leq Q_i^k
\]
where $Q^k_i$ is the maximum water delivery capacity of source $i$ in sub-region $k$.

2.2.4. Non-zero constraint. All water supplies are required to be non-negative.

$$X^k_{ij} \geq 0$$  \hspace{1cm} (6)

2.2.5. Total water use control. Requiring the sum of available water to be less than or equal to the total amount of water consumption limit in the “three red lines”.

$$\sum_{i=1}^{1/k} p^k_i \leq W$$  \hspace{1cm} (7)

where $W$ is the control index of total water consumption.

3. Artificial fish swarm algorithm

The AFSA was proposed by Li and others in 2002 [18]. This algorithm can simulate the behavior of real fish foraging, gathering and rear-ending in water through artificial fish. The search principle of optimization objective is searching position with the largest number of fishes, which represents the greatest amount of nutrients in the water domain, i.e. the largest benefits. The AFSA only needs to compare the value of the objective function, and it does not require much on the nature of the objective function. The AFSA is generated randomly or set to a fixed value, and has a wide range of

![Diagram of Artificial Fish Swarm Algorithm](image-url)

**Figure 1.** Artificial fish swarm algorithm flow.
applications.
Suppose that there are \( N \) artificial fish in a search area, and each artificial fish state can be expressed as a vector \( X = (X_1, X_2, \ldots, X_n) \). \( X_i \) is an individual within \( X \). The food concentration in the current position of the artificial fish is expressed as \( Y = f(X) \), and \( Y \) is the objective function value. The distance between the artificial fish is expressed as \( d_{ij} = \| X_i - X_j \| \), where \( X_i \) and \( X_j \) denote the individual state of artificial fish and the random state in the visual field of artificial fish, respectively. Visual is the range of the artificial fish, Step is the step of the artificial fish, Try-number is the maximum number of foraging tests of the artificial fish, and \( \delta \) is the crowding factor. The flow chart of the AFSA is shown in figure 1.

4. Case study

4.1. Study area

Haixing County is located in the southeast of Hebei Province, China and belongs to North China (figure 2). It has a temperate sub-humid climate with an average annual precipitation of 567.4 mm. The annual variation of precipitation is large, and the distribution is uneven during the year. The regional type of groundwater belongs to the saltwater area, with an average annual water resource is \( 54.8 \times 10^6 \) m\(^3\) and an average per capita water resource is 234 m\(^3\). It reflects the imbalance between supply and demand of water resources. The study area is divided into 8 sub-areas, including 7 towns and this county.

![Study area location](image)

**Figure 2.** Study area location.

4.2. Allocation principles

The optimal allocation of water resources in Haixing County requires the joint operation of Surface Water, Shallow Groundwater, Reclaimed Water, Water Diversion from Zhangweinan Reservoir, Yellow Water Diversion and South-North Water Transfer, and following the principle of first near and then far. The allocation principles include the following points. The external water is preferred in domestic water. In Haixing County, most shallow groundwater is brackish water, so, shallow groundwater is usually not used in daily life. Industrial water uses reclaimed water first, and then external water. All ecological water is reclaimed water. Local surface water is preferentially used in agricultural water, and then external water is supplied to agricultural water. If the volume of water supply is still not satisfied with demand for agricultural water, then the shallow groundwater can be used rationally.

4.3. Forecast of water demand and supply

Forecasts of water supply and demand were used as constraints for this model.
In this study 2016 is chosen as base year and 2020 is as the planning year. The water demand quality of life, industry, ecology and agriculture in 2020 in normal year (\( p = 50\% \)) was forecasted according to the development planning of Haixing County (table 1).

**Table 1.** Water demand of different users in Haixing County in 2020 (\( p = 50\% \)) (10\(^3\) m\(^3\)).

| Administrative Division | Domestic | Industry | Ecology | Agriculture | Total |
|------------------------|----------|----------|---------|-------------|-------|
| Xinji                  | 658      | 0        | 109     | 2235        | 3002  |
| Zhaomaotao             | 1141     | 5        | 109     | 8550        | 9805  |
| Xiaoshan               | 785      | 1052     | 109     | 3128        | 5074  |
| Suji                   | 834      | 0        | 109     | 5181        | 6124  |
| Xiangfang              | 598      | 1166     | 109     | 2568        | 4441  |
| Gaowan                 | 894      | 0        | 109     | 4594        | 5597  |
| Zhanghuiting           | 986      | 0        | 109     | 3273        | 4368  |
| Haixing County         | 2544     | 441      | 200     | 0           | 3185  |
| Total                  | 8440     | 2664     | 963     | 29529       | 41596 |

Note: The upper values of the constraint condition are the corresponding value of table 1, and the lower ones is 80% of values [19].

Then, water supply quantity of external water diversion, surface water, reclaimed water and shallow groundwater in 2020 of normal year was forecast, according to the current situation of water supply and engineering planning (table 2).

**Table 2.** Water supply for different water sources in Haixing County in 2020 (\( p = 50\% \)) (10\(^3\) m\(^3\)).

| Administrative Division | External Water Diversion | Local Surface Water | Reclaimed Water | Shallow Groundwater | Total |
|------------------------|--------------------------|---------------------|-----------------|---------------------|-------|
| Xinji                  | 2249                     | 451                 | 229             | 53                  | 2982  |
| Zhaomaotao             | 5804                     | 1268                | 229             | 204                 | 7505  |
| Xiaoshan               | 2873                     | 1230                | 229             | 75                  | 4407  |
| Suji                   | 3807                     | 1024                | 229             | 123                 | 5183  |
| Xiangfang              | 2263                     | 592                 | 229             | 61                  | 3145  |
| Gaowan                 | 3690                     | 742                 | 229             | 110                 | 4771  |
| Zhanghuiting           | 3341                     | 573                 | 229             | 78                  | 4221  |
| Haixing County         | 2300                     | 254                 | 400             | 173                 | 3127  |
| Total                  | 26327                    | 6134                | 2003            | 877                 | 35341 |

4.4. Results and analysis
Before the model is solved, the four coefficients should be determined, which are water supply cost, water use efficiency, water supply sequence and preferential water supply. The water supply cost coefficient can refer to the standard of water fee collection. For the regions with data, they were determined according to the data, while others were selected on the basis of similar water source projects in the nearby areas [20]. Based on the actual situation of Haixing County, the coefficient of water supply cost was determined. The coefficients for domestic, industrial and environmental water use were 3.0, 4.0 and 2.5 RMB/m\(^3\), respectively, and 0.5 RMB/m\(^3\) for agricultural water use. The water efficiency coefficient was divided into living, industry, agriculture and ecology. The efficiency coefficient for domestic water use was difficult to determine, in order to satisfy users, and generally take a larger value, which was 400 RMB/m\(^3\). The industrial water efficiency coefficient is the reciprocal of the water consumption of the added value of ten thousand RMB for industry, taking 300 RMB/m\(^3\). Those for agricultural irrigation water use were defined by multiplying the yield increase efficiency by the water allocation coefficient and were assumed to be 10 RMB/m\(^3\) in the study. The ecological environment is closely related to residents' life, so the efficiency coefficient of ecological water use is the same as the domestic water use, which was 400 RMB/m\(^3\). The water supply sequence coefficient reflects the water supply priority of each water source. According to the principle of “using
enough external water, extracting reasonably groundwater, prioritizing the use of surface water and reclaimed water” [21] in Haixing County, the sequence coefficients for external water, surface water, reclaimed water and groundwater water supply were 0.4, 0.3, 0.2, and 0.1, respectively. The coefficient of preferential water supply reflects the importance of an industry relative to others. According to the principle of “living first, producing later”, the coefficient of preferential water supply for domestic, industrial, ecological and agricultural irrigation water users were 0.4, 0.3, 0.2, and 0.1 respectively.

The parameters of the artificial fish swarm were initialized. The number of artificial fish was 150, the visual field was 10, the moving step length was 20, and the crowding factor was 0.618. The maximum test frequency was 10, and the weight of economic and social benefits were 0.4 and 0.6 respectively. Based on the AFSA, the optimal allocation results of 50% guaranteed rate of water sources in 2020 (table 3).

| Administrative Division | Water Demand | Domestic | Industry | Ecology | Agriculture | Total | Water Deficit | Water Deficient Ratio /% |
|-------------------------|--------------|---------|----------|---------|-------------|-------|--------------|------------------------|
| Xinji                   | 2982         | 658     | 0        | 109     | 2215        | 2982  | 0            | 0.0                    |
| Zhaomaotao              | 7844         | 1141    | 5        | 109     | 6250        | 7505  | 339          | 4.3                    |
| Xiaoshan                | 4407         | 788     | 1007     | 109     | 2503        | 4407  | 0            | 0.0                    |
| Suji                    | 5183         | 835     | 0        | 109     | 4239        | 5183  | 0            | 0.0                    |
| Xiangfeng               | 3553         | 478     | 818      | 87      | 1762        | 3145  | 408          | 11.5                   |
| Gaowan                  | 4771         | 895     | 0        | 109     | 3767        | 4771  | 0            | 0.0                    |
| Zhanghuiting            | 4221         | 986     | 0        | 109     | 3126        | 4221  | 0            | 0.0                    |
| Haixing County          | 3127         | 2554    | 413      | 160     | 3127        | 747   | 0            | 0.0                    |
| Total                   | 36088        | 8335    | 2243     | 901     | 23862       | 35341 | 747          | 2.1                    |

The optimized allocation is dominated by external water supply and surface water supply, and combined with reclaimed water and groundwater (tables 2 and 3). To some extent, the configuration results have alleviated the water use conflicts of various water departments in different regions. The results indicate that the total water demand for all users in the county is $3.6088\times 10^6$ m$^3$, and the total allocated volume is $3.5341\times 10^6$ m$^3$, resulting in a total water shortage of $0.747\times 10^6$ m$^3$, and the water shortage rate is only 2.1%. The main reason of water shortage in Zhaomaotao and Xiangfeng is that the water demand is relatively larger than the external water allocation index. Most of the shallow groundwater is brackish water that is not suitable for use. Therefore, only by raising people's awareness of water conservation and further increasing water transfer in the river basin can we better solve the problem of water shortage.

5. Conclusions and discussion

The optimal allocation of water resources is developing from a single target to a multi-objective. In this study, water resource of Haixing County was allocated through a multi-objective optimization model based on AFSA. This model aims at the maximum integrated benefit of social and economy, of which two red lines of water use amount and efficiency were considered as the constraints. The results show that total water demand in Haixing County is $3.6088 \times 10^6$ m$^3$, and total allocated volume is $3.5341 \times 10^6$ m$^3$, which means total water shortage is $0.747 \times 10^6$ m$^3$, and the water shortage rate is only 2.1%. The amount of allocated water could meet the basic water demand in future in Haixing County. The optimization results are in accordance with the actual situation of water resource exploitation and utilization, which illustrates that the optimization allocation of water resources through AFSA is reasonable. The research could provide a crucial technical support for regional water resource management.

Due to the lack of sewage data, only social and economic benefits were considered as the objective in the study. In the future, environment and ecological benefits also should be considered in the
optimal allocation AFSA model in order to improve the applicability of AFSA model.

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