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An Ameliorative Whale Optimization Algorithm for Multi-Objective Optimal Allocation of Water Resources in Handan, China

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Abstract: With the deepening discrepancy between water supply and demand caused by water shortages, alleviating water shortages by optimizing water resource allocation has received extensive attention. How to allocate water resources optimally, rapidly, and effectively has become a challenging problem. Thus, this study employs a meta-heuristic swarm-based algorithm, the whale optimization algorithm (WOA). To overcome drawbacks like relatively low convergence precision and convergence rates, when applying the WOA algorithm to complex optimization problems, logistic mapping is used to initialize swarm location, and inertia weighting is employed to improve the algorithm. The resulting ameliorative whale optimization algorithm (AWOA) shows substantially enhanced convergence rates and precision than the WOA and particle swarm optimization algorithms, demonstrating relatively high reliability and applicability. A water resource allocation optimization model with optimal economic efficiency and least total water shortage volume is established for Handan, China, and solved by the AWOA. The allocation results better reflect actual water usage in Handan. In 2030, the $p = 50\%$ total water shortage is forecast as $404.34 \times 10^6 \text{ m}^3$ or 14.8%. The shortage is mainly in the primary agricultural sector. The allocation results provide a reference for regional water resources management.

Keywords: water resources; optimal allocation; multi-objective; WOA; AWOA

1. Introduction

Water is one of the most indispensable natural resources for human survival and development [1]. Rapid social and economic development and population growth, along with climate change, have aggravated water shortages [2–8]. The recent situation is unlike early water supply management. There are fewer exploitable water resources and exploitation costs are increasingly expensive, often leading to more serious environmental problems. By optimizing water resource allocation, water resources are transferred from low- to high-value uses, and the efficiency of water usage is enhanced. These are important ways to solve water shortages.

Optimal allocation of water resources has been studied for years all over the world. The first research focused on single-objective water allocation management in an irrigation area. However, it has grown to cover areas like mega-scale multi-objective regional water resource allocation optimization. The coverage and scope of water resource allocation have expanded greatly. The earliest research on water resource allocation optimization dates to Masse et al.'s study on reservoir optimization

in the 1940s [9]. In 1962, Maass et al. established a single-objective non-linear static planning model and considered the maximum total net benefit in regional water resource exploitation and utilization as the objective function [10]. In 1962, Buras constructed a dynamic programming model to determine the magnitudes of surface and underground water reservoirs and water supply strategies for each irrigation area [11]. It is more common to describe problems in water resource systems using mathematical models because of advancements in mathematical programming and simulation techniques [12]. Linear [13], non-linear [14], random linear [15], and dynamic [16] programming types are among the methods extensively employed in optimizing water resource allocation. In the 1990s, the United Nations published the *Guidebook to Water Resources, Use and Management in Asia and the Pacific* [17], signifying the relative maturity of development of water resource allocation optimization.

Optimal allocation is a dynamic and challenging area that researchers have been studying for a long time. For recent multi-objective, multi-variable, and high-dimensional allocation models, traditional optimization algorithms are not satisfactory in their convergence, calculation efficiency, and parameter sensitivity. For large-scale allocation optimization models, the curse of dimensionality often makes solutions for optimization difficult or leads to results that are inconsistent with reality. Nature provides great inspiration for mechanisms, principles, and concepts to solve complex optimization problems [18]. By simulating biological evolution processes—food-hunting behavior of organisms in nature, or physical rules—more efficient optimization algorithms can be designed to better tackle multi-objective optimization problems. This has attracted attention from various researchers.

Nature-inspired meta-heuristic optimization algorithms, including evolution-, physics-, and swarm-based methods, have become increasingly popular in engineering applications. This is because their principles are simple and easily implementable. There is no requirement for gradient information and they can avoid local optima. In particular, nature-inspired swarm-based meta-heuristic algorithms are more favorable than their evolution- and physics-based counterparts when they are applied to optimization problems [19]. The most popular swarm-based algorithm is the particle swarm optimization (PSO) algorithm proposed by Kennedy and Eberhart in 1995 [20]. PSO is derived by simulating the social behavior of flocks of birds when they hunt for food [20]. The concept is as follows: Each solution for the optimization problem is considered a particle. A fitness function is defined to measure the extent to which each particle solution is optimal. Each particle flies in the search space according to its own “flight experiences” and those of other particles, which subsequently achieves an overall optimal solution. Another widely used swarm-based algorithm is the ant colony optimization (ACO) algorithm, first proposed by Dorigo et al. [21]. The concept is as follows: Pathways of ants denote possible solutions to an optimization problem while all the pathways of the entire ant colony give the solution space of the problem. Ants that take shorter pathways release more pheromones. The pheromone concentrations along the shorter pathways accumulate, and hence, increase with time, as more ants choose these pathways. Eventually, due to the positive feedback mechanism, all ants will travel along the optimal pathway. This corresponds to the optimal solution to the optimization problem. The artificial fish swarm algorithm (AFSA) is another popular swarm-based algorithm, first suggested by Li et al. in 2002 [22]. This algorithm is fundamentally based on the phenomenon wherein, in order to seek the optimal solution, “maximum fish survival takes place in localities where nutrients are the most concentrated in the water”. The AFSA mainly simulates how fish swarms look for food, swarm, and chase. Other representative swarm-based algorithms include the firefly algorithm (FA) [23], fruit fly optimization algorithm [24], termite algorithm [25], and wasp swarm algorithm [26], as well as dolphin echolocation [27]. Although swarm-based algorithms yield well-known advantages, there is no single algorithm capable of handling all optimization problems. Currently, the PSO [28–30], ACO [31,32], AFSA [33,34], and FA [35] have been successfully applied to water resource allocation optimization problems and their effectiveness has been well proven.

Recently, a new swarm algorithm, namely, the whale optimization algorithm (WOA), has been introduced [19]. It is easy to operate, with less parameters to be adjusted. The WOA is highly capable of avoiding local optima [36]. Nevertheless, for complex optimization problems, the WOA has relatively

low convergence precision and convergence rates. In order to overcome these issues, this study proposes the ameliorative whale optimization algorithm (AWOA), and compares its performance to WOA and PSO's performance in solving multi-objective water resource allocation optimization models. The results indicate that the AWOA yields higher convergence precision and rates.

2. Materials and Methods

2.1. Whale Optimization Algorithm

The WOA is a novel swarm intelligence optimization algorithm proposed by Australian researchers Mirjalili and Lewis in 2016 [19]. This algorithm is inspired by the hunting mechanism of humpback whales in nature, and simulates the shrinking encircling, spiral updating position, and random hunting mechanisms of humpback whale pods. This model consists of the following three stages: Encircling prey, bubbling-net attacking, and search for prey [19].

2.1.1. Encircling Prey

For encircling prey, the WOA optimization algorithm assumes that the current best solution is the target prey. Other individual whales then try to update their positions toward the optimal position. This behavior is represented by the following equations:

$$\vec{X}(t+1) = \vec{X}_p(t) - \vec{A} \cdot D \quad (1)$$

$$D = \left| \vec{B} \otimes \vec{X}_p(t) - \vec{X}(t) \right| \quad (2)$$

$$\vec{A} = 2a\vec{r} - a \quad (3)$$

$$\vec{B} = 2\vec{r} \quad (4)$$

$$a = 2 - 2\frac{t}{t_{\max}} \quad (5)$$

where t represents the current iteration, $\vec{X}(t)$ is the position vector at iteration t , $\vec{X}_p(t)$ is the position vector of the best solution obtained so far, D represents the distance between the position of $\vec{X}_p(t)$ and $\vec{X}(t)$, \vec{A} and \vec{B} are coefficient vectors, \otimes is an element-by-element multiplication operator (e.g., $(x_1, x_2, \dots, x_n) \otimes (y_1, y_2, \dots, y_n) = (x_1y_1, x_2y_2, \dots, x_ny_n)$), \vec{r} is a random vector in $[0, 1]$, a is a control parameter that is linearly decreased from 2 to 0 over the course of iterations, and t_{\max} is the maximum number of iterations.

2.1.2. Bubble-Net Attacking Method (Exploitation Phase)

The bubble-net behavior of humpback whales includes the shrinking, encircling, and spiral updating position.

- Shrinking encircling mechanism

This mechanism is mainly achieved by decreasing the value of control parameter a . \vec{A} is a random value in the interval $[-a, a]$ (a is linearly decreased from 2 to 0). When random values for \vec{A} are in the interval $[-1, 1]$, the new position of the individual whales can be defined anywhere between the original position and the current best position. The mathematical modeling is expressed by Equations (1) and (2).

- Spiral updating position

For the spiral updating position, a logarithmic spiral equation is created between the position of the whales and the current best solution to simulate the spiral movement of humpback whales. The mathematical model is shown as

$$\vec{X}(t+1) = D' e^{bl} \cos(2\pi l) + \vec{X}_p(t) \tag{6}$$

$$D' = \left| \vec{X}_p(t) - \vec{X}(t) \right| \tag{7}$$

where D' represents the distance between the i -th whale and its prey (current best solution), b is a constant for defining the shape of the logarithmic spiral, and l is a random number in $[-1, 1]$.

When humpback whales attack their prey, they move simultaneously within a shrinking encircling circle and along a spiral-shaped path. The WOA assumes there is a 50% probability of choosing between the shrinking encircling mechanism and the spiral model to update the position of whales during optimization. The mathematical model is as follows:

$$\vec{X}(t+1) = \vec{X}_p(t) - \vec{A} \cdot D \quad p < 0.5 \tag{8}$$

$$\vec{X}(t+1) = D' e^{bl} \cos(2\pi l) + \vec{X}_p(t) \quad p \geq 0.5 \tag{9}$$

where p is a random probability in $[0, 1]$.

2.1.3. Search for Prey (Exploration Phase)

In the search for prey or exploration phase, the positions of other individual whales are updated according to a randomly chosen individual whale. By setting $|| \geq 1$, individual whales are forced to move far away from the reference whale in search of other better prey, thereby allowing the WOA algorithm to perform a global search. The model can be expressed as

$$\vec{X}(t+1) = \vec{X}_{rand}(t) - \vec{A} \cdot D \tag{10}$$

$$D = \left| \vec{B} \otimes \vec{X}_{rand}(t) - \vec{X}(t) \right| \tag{11}$$

where \vec{X}_{rand} is a position vector randomly selected from the current whale population.

2.2. Ameliorative Whale Optimization Algorithm

Compared to other optimization algorithms, the advantages of the WOA are its simple operation and limited number of adjustment parameters, as there are only two adjustment parameters (\vec{A} and \vec{B}). Through the adjustment of \vec{A} , the algorithm can achieve a good balance between the capabilities of exploration and exploitation, thereby increasing the possibility of getting away from the local optimum. However, the exploitation phase in the WOA is completely dependent on randomness, thereby resulting in low convergence accuracy and slow convergence speed.

In response to the aforementioned drawbacks of the WOA, the AWOA is proposed in this study. The improved method is described in detail below.

First, in order to effectively improve the quality of the initial population position, the logistic map [37] is used to obtain the initial solution.

$$X_{k+1} = \mu X_k (1 - X_k) \tag{12}$$

where $X_k \in [0, 1]$ and μ is a control parameter, $\mu = 4$.

Second, after analyzing the weaknesses of the PSO algorithms, Shi and Eberhart [38] introduced the inertia weight ω to facilitate rapid convergence to a global optimal solution. Their analysis

indicated that a larger inertia weight facilitates a global search, while a smaller one facilitates a local search. In order to improve local search capability, increase convergence accuracy, and speed up convergence, inertia weight is introduced in the WOA to improve the algorithm. The inertia weight introduced is expressed as follows:

$$\omega = \omega' - (\omega' - \omega'') \left(\frac{t}{T_{\max}} \right)^{\frac{1}{i}} \quad (13)$$

ω' is the maximum value of inertia weight, ω'' is the minimum value of inertia weight, t is the current iteration number, and T_{\max} is the maximum number of iterations. The improved position vector update formula is shown as

$$\vec{X}(t+1) = \vec{X}_p(t) - \omega \vec{A} \cdot D \quad p < 0.5 \quad (14)$$

$$\vec{X}(t+1) = \omega D' e^{bl} \cos(2\pi l) + \vec{X}_p(t) \quad p \geq 0.5 \quad (15)$$

ω is progressively decreased with the number of iterations, thereby making it useful for global search and local optimization at the start and end of the iteration process, respectively. As the rate of decrement in the introduced ω is large, it facilitates local optimization in the algorithm, increases convergence accuracy, and speeds up convergence.

2.3. Best Individual Selection Based on Pareto

In a single-objective problem, the fitness function value is the objective function value. In a multi-objective problem, based on the solution strategy of the Pareto solution set, all individuals in the population can be sorted into different non-inferior frontiers using a fast non-dominated sorting algorithm. With a crowded-comparison operator, the best individual can be selected by setting the crowding distance as the winning standard among the same level groups after sorting.

2.3.1. Fast Non-Dominated Sorting

With fast non-dominated sorting, relatively good individuals in the population can be selected, thereby reflecting the superiority or inferiority of the individuals. The population size Q is assumed to be N ; i is an individual within Q ; and two parameters of the individual i , namely, n_i (the number of dominating individuals in the population) and S_i (the set of individuals dominated by individual i in the population), have to be calculated. First, all individuals in the population with $n_i = 0$ are sorted into F_1 , and F_1 is taken as the current set. For each individual k in set F_1 , those dominated by individual k are sorted into S_k . For each individual in the set S_k , 1 is subtracted from each n_k value, if $n_k = n_k - 1 = 0$, and then, the corresponding individual is saved into set H . Finally, all individuals in set F_1 are recorded as the first level of non-dominating frontiers, while set H is taken as the current set. Then, the steps mentioned above are repeated until the entire population has been sorted [39–42].

2.3.2. Crowding Distance and Crowded-Comparison Operator

- Crowding distance

To improve the diversity and distribution of a population, the concept of crowding distance was proposed by Srinivas and Deb [43]. Crowding distance indicates the density surrounding an individual n in the population. The available space around individual n is represented by the length of the largest rectangle-containing individual n , which is expressed as n_d . As shown in Figure 1, the formula for calculating the crowding distance of individual i [39] is

$$n_d = \sum_{m=1}^M f_m(i+1) - f_m(i-1) \quad (16)$$

where $f_m(i)$ represents the objective function value of individual i . M is the number of objective functions. The objective function corresponding to individual i needs to be normalized because of its different units. According to [44], Equation (16) can be rewritten as

$$n_d = \sum_{m=1}^M \frac{f_m(i+1) - f_m(i-1)}{f_{m\max} - f_{m\min}} \tag{17}$$

where $f_{m\max}$ represents the maximum value obtained by all individuals in the population in the i -th objective function, and $f_{m\min}$ represents the minimum value obtained by all individuals in the population in the i -th objective function. For each objective function, after all individuals in the population have undergone fast non-dominated sorting, the crowding distance of two individuals at the boundary of each level is infinite.

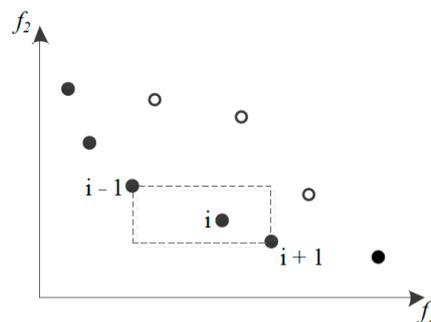


Figure 1. Crowding degree of individual i .

- Crowded-comparison operator

After carrying out the fast non-dominated sorting operations and calculation of crowding degree for each individual i in the population, each individual acquires two attributes, i_{rank} (non-dominated rank) and i_d (crowding degree). i_{rank} and i_d can be used to differentiate between the dominance and non-dominance relationship of any two individuals in the population. The crowded-comparison operator is expressed as \geq_n :

$$i \geq_n j \text{ (if } (i_{rank} < j_{rank}) \text{ or } (i_{rank} = j_{rank} \text{ and } i_d > j_d)) \tag{18}$$

When the non-dominated ranks between two individuals are different, the individual with the lower rank is considered superior; when the non-dominated ranks between two individuals are the same, the individual with the greater crowding distance is considered superior [39].

2.4. AWOA Solving Steps

1. Initialization of parameters: Whale population size: N , with random generation of the initial population; maximum number of iterations: T_{\max} ; maximum value of inertia weight: ω' ; minimum value of inertia weight: ω'' .
2. The location of whale population is initialized using logistic mapping, and initial variables are transformed into a range of values corresponding to initial variables of the objective function.
3. Fast non-dominated sorting and calculation of individual crowding degree are carried out for all individuals in the population, and the best individual is then selected as the optimal position based on Equation (18).
4. When $p < 0.5$ and $|A| < 1$, the current position of individual whales are updated with Equation (14); when $|A| \geq 1$, a random individual whale \vec{X}_{rand} is selected, and the current positions of individual whales are updated with Equations (10) and (11).

5. When $p \geq 0.5$, the current positions of individual whales are updated with Equation (15).
6. All individual whales are checked to determine if their updated locations are beyond the search space, and whale locations beyond the search space are corrected.
7. The number of iterations is checked. If the maximum number of iterations has been reached, the algorithm is stopped; otherwise, proceed to step (3) to continue the algorithm.

3. Case Study

3.1. Background of Study Area

Handan is located in the south of Hebei Province (latitude $36^{\circ}04'–37^{\circ}01'$ N, longitude $113^{\circ}28'–115^{\circ}28'$ E), and covers an area of 12,047 km². Taking 100 m contours as the boundary, the western part is covered by middle to low mountains, hills, and basins over an area of 4460 km², while the eastern part consists of plains, over an area of 7587 km². Handan has a temperate semi-humid and -arid continental monsoon climate with an average annual precipitation of 548.9 mm concentrated in June to September. Handan is divided into 16 administrative divisions (Figure 2)—Handan city, Shexian, Wu'an, Fengfeng, Cixian, Yongnian, Quzhou, Jize, Linzhang, Cheng'an, Weixian, Guangping, Feixiang, Daming, Guantao, and Qiuxian.

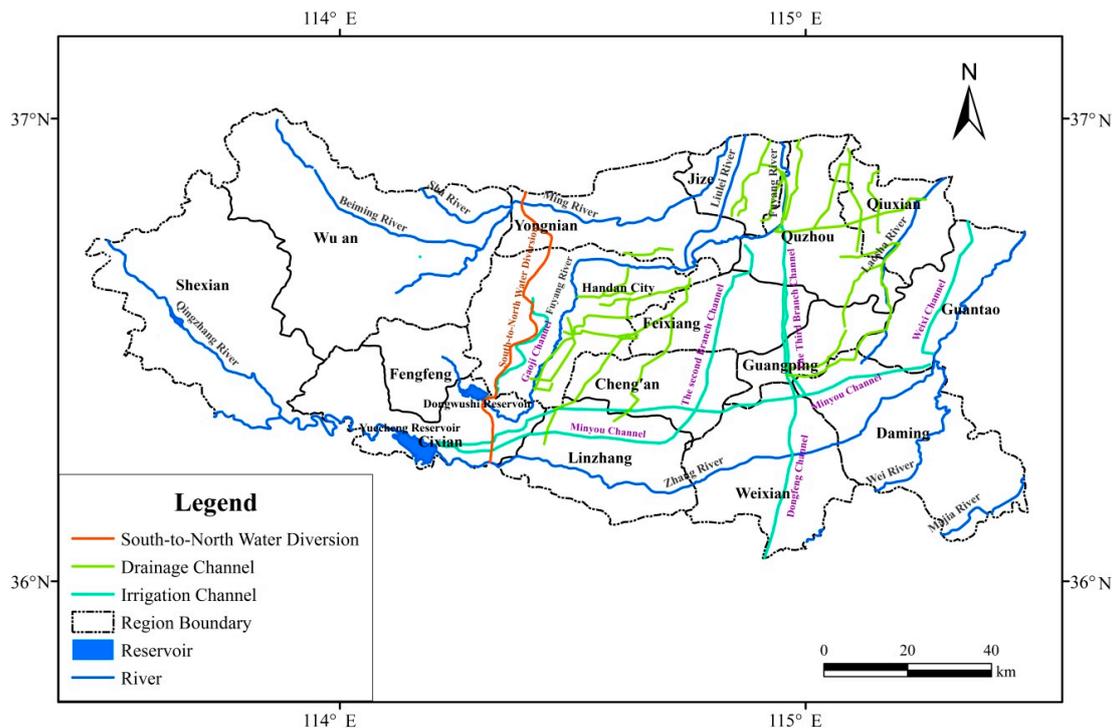


Figure 2. The map of administrative division and water supply system in Handan.

Handan is a region with water shortages because of insufficient water resources. Average water resources per capita are less than 180 m³, equivalent to only one-twelfth of the national average and far lower than the global average. With the rapid socioeconomic developments in the region, water demand has surged. Reduced precipitation and uneven spatial and temporal distribution of precipitation due to climate change have intensified regional water shortages, which can be alleviated only by over-exploitation of groundwater. Groundwater over-exploitation causes associated levels to drop continuously, and cones of depression to expand. Other severe consequences are scrapped wells, ground subsidence, and earth fissures. To safeguard economic development, apart from the South–North Water Transfer Project, Handan has imported large amounts of water from the Yellow

River to alleviate regional water shortages problem. In order to ensure water supply for the public, industry, and ecology, as well as attain maximum socioeconomic benefits, it is necessary to examine how imported water can be rationally utilized and coordinated with the local water supply.

Sources for the water supply in Handan include local surface water, groundwater, recycled water, the Yuecheng reservoir, the Dongwushi reservoir, water transferred through the South–North Water Transfer Project, and water imported from the Yellow River. Medium- and small-scale reservoirs, impoundment, and ponds in the administrative divisions support the local surface water supply. Groundwater refers to the exploitable groundwater in the divisions. Recycled water is the water supply that sewage treatment plants in all divisions can provide. The Yuecheng reservoir and the Dongwushi reservoir are two essential water supply sources in the region. They are responsible mainly for the agricultural, industrial, and ecological water supply in the eastern plain area. In particular, the Yuecheng reservoir supplies water to eight counties, including Cixian, Linzhang, Cheng’an, Weixian, Guangping, Feixiang, Daming, and Guantao, while the Dongwushi reservoir supplies water to Handan city and five counties, namely, Yongnian, Quzhou, Jize, Feixiang, and Qiuxian. Water transferred through the South–North Water Transfer Project is relatively expensive because it is transported over a long distance. According to the project requirements, this water can be used only as domestic and industrial water. It is supplied to Handan city and 12 counties—Cixian, Yongnian, Quzhou, Jize, Linzhang, Cheng’an, Weixian, Guangping, Feixiang, Daming, Guantao, and Qiuxian. Water imported from the Yellow River is sourced through the Dongfeng drainage in the eastern plains, with an average volume of $100 \times 10^6 \text{ m}^3$. Due to the water quality, this water source is mainly used as agricultural water and supplements industrial and ecological water. It is supplied to seven counties: Quzhou, Weixian, Guangping, Feixiang, Daming, Guantao, and Qiuxian.

3.2. Optimal Water Resource Allocation Model

According to the characteristics of the Handan water resources system, the region is divided into 16 sub-regions based on administrative divisions. Socioeconomic benefits are selected as objective functions, and are combined with corresponding constraint conditions to establish a regional multi-objective water resource allocation optimization model. Water sources in the region can be classified into public water and independent sources according to the scope of their supplies. Public water sources can supply water to two or more sub-regions simultaneously, like the Yuecheng reservoir, the Dongwushi reservoir, water transferred via the South–North Water Transfer Project, and water imported from the Yellow River. Independent water sources are only capable of supplying water in their own sub-regions (e.g., local surface water, groundwater, and recycled water). Water uses in Handan include those of urban and rural domestic use; primary, secondary, and tertiary sector use; and ecological uses. The primary sector covers agriculture, forestry, livestock farming, and fisheries; the secondary sector comprises industries that produce finished and usable products and construction industries; the tertiary sector includes catering and services.

3.2.1. Objective Functions

- Social benefits target

Since it is difficult to measure social benefits, the least regional water shortage volume is used to represent social benefits indirectly in this study.

$$\max f_1(x) = -\min \sum_{k=1}^{16} \sum_{j=1}^6 \left[D_{kj} - \left(\sum_{i=1}^3 x_{kij} + \sum_{c=1}^4 x_{kcj} \right) \right] \quad (19)$$

where D_{kj} is the water demand of user j in sub-region k ($\times 10^6 \text{ m}^3$).

- Economic benefits target

Economic benefits are expressed by the maximum sum of net efficiency yielded through the supplies by regional independent and public water sources.

$$\max f_2(x) = \max \sum_{k=1}^{16} \sum_{j=1}^6 \left[\sum_{i=1}^3 (b_{kij} - c_{kij}) x_{kij} \alpha_{ki} + \sum_{c=1}^4 (b_{kcj} - c_{kcj}) x_{kcj} \alpha_{kc} \right] \beta_{kj} \quad (20)$$

where x_{kij} and x_{kcj} denote the water supplies by independent source i and public source c to user j in sub-region k ($\times 10^6 \text{ m}^3$), respectively; b_{kij} and b_{kcj} are the coefficients of efficiency per unit water supply by independent source i and public source c to user j in sub-region k , respectively, (CNY/ m^3); c_{kij} and c_{kcj} are the coefficients of cost per unit water supply by independent source i and public source c to user j in sub-region k , respectively (CNY/ m^3); α_{ki} and α_{kc} denote coefficients of water supply sequence by independent source i and public source c in sub-region k , respectively; and β_{kj} is the coefficient of water supply fairness of user j in sub-region k .

3.2.2. Constraint Conditions

- Water supply capacity constraints by the water supply system

$$\text{Independent water source } \sum_{j=1}^6 x_{kij} \leq W_{ki} \quad (21)$$

$$\text{Public water source } \begin{cases} \sum_{j=1}^6 x_{kcj} \leq W_{kc} \\ \sum_{k=1}^{16} W_{kc} \leq W_c \end{cases} \quad (22)$$

where W_{ki} and W_c are the available water supplies by independent source i and public source c in sub-region k , respectively.

- Water delivery capacity constraints by the water delivery system

$$\text{Independent water source } x_{kij} \leq Q_{ki} \quad (23)$$

$$\text{Public water source } W_{kc} \leq Q_{kc} \quad (24)$$

where Q_{ki} and Q_{kc} denote the maximum water delivery capacities of independent source i and public source c in sub-region k , respectively.

- Users' water demand constraints

$$D_{kj\min} \leq \left(\sum_{i=1}^3 x_{kij} + \sum_{c=1}^4 x_{kcj} \right) \leq D_{kj\max} \quad (25)$$

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

- Non-negative variables

$$x_{kij} \geq 0 \quad (26)$$

$$x_{kcj} \geq 0 \quad (27)$$

3.3. Water Demand and Supply Forecasting

Taking the situations in 2015 as the status quo, according to the long-term development planning of Handan, the water demand of six user types in the region in 2030 under a guaranteed rate of $p = 50\%$ is predicted. The results are presented in Table 1. The prediction was carried out using the

quota method. The quotas were determined with reference to *Hebei Province Water Use Quota DB13/T 1161-2016* [44]. The upper limit of the water demand of each user in different sub-regions in the target year is taken as the predicated water demand. The lower limit is 80% of the predicted volume.

Table 1. Water demand of different water users in each sub-region of Handan in 2030 ($p = 50\%$) (10^6 m^3).

Administrative Division	Urban Domestic	Rural Domestic	Primary Sector	Secondary Sector	Tertiary Sector	Ecology	Total
Handan city	82.53	3.86	171.48	74.78	70.98	114.84	518.47
Shexian	18.45	1.07	28.35	19.61	16.29	6.20	89.97
Wu'an	38.38	1.35	98.27	71.00	33.92	17.19	260.12
Fengfeng	21.01	2.30	25.66	17.99	11.82	9.41	88.18
Cixian	17.00	1.92	40.81	13.27	10.15	3.81	86.95
Yongnian	30.54	4.35	149.06	16.35	9.88	5.47	215.63
Quzhou	15.54	2.97	121.42	12.04	4.97	2.09	159.03
Jize	9.79	2.02	68.09	9.57	6.99	1.32	97.77
Linzhang	24.33	2.84	140.34	7.75	6.14	3.27	184.67
Cheng'an	17.06	0.86	98.20	14.98	9.22	3.82	144.14
Weixian	33.85	3.48	163.49	8.87	6.31	11.37	227.37
Guangping	10.93	1.28	59.34	5.29	5.49	1.47	83.80
Feixiang	13.38	2.22	106.48	7.37	4.01	3.90	137.35
Daming	32.33	2.97	158.61	11.30	6.95	3.62	215.79
Guantao	12.81	1.32	87.06	10.53	4.81	1.72	118.25
Qiuxian	9.24	1.11	75.15	6.39	5.48	1.24	98.61
Total	387.16	35.91	1591.82	307.06	213.41	190.72	2726.08

The available water supply in Handan in 2030 is estimated using the prediction on three types of independent water sources and four types of public water sources. For independent sources, the available water supply forecast on local surface water and groundwater is based on the results of the Second Water Resources Evaluation in Handan [45]. The recycled water is calculated by multiplying the urban domestic and industrial water use volumes by their corresponding sewage conversion factor, followed by the sewage collection factor and then the recycled water conversion factor. For public sources, the available supply by the South–North Water Transfer Project directly uses the results in *Supporting Works Plan in Handan for the South–North Water Transfer Project (Middle Line) in Hebei Province* [46]. The available supply from water imported from the Yellow River uses the available allocated volume listed in the *Proposal for the Yellow River-to-Baiyangdian Water Transfer Project* [47]. The available supplies by the Yuecheng reservoir and Dongwushi reservoir are based on research by Wang and Li [48]. The amount of available water supply in Handan is shown in Table 2.

Table 2. The amount of water supply in 2030 (10^6 m^3).

Administrative Division	Local Surface Water	Ground Water	South-To-North Transferred Water	Dongwushi Reservoir	Yuecheng Reservoir	Yellow River Transferred Water	Recycled Water
Handan city	1.93	77.44		✓			107.06
Shexian	51.05	81.56					24.76
Wu'an	114.90	93.46					57.58
Fengfeng	1.95	126.03					23.29
Cixian	28.77	106.95	10.06		✓		18.94
Yongnian	21.76	98.56	19.63	✓			27.52
Quzhou	4.92	27.88	6.12	✓		✓	14.72
Jize	1.05	37.71	4.07	✓			11.98
Linzhang	0.00	101.13	5.94		✓		19.83
Cheng'an	0.73	53.54	6.26		✓		18.76
Weixian	2.03	58.64	6.96		✓	✓	25.87
Guangping	0.47	24.54	9.00		✓	✓	10.91
Feixiang	2.70	46.48	4.53	✓	✓	✓	11.91
Daming	1.28	133.00	6.28		✓	✓	25.83
Guantao	1.36	41.53	4.47		✓	✓	12.68
Qiuxian	1.67	21.97	8.96	✓		✓	10.11
Total	236.58	1130.42	388.62	221.79	197.56	100.00	421.75

Note: ✓ indicates that the administrative division can be allocated a certain amount of water.

3.4. Model Parameter Determination

3.4.1. Coefficient of Water Supply Efficiency b_{kij}

The efficiency coefficients for domestic and environmental water uses are, in general, difficult to determine. Since domestic water use is given the highest priority, the efficiency coefficients for urban and rural domestic water use are taken as 600 and 500 CNY/m³, respectively. Those for primary sector water use are defined by multiplying the yield increase efficiency by the water allocation coefficient and are assumed to be 10 CNY/m³ in this study. Those for secondary and tertiary sector water use are based on the reciprocals of the water quotas and are 450 and 400 CNY/m³, respectively. To maintain sustainable development, a relatively high value is assigned for the efficiency coefficient for ecological water use; in this study, it is 350 CNY/m³ [49,50].

3.4.2. Coefficient of Water Supply Cost c_{kij}

According to the latest water cost in Handan, the water supply coefficient is defined. The coefficients for urban and rural domestic water use are 3.75 and 1.2 CNY/m³, respectively. The coefficients for primary, secondary, and tertiary sector water use are 0.38, 9.2, and 5.8 CNY/m³, respectively, and 1.8 CNY/m³ for ecological water use.

3.4.3. Coefficient of Water Supply Sequence α_{ki}

The water supply sequence coefficient α_{ki} reflects the water supply priority of water source i in sub-region k , relative to other sources. The priority of each source is converted into a coefficient in the $[0, 1]$ interval, that is, the coefficient of water supply sequence. n_{ki} denotes the water supply order of source i in sub-region k and n_{kmax} represents the maximum order in sub-region k . The determination of α_{ki} is based on the following formula [51]:

$$\alpha_{ki} = \frac{1 + n_{kmax} - n_{ki}}{\sum_{i=1}^I (1 + n_{kmax} - n_{ki})} \tag{28}$$

There are seven types of water supply sources in the Handan water resource allocation optimization model. Different users in each sub-region have different needs for the water supply sequence of these seven sources. First, the supply sequences of these seven sources for different users are determined. Second, the sequence coefficients are calculated using Equation (28). The coefficients for different water users are shown in Table 3.

Table 3. Coefficients of water supply sequence for different water users.

Water Supply	Urban Domestic	Rural Domestic	Primary Sector	Secondary Sector	Tertiary Sector	Ecology
Local surface water			0.29			0.27
Ground water	0.33	1.00	0.05	0.05	0.33	
South-to-North transferred water	0.67			0.29	0.67	
Dongwushi Reservoir			0.14	0.19		0.13
Yuecheng Reservoir			0.10	0.14		0.07
Yellow River transferred water			0.19	0.10		0.20
Recycled water			0.24	0.24		0.33

3.4.4. Coefficient of Water Supply Fairness β_{kj}

The water supply fairness coefficient β_{kj} measures the priority of user j receiving water supply in sub-region k relative to other users. β_{kj} and α_{ik} are similar; both are associated with the water supply sequence of users. First, according to the nature and importance of a user, the corresponding water supply sequence is obtained. Then, the coefficient is determined through the formula for α_{ik} .

According to the water supply sequence, the supply order for urban domestic, rural domestic, secondary sector, tertiary sector, ecological, and primary sector water uses are 1, 2, 3, 4, 5, and 6, respectively. Using Equation (28), the fairness coefficients for urban domestic, rural domestic, secondary sector, tertiary sector, ecological, and primary sector water uses are 0.29, 0.24, 0.19, 0.14, 0.10, and 0.05, respectively.

4. Results and Discussions

4.1. Results Analysis

The AWOA is employed to solve the Handan water resource allocation optimization model. The initialization swarm size is 150 and there are 180 iterations. There are 20 runs, and each run starts with a different random initialization swarm. Through numerous simulation experiments, the maximum and minimum inertia weights of the AWOA are finally determined to be $\omega' = 0.9$ and $\omega'' = 0.2$, respectively.

The aforementioned parameters are entered into the MATLAB (MATLAB 9.0, R2016a, MathWorks, Natick, MA, USA) for solving in order to obtain the Pareto front. Nine solutions are included on the Pareto front, as shown in Table 4. The Pareto optimal solution set cannot explain further how to choose a scenario as the final decision on the Pareto front. For any non-inferior solution of multi-objective models, there is no other possibility that the two objective function values corresponding to the non-inferior solutions can be improved from the two objective functions corresponding to other non-inferior solutions. Policymakers can sacrifice only one goal in a certain range in return for another goal improvement. They show their preferences in the alternative tradeoff between such goals. After one operation, a number of Pareto optimal solutions are obtained under the AWOA, which results in higher solution efficiency, and provides greater choices for policymakers. Table 4 shows that if there is a special preference for the minimum amount of water, we can choose scenario 1; if there is a special preference for the best economic benefits, we can choose scenario 9; and if we consider the minimum amount of water shortage and the best economic benefits, we can choose one of the scenarios from 2 to 8. As there is a serious shortage of water resources in Handan, meeting the water demand of different water sectors is an urgent challenge, which must be solved to improve current water resources management. Thus, scenario 1 better reflects the fairness of water consumption among different households. Therefore, it is chosen as an effective scenario, and this study analyzes it in detail.

Table 4. Results of Pareto front under AWOA.

Scenarios	Social Benefit (10^6 m^3)	Economic Benefit (10^6 CNY)
1	−404.340	45,148.03
2	−404.342	45,148.10
3	−404.344	45,148.17
4	−404.348	45,148.26
5	−404.350	45,148.33
6	−404.351	45,148.39
7	−404.354	45,148.45
8	−404.356	45,148.49
9	−404.368	45,148.51

The optimal water resource allocation results in each sub-region in Handan are shown in Figure 3. The total water demand for all users in the region is $2726.08 \times 10^6 \text{ m}^3$, and the total allocated volume is $2321.74 \times 10^6 \text{ m}^3$, resulting in a total water shortage of $404.34 \times 10^6 \text{ m}^3$ and a shortage rate of 14.8%. The four sub-regions with relatively high shortage rates are Weixian, Quzhou, Cheng'an, and Handan city, with rates of 43.3%, 38.5%, 32.4%, and 22.3%, respectively. In Shexian, Fengfeng, Cixian, Jize, and Feixiang, the allocated volume can meet the water demand, and there is no water

shortage. The allocated volumes by local surface water, groundwater, water transferred through the South–North Water Transfer Project, the Dongwushi reservoir, the Yuecheng reservoir, imported water from the Yellow River, and recycled water in Handan are $153.06 \times 10^6 \text{ m}^3$, $1007.32 \times 10^6 \text{ m}^3$, $259.11 \times 10^6 \text{ m}^3$, $221.79 \times 10^6 \text{ m}^3$, $197.56 \times 10^6 \text{ m}^3$, $100.00 \times 10^6 \text{ m}^3$, and $382.90 \times 10^6 \text{ m}^3$, respectively. They account for 6.6%, 43.4%, 11.2%, 9.6%, 8.5%, 4.3%, and 16.5%, respectively, of the total water allocation in the region. It is noteworthy that groundwater resources are the main water source of Handan.

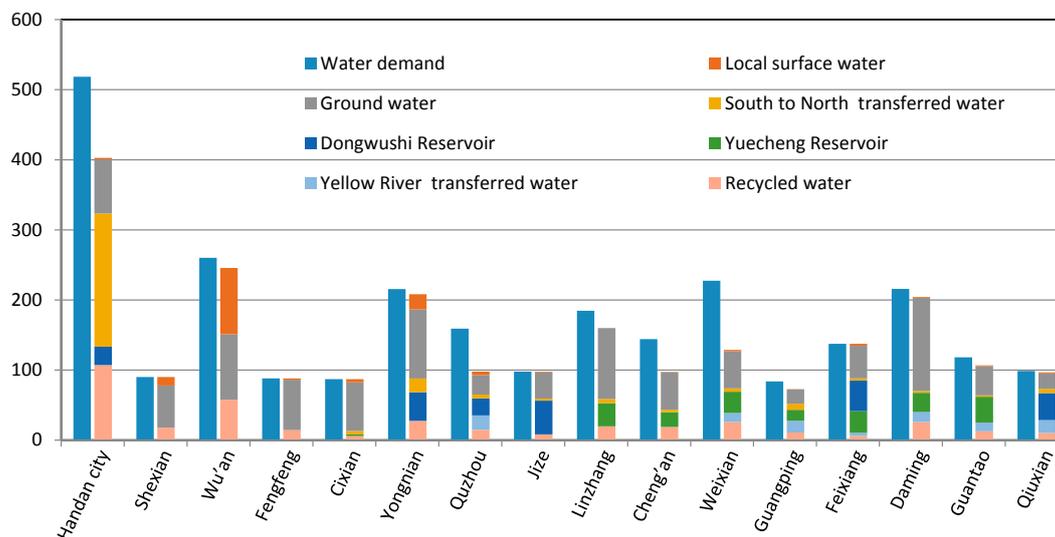


Figure 3. Optimal water resource allocation results in Handan (10^6 m^3).

Figure 4 illustrates the urban domestic water allocation in each sub-region in Handan. The total urban domestic water demand is $387.16 \times 10^6 \text{ m}^3$ while the total allocated volume is $387.16 \times 10^6 \text{ m}^3$. The water supply can fully satisfy the urban domestic water demand in all sub-regions. The water demand is mainly supported by groundwater and water transferred through the South–North Water Transfer Project, the allocated volumes of which are $263.07 \times 10^6 \text{ m}^3$ and $124.09 \times 10^6 \text{ m}^3$, respectively, accounting for 67.9% and 32.1%, respectively, of the total supply. It is noteworthy that groundwater is the dominant water source for urban domestic water demand.

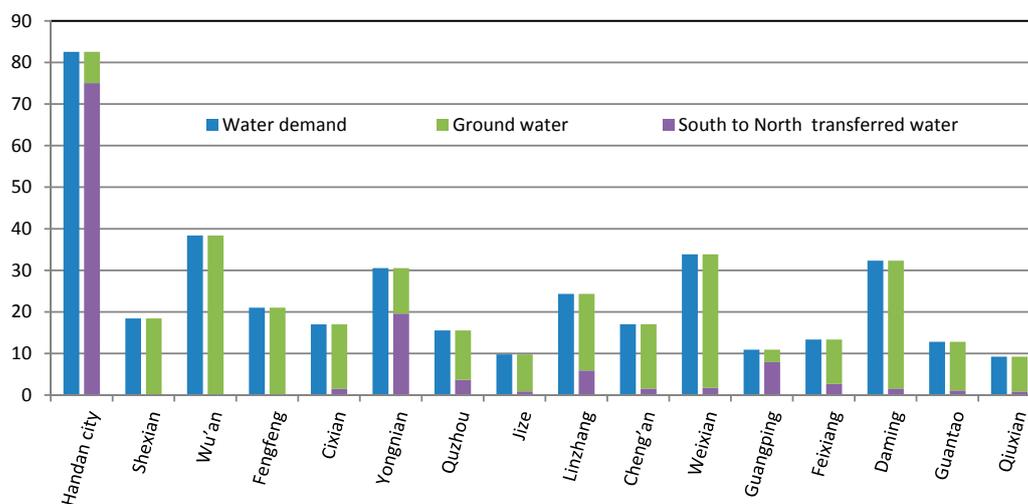


Figure 4. Urban domestic water allocation results in each sub-region in Handan (10^6 m^3).

Figure 5 gives the rural domestic water allocation in each sub-region in Handan. The rural domestic water supply is able to meet the demand in all sub-regions. The total rural domestic water demand is $35.91 \times 10^6 \text{ m}^3$ while the total allocated volume is $35.91 \times 10^6 \text{ m}^3$, supported wholly by groundwater.

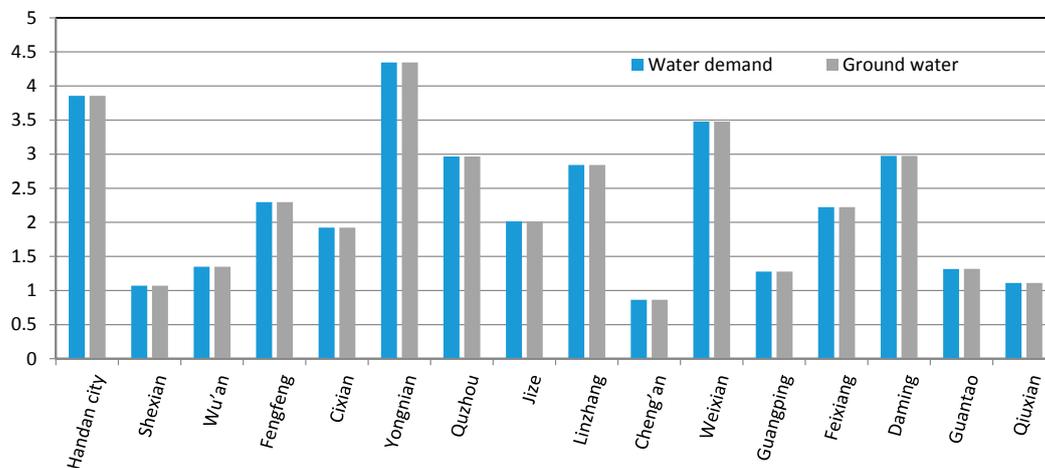


Figure 5. Rural domestic water allocation in each sub-region in Handan (10⁶ m³).

Figure 6 shows the primary sector water allocation in each sub-region in Handan. The total water demand of the primary sector in the region is $1591.82 \times 10^6 \text{ m}^3$, whereas the total allocated volume is $1210.66 \times 10^6 \text{ m}^3$, with a shortage of $381.15 \times 10^6 \text{ m}^3$, and an average shortage rate of 23.9%. The four sub-regions with relatively great shortages are Handan city, Weixian, Quzhou, and Cheng'an and their shortage rates are 62.4%, 60.3%, 50.4%, and 47.5%, respectively. In Shexian, Wu'an, Fengfeng, Cixian, Jize, and Feixiang, water supply can meet the primary sector water demand. The allocated volume supported by local surface water, groundwater, the Dongwushi reservoir, the Yuecheng reservoir, imported water from the Yellow River, and recycled water are $127.18 \times 10^6 \text{ m}^3$, $477.69 \times 10^6 \text{ m}^3$, $189.08 \times 10^6 \text{ m}^3$, $165.70 \times 10^6 \text{ m}^3$, $85.83 \times 10^6 \text{ m}^3$, and $165.19 \times 10^6 \text{ m}^3$, respectively, accounting for 10.5%, 39.5%, 15.6%, 13.7%, 7.1%, and 3.6% of the total supply, respectively. Again, groundwater is the main water source for the primary sector.

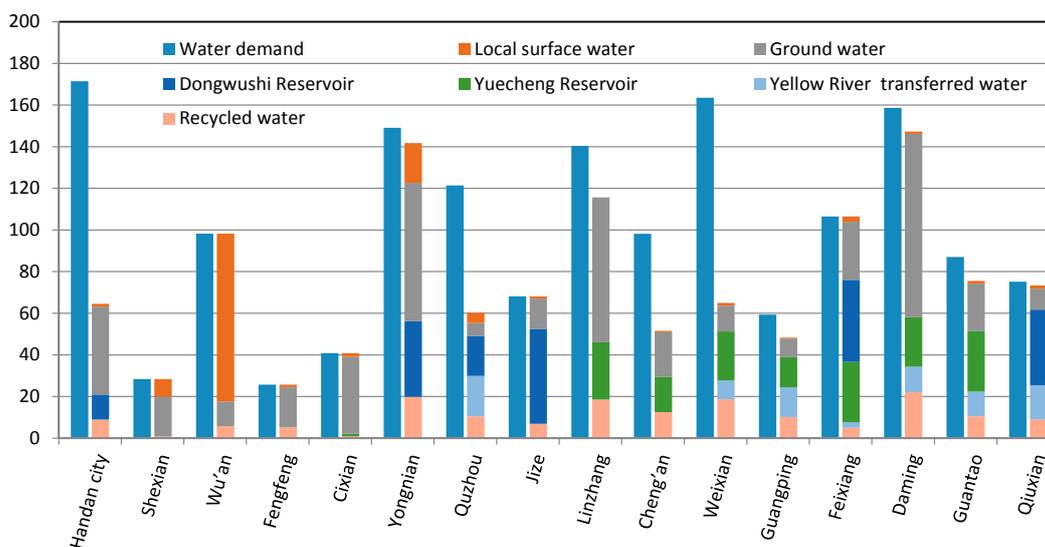


Figure 6. Primary sector water allocation in each sub-region in Handan (10⁶ m³).

The secondary sector water allocation in each sub-region in Handan is shown in Figure 7. The total water demand of the secondary sector is $307.06 \times 10^6 \text{ m}^3$, and the total allocated volume is $292.60 \times 10^6 \text{ m}^3$, leading to a shortage of $14.46 \times 10^6 \text{ m}^3$, and an average shortage rate of 4.7%. In all sub-regions except Wu'an, the supply meets the demand. In Wu'an, the demand is $71.00 \times 10^6 \text{ m}^3$, and the allocated volume is $56.54 \times 10^6 \text{ m}^3$. There is a shortage of $14.46 \times 10^6 \text{ m}^3$. Water sources for the secondary sector water supply include groundwater, water transferred through the South–North Water Transfer Project, the Dongwushi reservoir, the Yuecheng reservoir, imported water from the Yellow River, and recycled water. Their allocated volumes are $81.02 \times 10^6 \text{ m}^3$, $71.26 \times 10^6 \text{ m}^3$, $14.03 \times 10^6 \text{ m}^3$, $19.35 \times 10^6 \text{ m}^3$, $8.40 \times 10^6 \text{ m}^3$, and $98.55 \times 10^6 \text{ m}^3$, and contribute to total supply by 26.4%, 23.2%, 4.6%, 6.3%, 2.7%, and 32.1%, respectively. The main water source for the secondary sector is recycled water.

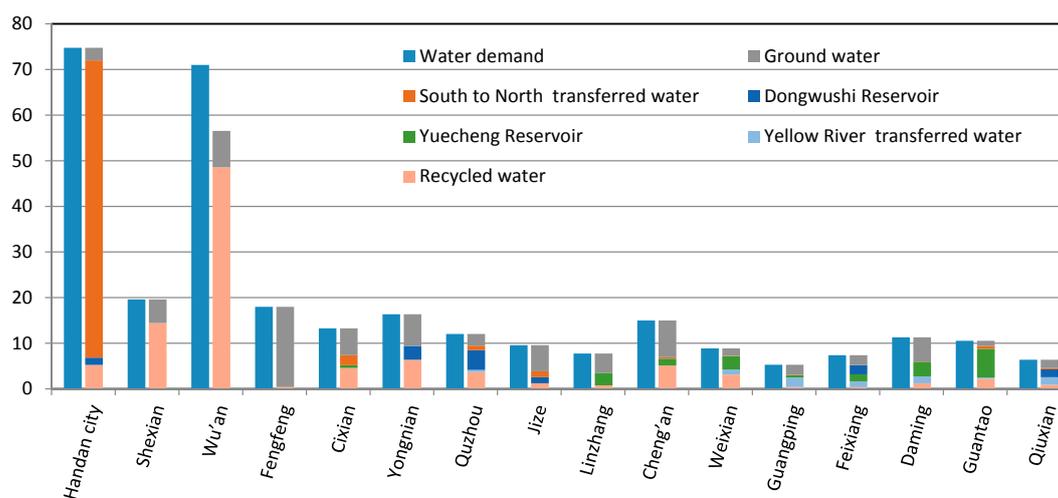


Figure 7. Secondary sector water allocation in each sub-region in Handan (10^6 m^3).

Figure 8 shows the tertiary sector water allocation in each sub-region in Handan. As shown in Figure 8, the total water demand and allocated volume are $213.41 \times 10^6 \text{ m}^3$ and $213.41 \times 10^6 \text{ m}^3$, respectively. In all sub-regions, the supply can satisfy the demand. The tertiary sector water demand is wholly supported by groundwater and water transferred through the South–North Water Transfer Project, the supplies of which are $8.40 \times 10^6 \text{ m}^3$ and $98.55 \times 10^6 \text{ m}^3$, respectively, and account for 70.1% and 29.9% of the total, respectively. Groundwater is the dominant water source for the tertiary sector.

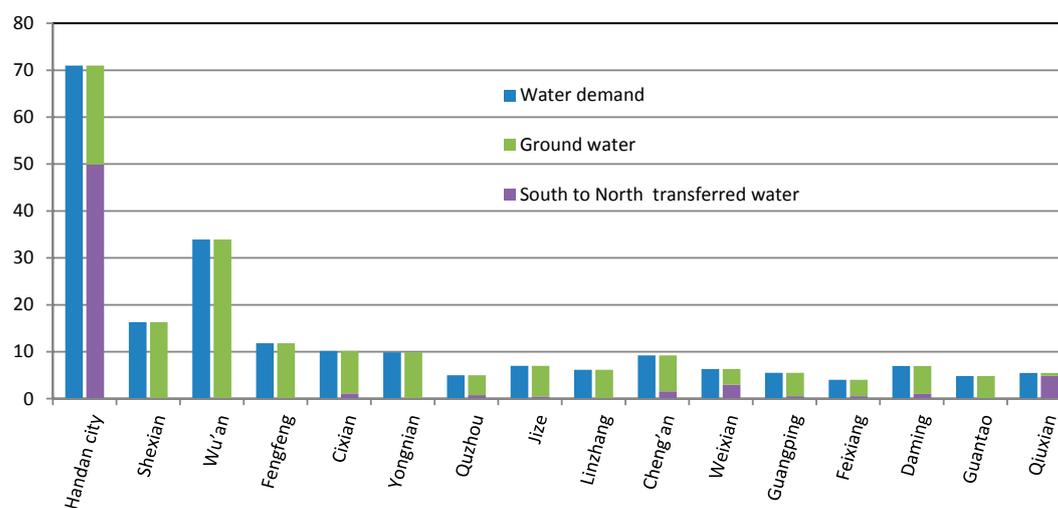


Figure 8. Tertiary sector water allocation in each sub-region in Handan (10^6 m^3).

Figure 9 shows the ecological water allocation in each sub-region in Handan. The total water demand and total allocated volume are $190.72 \times 10^6 \text{ m}^3$ and $182.00 \times 10^6 \text{ m}^3$, respectively. The shortage is $8.72 \times 10^6 \text{ m}^3$, and the shortage rate is 4.6%. In all sub-regions, except Handan city, the supply can satisfy the demand. In Handan city, the demand is $114.84 \times 10^6 \text{ m}^3$, while the allocated volume is $106.12 \times 10^6 \text{ m}^3$, resulting in a deficiency of $8.72 \times 10^6 \text{ m}^3$. The supplies by local surface water, the Dongwushi reservoir, the Yuecheng reservoir, imported water from the Yellow River, and recycled water are $25.88 \times 10^6 \text{ m}^3$, $18.68 \times 10^6 \text{ m}^3$, $12.50 \times 10^6 \text{ m}^3$, $5.77 \times 10^6 \text{ m}^3$, and $119.17 \times 10^6 \text{ m}^3$, respectively, accounting for 14.2%, 10.3%, 6.9%, 3.2%, and 65.5%, respectively, of the total. Recycled water is the main source for the ecological water demand.

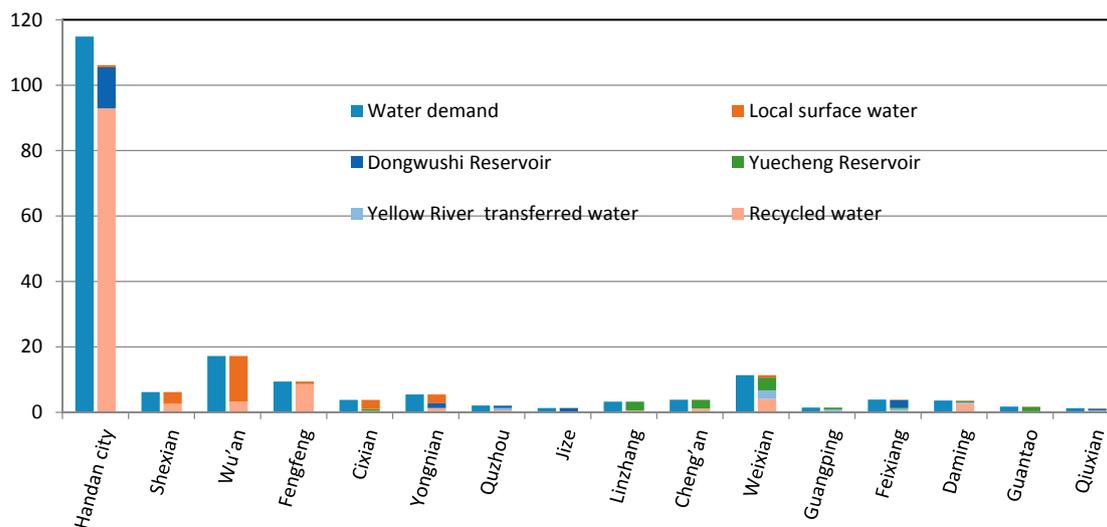


Figure 9. Ecological water allocation in each sub-region in Handan (10^6 m^3).

Table 5 lists the volumes of local surface water allocated to each user in each sub-region in Handan. Due to the water quality, local surface water is allocated only to the primary sector and ecology. The corresponding allocated volumes are $127.18 \times 10^6 \text{ m}^3$ and $25.88 \times 10^6 \text{ m}^3$, respectively, and the total is $153.06 \times 10^6 \text{ m}^3$. Since the total available water supply by local surface water in the region is $236.58 \times 10^6 \text{ m}^3$, $83.52 \times 10^6 \text{ m}^3$ of water not utilized. From Figures 6 and 9, local surface water accounts for 10.5% and 14.2% of the total volumes allocated to the primary sector and ecology, respectively. In Wu'an, the highest volumes of local surface water are allocated to the primary sector and ecology. The corresponding volumes are $80.68 \times 10^6 \text{ m}^3$ and $13.93 \times 10^6 \text{ m}^3$, which account for 63.4% and 53.8%, respectively, of the total volumes of local surface water allocated. This is because Wu'an has abundant local surface water, or 48.6% of the total in Handan.

Table 5. Results for local surface water allocated to every user (10^6 m³).

Administrative Division	Primary Sector	Ecology	Total
Handan city	1.29	0.64	1.93
Shexian	8.48	3.57	12.05
Wu'an	80.68	13.93	94.61
Fengfeng	1.17	0.78	1.95
Cixian	1.75	2.79	4.54
Yongnian	19.04	2.72	21.76
Quzhou	4.88	0.04	4.92
Jize	1.02	0.03	1.05
Linzhang	0.00	0.00	0.00
Cheng'an	0.70	0.03	0.73
Weixian	1.31	0.72	2.03
Guangping	0.44	0.03	0.47
Feixiang	2.54	0.16	2.70
Daming	1.08	0.20	1.28
Guantao	1.27	0.09	1.36
Qiuxian	1.53	0.14	1.67
Total	127.18	25.88	153.06

Table 6 shows the volumes of groundwater allocated to each user in each sub-region in Handan. Groundwater is allocated to urban domestic, rural domestic, primary sector, secondary sector, and tertiary sector uses in volumes of 263.07×10^6 m³, 35.91×10^6 m³, 477.69×10^6 m³, 81.02×10^6 m³, and 149.63×10^6 m³, respectively. These account for 26.1%, 3.6%, 47.4%, 8.0%, and 14.9% of the total volume of groundwater allocated, respectively. Groundwater is mostly supplied to the primary sector. This is in line with actual local groundwater usage. The total available water supply by groundwater and total allocated volume are 1130.42×10^6 m³ and 1007.32×10^6 m³, respectively. There is 123.10×10^6 m³ of unallocated water remaining.

Table 6. Results for groundwater allocated to every user (10^6 m³).

Administrative Division	Urban Domestic	Rural Domestic	Primary Sector	Secondary Sector	Tertiary Sector	Total
Handan city	7.50	3.86	42.22	2.76	21.11	77.44
Shexian	18.45	1.07	19.11	5.17	16.29	60.09
Wu'an	38.38	1.35	11.84	7.97	33.92	93.46
Fengfeng	21.01	2.30	19.25	17.59	11.82	71.96
Cixian	15.45	1.92	36.99	5.88	9.06	69.29
Yongnian	10.92	4.35	66.48	6.94	9.88	98.56
Quzhou	11.89	2.97	6.23	2.57	4.23	27.88
Jize	8.90	2.02	14.54	5.72	6.54	37.71
Linzhang	18.41	2.84	69.53	4.22	6.13	101.13
Cheng'an	15.51	0.86	21.49	8.02	7.66	53.54
Weixian	32.11	3.48	12.38	1.60	3.33	52.89
Guangping	3.00	1.28	8.93	2.21	4.96	20.38
Feixiang	10.70	2.22	27.90	2.17	3.49	46.48
Daming	30.76	2.97	88.03	5.29	5.94	133.00
Guantao	11.69	1.32	22.73	1.14	4.65	41.53
Qiuxian	8.40	1.11	10.05	1.78	0.63	21.97
Total	263.07	35.91	477.69	81.02	149.63	1007.32

The allocation results of water transferred through the South–North Water Transfer Project to each user in each sub-region in Handan are listed in Table 7. The transferred water is mostly supplied for urban domestic, secondary, and tertiary sector uses. The total available water supply and total allocated volumes are 388.62×10^6 m³ and 259.11×10^6 m³, respectively, resulting in a surplus of

$129.51 \times 10^6 \text{ m}^3$ not allocated for any use. The allocated volumes for urban domestic, secondary, and tertiary sector uses are $124.09 \times 10^6 \text{ m}^3$, $71.26 \times 10^6 \text{ m}^3$, and $63.77 \times 10^6 \text{ m}^3$, respectively. These account for 47.9%, 27.5%, and 24.6%, respectively, of the total allocated volume of water transferred through the South–North Water Transfer Project. The transferred water is mainly supplied for urban domestic use, since its quality is relatively high and consequently, it is able to fulfill the quality requirements for urban domestic water.

Table 7. Results for South to North transferred water allocated to every user (10^6 m^3).

Administrative Division	Urban Domestic	Secondary Sector	Tertiary Sector	Total
Handan city	75.03	65.16	49.87	190.06
Shexian	0.00	0.00	0.00	0.00
Wu'an	0.00	0.00	0.00	0.00
Fengfeng	0.00	0.00	0.00	0.00
Cixian	1.55	2.20	1.09	4.84
Yongnian	19.62	0.00	0.00	19.62
Quzhou	3.65	1.01	0.74	5.41
Jize	0.89	1.29	0.45	2.63
Linzhang	5.92	0.00	0.01	5.93
Cheng'an	1.55	0.36	1.56	3.47
Weixian	1.74	0.08	2.99	4.81
Guangping	7.93	0.14	0.53	8.60
Feixiang	2.68	0.03	0.52	3.23
Daming	1.57	0.05	1.01	2.63
Guantao	1.12	0.62	0.16	1.90
Qiuxian	0.84	0.32	4.85	6.01
Total	124.09	71.26	63.77	259.11

The total available water supply by the Dongwushi reservoir and the total allocated volume are both $221.79 \times 10^6 \text{ m}^3$, signifying that the total available supply is completely allocated for different uses. The results are listed in Table 8. The Dongwushi reservoir is a public water source and mainly supplies water to Handan city, Yongnian, Quzhou, Jize, Feixiang, and Qiuxian. The Dongwushi reservoir mostly supports the primary and secondary sector and ecological water uses. From Table 8, the allocated volumes to the primary sector, secondary sector, and ecology are $189.08 \times 10^6 \text{ m}^3$, $14.03 \times 10^6 \text{ m}^3$, and $18.68 \times 10^6 \text{ m}^3$, respectively, accounting for 85.3%, 6.3%, and 8.4%, respectively, of the total allocated volume from the Dongwushi reservoir. Most of the water from the reservoir is supplied to the primary sector because the water quality is not high enough to satisfy domestic requirements, but is suitable for irrigation in the primary sector. The allocation results are consistent with the current allocation situation of the reservoir.

Table 8. Results of Dongwushi reservoir allocated to every user (10^6 m^3).

Administrative Division	Primary Sector	Secondary Sector	Ecology	Total
Handan city	12.07	1.61	12.58	26.26
Shexian	0.00	0.00	0.00	0.00
Wu'an	0.00	0.00	0.00	0.00
Fengfeng	0.00	0.00	0.00	0.00
Cixian	0.00	0.00	0.00	0.00
Yongnian	36.35	3.03	1.45	40.83
Quzhou	19.20	4.31	0.77	24.27
Jize	45.61	1.35	1.18	48.14
Linzhang	0.00	0.00	0.00	0.00
Cheng'an	0.00	0.00	0.00	0.00
Weixian	0.00	0.00	0.00	0.00
Guangping	0.00	0.00	0.00	0.00
Feixiang	39.46	1.98	2.23	43.67
Daming	0.00	0.00	0.00	0.00
Guantao	0.00	0.00	0.00	0.00
Qiuxian	36.39	1.75	0.46	38.61
Total	189.08	14.03	18.68	221.79

The Yuecheng reservoir is a public water source mainly supplied to Cixian, Linzhang, Cheng'an, Weixian, Guangping, Feixiang, Daming, and Guantao. The main users are primary sector, secondary sector, and ecology. The allocation results are shown in Table 9. The total available water supply equals the total allocated volume, which is $197.56 \times 10^6 \text{ m}^3$. Thus, the total available supply is completely allocated. The volumes allocated to the primary sector, secondary sector, and ecology are $165.70 \times 10^6 \text{ m}^3$, $19.35 \times 10^6 \text{ m}^3$, and $12.50 \times 10^6 \text{ m}^3$, respectively. These account for 83.9%, 9.8%, and 6.3% of the total allocated volume, respectively, indicating that the main user of the Yuecheng reservoir is the primary sector.

Table 9. Results for Yuecheng reservoir allocated to every user (10^6 m^3).

Administrative Division	Primary Sector	Secondary Sector	Ecology	Total
Handan city	0.00	0.00	0.00	0.00
Shexian	0.00	0.00	0.00	0.00
Wu'an	0.00	0.00	0.00	0.00
Fengfeng	0.00	0.00	0.00	0.00
Cixian	1.17	0.60	0.58	2.35
Yongnian	0.00	0.00	0.00	0.00
Quzhou	0.00	0.00	0.00	0.00
Jize	0.00	0.00	0.00	0.00
Linzhang	27.57	2.77	2.74	33.08
Cheng'an	16.88	1.48	2.65	21.01
Weixian	23.56	2.96	3.91	30.43
Guangping	14.58	0.46	0.50	15.54
Feixiang	28.94	1.54	0.44	30.92
Daming	23.85	3.24	0.36	27.45
Guantao	29.15	6.30	1.32	36.77
Qiuxian	0.00	0.00	0.00	0.00
Total	165.70	19.35	12.50	197.56

Imported water from the Yellow River is a public water source. The imported water is mainly supplied to Quzhou, Weixian, Guangping, Feixiang, Daming, Guantao, and Qiuxian. It is mostly allocated for the primary sector, secondary sector, and ecological uses. From Table 10, the allocated volumes to the primary sector, secondary sector, and ecology are $85.83 \times 10^6 \text{ m}^3$, $8.40 \times 10^6 \text{ m}^3$, and $5.77 \times 10^6 \text{ m}^3$, respectively, accounting for 85.8%, 8.4%, and 5.8%, respectively, of the total

allocated volume of $100.00 \times 10^6 \text{ m}^3$. All imported water is allocated completely, and mostly to the primary sector.

Table 10. Results for Yellow River transferred water allocated to every user (10^6 m^3).

Administrative Division	Primary Sector	Secondary Sector	Ecology	Total
Handan city	0.00	0.00	0.00	0.00
Shexian	0.00	0.00	0.00	0.00
Wu'an	0.00	0.00	0.00	0.00
Fengfeng	0.00	0.00	0.00	0.00
Cixian	0.00	0.00	0.00	0.00
Yongnian	0.00	0.00	0.00	0.00
Quzhou	19.45	0.47	0.73	20.64
Jize	0.00	0.00	0.00	0.00
Linzhang	0.00	0.00	0.00	0.00
Cheng'an	0.00	0.00	0.00	0.00
Weixian	9.06	1.12	2.63	12.81
Guangping	14.19	2.09	0.59	16.86
Feixiang	2.63	1.29	0.65	4.57
Daming	12.22	1.49	0.51	14.22
Guantao	11.88	0.29	0.27	12.44
Qiuxian	16.40	1.65	0.40	18.45
Total	85.83	8.40	5.77	100.00

The allocation results for recycled water in Handan are listed in Table 11. Recycled water is mostly allocated to the primary sector, secondary sector, and ecology in volumes of $165.19 \times 10^6 \text{ m}^3$, $98.55 \times 10^6 \text{ m}^3$, and $119.17 \times 10^6 \text{ m}^3$, respectively. These account for 43.1%, 25.7%, and 31.1% of the total allocated volume, respectively. The total available supply by recycled water is $421.75 \times 10^6 \text{ m}^3$ and the total allocated volume is $382.90 \times 10^6 \text{ m}^3$, resulting in a surplus of $38.85 \times 10^6 \text{ m}^3$ not utilized.

Table 11. Results for recycled water allocated to every user (10^6 m^3).

Administrative Division	Primary Sector	Secondary Sector	Ecology	Total
Handan city	8.92	5.25	92.89	107.06
Shexian	0.76	14.44	2.62	17.82
Wu'an	5.75	48.57	3.26	57.58
Fengfeng	5.24	0.40	8.63	14.27
Cixian	0.90	4.59	0.44	5.93
Yongnian	19.84	6.38	1.30	27.52
Quzhou	10.48	3.68	0.56	14.72
Jize	6.92	1.21	0.11	8.24
Linzhang	18.54	0.76	0.53	19.83
Cheng'an	12.50	5.12	1.14	18.76
Weixian	18.67	3.11	4.10	25.87
Guangping	10.17	0.39	0.35	10.91
Feixiang	5.01	0.36	0.41	5.78
Daming	22.05	1.23	2.55	25.83
Guantao	10.46	2.18	0.04	12.68
Qiuxian	8.98	0.89	0.24	10.11
Total	165.19	98.55	119.17	382.90

In Handan, the total water demand of all users, the total available water supply, and the total allocated volume are $2726.07 \times 10^6 \text{ m}^3$, $2696.71 \times 10^6 \text{ m}^3$, and $2321.74 \times 10^6 \text{ m}^3$, respectively. There is a surplus of $374.97 \times 10^6 \text{ m}^3$ not allocated, and the volumes are listed in Table 12. Water from the Dongwushi reservoir, Yuecheng reservoir, and water imported from the Yellow River are fully allocated for different uses. Moreover, $83.52 \times 10^6 \text{ m}^3$ of local surface water, $123.10 \times 10^6 \text{ m}^3$ of

groundwater, $129.51 \times 10^6 \text{ m}^3$ of water transferred through the South–North Water Transfer Project, and $38.84 \times 10^6 \text{ m}^3$ of recycled water are not used. In five sub-regions, namely, Shexian, Fengfeng, Cixian, Jize, and Feixiang, the allocated volume can completely satisfy the water demand, and there is a surplus of $223.23 \times 10^6 \text{ m}^3$ of water. In Handan city, the water demand of the primary sector and ecology are not satisfied, while that of other users is entirely met. In Handan city, $106.30 \times 10^6 \text{ m}^3$ of water transferred through the South–North Water Transfer Project is not utilized. Since the water transferred can only be allocated to urban domestic, secondary sector, or tertiary sector uses, the surplus cannot be used to make up the shortage in the primary sector and ecology. In Wu’an, the water demand of the secondary sector is not satisfied while that of other users is fully met. Although $20.29 \times 10^6 \text{ m}^3$ of local surface water remains unutilized, it cannot supplement the insufficient supply to the secondary sector, as the local surface water is supplied only to the primary sector and ecology. In Yongnian, Quzhou, Linzhang, Cheng’an, Weixian, Guangping, Daming, Guantao, and Qiuxian, the water demand of the primary sector is not satisfied. The surplus in these nine sub-regions consists solely of water transferred through the South–North Water Transfer Project. Due to the relatively high cost of the transferred water, it cannot be used to make up the shortage in the primary sector. Lastly, $9.91 \times 10^6 \text{ m}^3$ of groundwater is not utilized in Weixian and Guangping.

Table 12. Surplus volumes not allocated (10^6 m^3).

Administrative Division	Local Surface Water	Ground Water	South-To-North Transferred Water	Recycled Water	Sum
Handan city			106.30		106.30
Shexian	39.00	21.47		6.94	67.41
Wu’an	20.29				20.29
Fengfeng		54.07		9.02	63.09
Cixian	24.23	37.66	5.22	13.01	80.12
Yongnian			0.01		0.01
Quzhou			0.71		0.71
Jize			1.44	3.74	5.18
Linzhang			0.01		0.01
Cheng’an			2.79		2.79
Weixian		5.75	2.15		7.90
Guangping		4.16	0.40		4.56
Feixiang			1.30	6.13	7.43
Daming			3.65		3.65
Guantao			2.58		2.58
Qiuxian			2.95		2.95
Total	83.52	123.10	129.51	38.85	374.97

4.2. Comparison with WOA and PSO

In order to test and verify the performance of the AWOA, the WOA and PSO algorithms are employed to solve the model. The results by the three algorithms are compared and analyzed. To ensure a fair comparison, all the parameters are set the same in the AWOA, WOA, and PSO algorithms. The initialization swarm size is 150, and there are 180 iterations. There are 20 runs and each run starts with a different random initialization swarm. Through numerous simulation experiments, other parameters in PSO are as follows: $c_1 = 0.002$, $c_2 = 0.002$, $\omega' = 0.9$, and $\omega'' = 0.2$.

The three algorithms of the AWOA, WOA, and PSO all reach the Pareto front through MATLAB software programming. The AWOA obtained nine non-inferior solutions on the Pareto front, five of which resulted from the WOA, and four from the PSO algorithm. For all three algorithms, the scenarios are chosen with preference for the minimum water shortage as the efficient solution, and to proceed with the comparative analysis. The calculation results by the three algorithms are presented in Table 13. The AWOA results in the greatest social benefit of $-404.34 \times 10^6 \text{ m}^3$, while the PSO algorithm ranks second, with a social benefit of $-412.75 \times 10^6 \text{ m}^3$. The WOA has the smallest

social benefit at $-413.50 \times 10^6 \text{ m}^3$. Meanwhile, the economic benefit of the AWOA is highest at $45,148.03 \times 10^6 \text{ CNY}$, followed the WOA ($44,804.69 \times 10^6 \text{ CNY}$). The PSO algorithm creates the least economic benefit of $44,426.78 \times 10^6 \text{ CNY}$. The detailed allocation results are listed in Tables 14–16, and are illustrated in Figure 10. The iterative processes of the three algorithms are obtained by taking the average of all individuals after each multi-objective optimization algorithm runs 20 times, each with 180 iterations, as shown in Figures 11–13. The comparison of the iterative processes of the three algorithms demonstrates that, although the iteration curve of the AWOA fluctuates, the fluctuation amplitude is relatively small, and the curve converges relatively quickly. The swarm in the WOA does not converge at the 180th iteration, while the PSO algorithm becomes stable at the 180th iteration. In summary, the AWOA has a better convergence rate and precision than the WOA and improved PSO algorithm.

Table 13. Results for objective function values of AWOA, WOA, and PSO.

Algorithm	Social Benefit (10^6 m^3)	Economic Benefit (10^6 CNY)
AWOA	−404.34	45,148.03
WOA	−413.50	44,804.69
PSO	−412.75	44,426.78

Table 14. Results for water allocation of AWOA (10^6 m^3).

Administrative Division	Urban Domestic	Rural Domestic	Primary Sector	Secondary Sector	Tertiary Sector	Ecology	Total
Handan city	82.53	3.86	64.50	74.78	70.98	106.12	402.76
Shexian	18.45	1.07	28.35	19.61	16.29	6.20	89.97
Wu'an	38.38	1.35	98.27	56.54	33.92	17.19	245.65
Fengfeng	21.01	2.30	25.66	17.99	11.82	9.41	88.18
Cixian	17.00	1.92	40.81	13.27	10.15	3.81	86.95
Yongnian	30.54	4.35	141.71	16.35	9.88	5.47	208.29
Quzhou	15.54	2.97	60.23	12.04	4.97	2.09	97.84
Jize	9.79	2.02	68.09	9.57	6.99	1.32	97.77
Linzhang	24.33	2.84	115.64	7.75	6.14	3.27	159.96
Cheng'an	17.06	0.86	51.57	14.98	9.22	3.82	97.51
Weixian	33.85	3.48	64.98	8.87	6.31	11.37	128.85
Guangping	10.93	1.28	48.31	5.29	5.49	1.47	72.76
Feixiang	13.38	2.22	106.48	7.37	4.01	3.90	137.35
Daming	32.33	2.97	147.23	11.30	6.95	3.62	204.40
Guantao	12.81	1.32	75.49	10.53	4.81	1.72	106.68
Qiuxian	9.24	1.11	73.35	6.39	5.48	1.24	96.81
Total	387.16	35.91	1210.66	292.60	213.41	182.00	2321.74

Table 15. Results for water allocation of WOA (10^6 m³).

Administrative Division	Urban Domestic	Rural Domestic	Primary Sector	Secondary Sector	Tertiary Sector	Ecology	Total
Handan city	82.53	3.86	117.51	74.78	70.98	61.44	411.09
Shexian	18.45	1.07	28.35	19.61	16.29	6.20	89.97
Wu'an	38.38	1.35	98.27	51.39	16.15	17.19	222.73
Fengfeng	21.01	2.30	25.66	17.99	11.82	9.41	88.18
Cixian	17.00	1.92	40.81	13.27	10.15	3.81	86.95
Yongnian	30.54	4.35	130.13	16.35	9.88	5.47	196.71
Quzhou	15.54	2.97	75.88	12.04	4.97	2.09	113.49
Jize	9.79	2.02	66.11	9.57	6.99	1.32	95.79
Linzhang	24.33	2.84	120.53	7.75	6.14	3.27	164.86
Cheng'an	17.06	0.86	56.72	14.98	9.22	3.82	102.66
Weixian	33.85	3.48	74.24	8.87	6.31	11.37	138.12
Guangping	10.93	1.28	54.50	5.29	5.49	1.47	78.96
Feixiang	13.38	2.22	106.48	7.37	4.01	3.90	137.35
Daming	32.33	2.97	136.86	11.30	6.95	3.62	194.03
Guantao	12.81	1.32	63.69	10.53	4.81	1.72	94.88
Qiuxian	9.24	1.11	73.35	6.39	5.48	1.24	96.81
Total	387.16	35.91	1269.10	287.45	195.63	137.32	2312.58

Table 16. Results for water allocation of PSO (10^6 m³).

Administrative Division	Urban Domestic	Rural Domestic	Primary Sector	Secondary Sector	Tertiary Sector	Ecology	Total
Handan city	82.53	3.86	115.43	74.78	70.98	74.28	421.85
Shexian	18.45	1.07	28.35	19.61	16.29	6.20	89.97
Wu'an	38.38	1.35	98.27	58.96	17.28	17.19	231.43
Fengfeng	21.01	2.30	25.66	17.99	11.82	9.41	88.18
Cixian	17.00	1.92	40.81	13.27	10.15	3.81	86.95
Yongnian	30.54	4.35	133.05	16.35	9.88	5.47	199.63
Quzhou	15.54	2.97	56.73	12.04	4.97	2.09	94.34
Jize	9.79	2.02	58.41	9.57	6.99	1.32	88.09
Linzhang	24.33	2.84	113.97	7.75	6.14	3.27	158.29
Cheng'an	17.06	0.86	58.61	14.98	9.22	3.82	104.55
Weixian	33.85	3.48	65.52	8.87	6.31	11.37	129.40
Guangping	10.93	1.28	59.34	5.29	5.49	1.47	83.80
Feixiang	13.38	2.22	105.01	7.37	4.01	3.90	135.89
Daming	32.33	2.97	137.58	11.30	6.95	3.62	194.75
Guantao	12.81	1.32	76.41	10.53	4.81	1.72	107.60
Qiuxian	9.24	1.11	75.15	6.39	5.48	1.24	98.61
Total	387.16	35.91	1248.31	295.02	196.76	150.16	2313.33

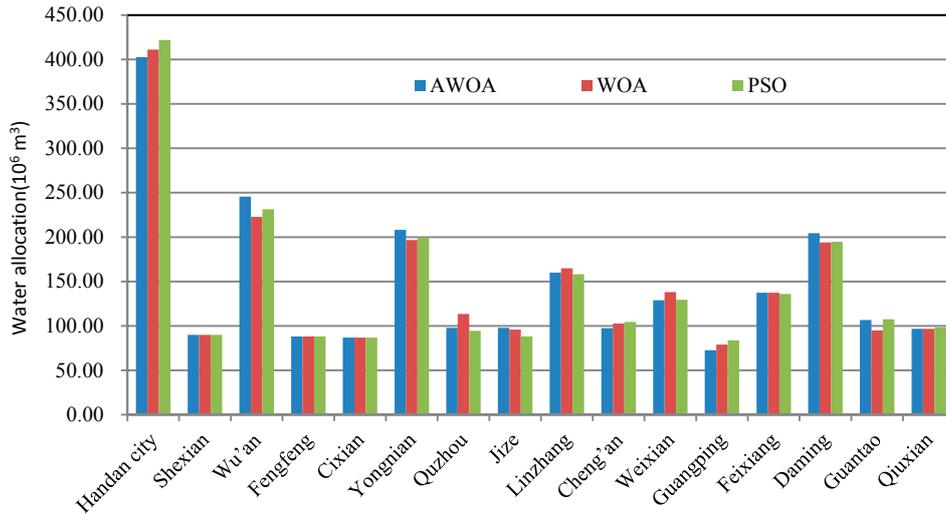


Figure 10. Water allocation based on three algorithms for each sub-region in Handan.

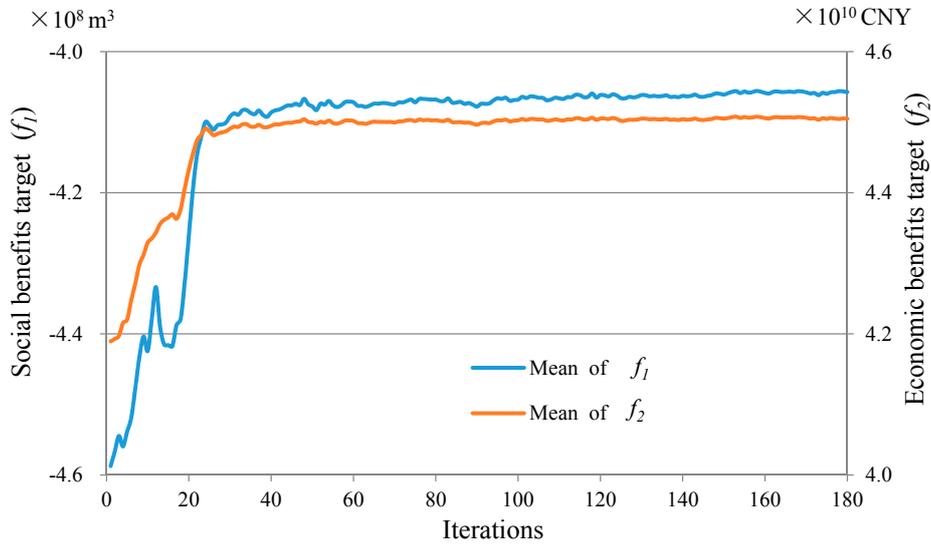


Figure 11. Iterative process of AWOA.

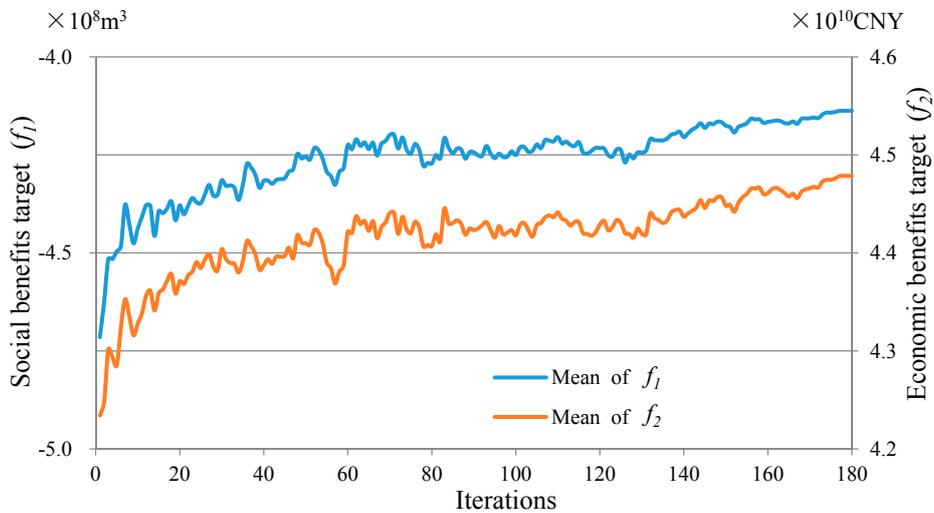


Figure 12. Iterative process of WOA.

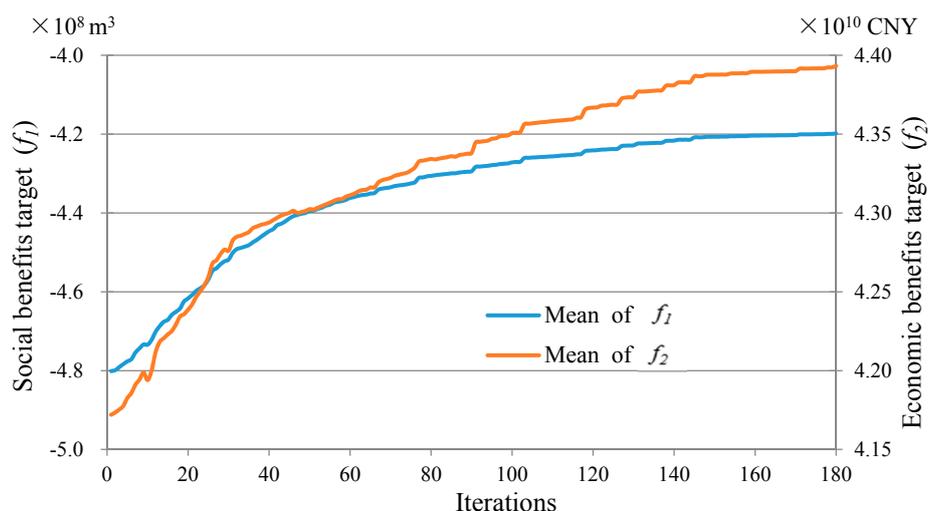


Figure 13. Iterative process of PSO.

4.3. Discussion

The WOA, proposed by Mirjalili and Lewis in 2016, has less application to water resources management. The WOA was used to solve long-term optimal operation of a single reservoir and cascade reservoirs by Cui Donglai [52] in 2017. The results were compared with those obtained from six algorithms, including the cuckoo search algorithm, differential evolution algorithm, shuffled frog-leaping algorithm, PSO algorithm, firefly algorithm, and SCE-UA algorithm. The results show that the WOA for the optimal operation of a single reservoir and cascade reservoirs is superior to the other six algorithms. The WOA is feasible and effective for reservoir optimal operation [52]. This study applied the WOA to the multi-objective optimization of water resources allocation model for the first time in the literature. When the number of iterations is set to 180 times, the algorithm cannot converge, and attempts to run 300 times, 500 times, 1000 times, 1500 times, and 2000 times while the WOA still cannot converge. In order to solve this problem, an AWOA is proposed in this study, where by logistic mapping is used to initialize swarm location, and inertia weighting is employed to strengthen local search capability. It can be concluded from Figure 11 and Table 13 that after the AWOA is applied to the multi-objective optimization of water resources allocation model in Handan, it speeds up the algorithm convergence and improves the accuracy of the algorithm.

The AWOA is compared with the PSO to verify which is superior when applied to the multi-objective water resources allocation model. As a mature swarm-based algorithm, PSO has obtained a large number of successful applications to the optimal allocation of water resources [29,30,53–60]. According to previous research results, efficiency of the water resources allocation problem can be effectively improved under PSO. The AWOA outperforms the PSO in terms of convergence rate and solution accuracy through Figures 11 and 13, and Table 13. The AWOA provides a new way to solve the complex multi-objective optimization of water resources allocation model.

5. Conclusions

Due to population growth and rapid socio-economic development, regions with water shortages are expanding, making shortages increasingly severe in China. This has developed into a critical issue that significantly hinders social and economic development. Alleviating water shortages by optimizing water resource allocation has become increasingly important. Water resource allocation optimization is a multi-objective problem, which cannot be solved easily with traditional programming methods. Based on previous research, this study introduces the WOA into multi-objective water resource allocation optimization models. To overcome drawbacks like relatively low convergence precision

and convergence rate when applying the WOA algorithm to complex optimization problems, logistic mapping is used to initialize swarm location, and enhance the quality of initialization swarm location. In addition, inertia weighting is employed to strengthen the local search capability. Compared to the WOA and PSO algorithm, the AWOA shows substantially enhanced convergence rates and precision.

The AWOA is utilized to solve the Handan water resource allocation optimization model. The results indicate that the total water demand for all users in the city is $2726.08 \times 10^6 \text{ m}^3$, and the total allocated volume is $2321.74 \times 10^6 \text{ m}^3$, resulting in a total water shortage of $404.34 \times 10^6 \text{ m}^3$, and a shortage rate of 14.8%. Water shortages occur mainly in the primary sector (agriculture), with a shortage volume of $381.15 \times 10^6 \text{ m}^3$. This accounts for 94.3% of the total shortage. The allocation optimization results show good agreement with the reality of water resource exploitation and utilization. This verifies the relatively high reliability and applicability of the AWOA in solving multi-objective multi-source multi-user water resource allocation optimization models.

The AWOA proposed in this study can effectively solve multi-objective water resource allocation optimization models. It provides a Pareto non-inferior solution set and hence, several reliable multi-source joint control plans. According to the preferences for the objective functions, the authority can select the appropriate plan to control and manage multiple water sources jointly.

Since the sewage disposal data are not complete, this study establishes only a water resource allocation optimization model that aims for the greatest economic benefit and smallest shortage volume. In future, with complete sewage disposal data, a water resource allocation optimization model targeting relatively optimal economic, environmental, and social benefits should be constructed and solved using the AWOA. This could verify the applicability of the AWOA to more multi-objective water resource allocation optimization problems.

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