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# Study on coordinated allocation of conventional and unconventional water resources in typical regions of North China

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**Introduction:** The North China Plain is an important production base of grain, cotton, and fruits in China. However, the climate is dry and rainless, and thus, water resources are scarce. The combination of water resources, population, and cultivated land is extremely unbalanced, making the region a serious water shortage area in China. In addition to long-term groundwater over-exploitation, water shortage has become an important bottleneck, restricting the economic and social development of the North China Plain and national food security. Therefore, making full use of unconventional water resources and reducing the proportion of conventional water resources will alleviate the shortage of water resources and improve the utilization of water resources.

**Methods:** Taking Hengshui City as an example, this paper establishes an optimal allocation model of water resources with the minimum relative water shortage rate as the objective function, the coordinated allocation of water resources between conventional and unconventional water resources is studied, and various available water sources are effectively allocated between regions and water use departments. The genetic algorithm is used to study the model, by taking 2020 as the starting year, and optimize the allocation of water resources in Hengshui City between 2020 and 2025.

**Results and Discussion:** The results show that the water demand of each county in Hengshui City will be guaranteed in 2025, and there will be no water shortage. In the 2025 level year, the total amount of unconventional water resources in Hengshui City will increase compared with that in 2020, with an increase of 21.9144 million m<sup>3</sup>. Among them, there will be an increase in brackish water consumption, 11.3244 million m<sup>3</sup>, and an increase in sewage reuse water consumption, 10.59 million m<sup>3</sup>, which will effectively alleviate the contradiction between supply and demand of water resources in Hengshui City.

## KEYWORDS

coordinate allocation of water resources, unconventional water resources, genetic algorithm, typical area of Hebei, Hengshui City

## 1 Introduction

The North China Plain is an important production base of grain, cotton, and fruits in China. However, the climate in this area is dry and rainy, and water resources are scarce. The *per capita* water resources are 523 m<sup>3</sup>, and the average water resources are 309 m<sup>3</sup>, which are 1/4 and 1/5 of the national average, respectively. The combination of water resources, population, and cultivated land is extremely unbalanced, making the region a serious water shortage area in China. Long-term groundwater over-exploitation has formed a groundwater “funnel group” consisting of a series of funnels with an area of 40,000 km<sup>2</sup> in the Hebei Plain, causing a series of ecological and geological hazards, such as land subsidence and collapse. The shortage of water resources has become an important bottleneck, restricting the economic and social development of the North China Plain and national food security (Li et al., 2021).

The utilization of unconventional water resources in northern China is relatively low, and it is necessary to increase the proportion of unconventional water supply, which is also an important measure to alleviate the current water shortage (Li et al., 2022; Huang et al., 2021; Wu et al., 2020). It is of great significance to develop unconventional water resources according to local conditions to alleviate the shortage of water resources in the North China Plain. In the North China Plain, except for Beijing, underground salt water with salinity greater than 2 g/L is widely distributed, and its distribution area is 7.11×10<sup>4</sup> km<sup>2</sup>, accounting for 51.48% of the total area of 13.81×10<sup>4</sup> km<sup>2</sup>. The recoverable resources of salt water with TDS<5 g/L in the North China Plain are approximately 30×10<sup>8</sup> m<sup>3</sup>, and there are still 13.51×10<sup>8</sup> m<sup>3</sup> of salt water resources that have not been developed and utilized. The shallow salt water has the characteristics of easy exploitation, fast supply, and low energy consumption. The utilization potential of shallow salt water should be fully explored (Zhang D. et al., 2022; Ma et al., 2020). The North China Plain is densely populated. With the acceleration of urbanization, reclaimed water, as a product of daily urban operation, has a low utilization rate and great potential for excavation (Zhang, 2013). In order to solve the increasingly acute contradiction between supply and demand of water resources, it is imperative to increase the development and utilization of unconventional water resources (Zhu, 2020; Wu X. et al., 2021; Wang et al., 2023). With the economic development, population growth, and urban expansion, the demand for water resources in cities is increasing year by year, and the contradiction between supply and demand is prominent. Under the background of global traditional water shortage, making full use of unconventional water resources has become an important means to alleviate urban water pressure (Liu, 2017; Morante-Carballo et al., 2022; Zhang et al., 2023).

This paper chooses Hengshui City to carry out the optimal allocation of unconventional and conventional water resources. Hengshui City belongs to the Heilongjiang area, and the distribution area of salt water is 91.8%, which belongs to the typical salt water distribution area of the North China Plain. At the same time, Hengshui is a large agricultural city, and agricultural irrigation water accounts for approximately 83% of the city's water supply. Water resources are over-exploited, groundwater over-exploitation is serious, and food production is not effectively

guaranteed. It is crucial to incorporate the development and utilization of unconventional water resources into the water resource management system (Liang and Zuo, 2012; Hu and Wu, 2018). Therefore, Hengshui is considered a strong representative of the unconventional water resource in the arid middle and lower reaches of the plains in northern China. This research can provide some experience and reference for the coordinated allocation of water resources in other arid middle and lower reaches of the plains in northern China.

## 2 Present situation of water resource development and utilization in Hengshui City

The data on the utilization status of conventional water resources and unconventional water resources in this part are derived from “Hengshui City Water Resources Planning.”

### 2.1 Conventional water resource utilization status

Hengshui City, in 2015, had a total water supply of 1.539 billion m<sup>3</sup>. From the perspective of water supply, surface water supply is 265 million m<sup>3</sup>, groundwater supply is 1.273 billion m<sup>3</sup>, and sewage treatment and reuse water supply is 590,000 m<sup>3</sup>, accounting for 17.2%, 82.7%, and 0.1% of the total water supply, respectively. From the perspective of water consumption, agricultural water consumption is 1.31 billion m<sup>3</sup>, industrial water consumption is 108 million m<sup>3</sup>, domestic water consumption is 105 million m<sup>3</sup>, and ecological environment water consumption is 9 million m<sup>3</sup>, accounting for 85%, 7%, 7%, and 1% of the total water consumption, respectively. In 2015, Hengshui City's overdraft deep groundwater was 900 million m<sup>3</sup>. Conventional water resources still account for the vast majority of water supply, and the main source of water consumption is agricultural water. Therefore, making full use of unconventional water resources and reducing the proportion of conventional water resources will alleviate the shortage of water resources and improve the utilization of water resources (Feng, 2015).

### 2.2 Status of unconventional water resource utilization

#### 2.2.1 Development and utilization of salt water resources

The natural resources of shallow groundwater in the brackish water area of Hengshui City are 767.0694 million m<sup>3</sup>/a, of which the natural resources of shallow freshwater are 19.7963 million m<sup>3</sup>/a, and the natural resources of shallow brackish water are approximately 747.2731 million m<sup>3</sup>/a (the natural resources of salinity 1~2 g/L, 2~3 g/L, 3~5 g/L, and > 5 g/L are 119.5131 million m<sup>3</sup>/a, 285.4454 million m<sup>3</sup>/a, 238.4545 million m<sup>3</sup>/a, and 123.6564 million m<sup>3</sup>/a, respectively).

The exploitable resources of shallow groundwater in the saline water area of Hengshui City are 415.9866 million m<sup>3</sup>/a, of which the

exploitable resources of shallow fresh water are 14.8664 million m<sup>3</sup>/a, and the exploitable resources of shallow saline water are approximately 401.1202 million m<sup>3</sup>/a (the exploitable resources of salinity 1~2 g/L, 2~3 g/L, 3~5 g/L, and >5 g/L are 59.547 million m<sup>3</sup>/a, 174.0753 million m<sup>3</sup>/a, 144.4893 million m<sup>3</sup>/a, and 23.0086 million m<sup>3</sup>/a, respectively).

## 2.2.2 Development and utilization of reclaimed water resources

Since 2014, Hengshui City reclaimed the water treatment capacity will usher in a new peak of growth. However, at present, the utilization of reclaimed water is less and the utilization method is relatively single. Taking the Hengshui sewage treatment plant as an example, the annual main pollutant emission reductions amount to COD 6558 tons, BOD 2218 tons, SS 4417 tons, TN 948 tons, and TP 119 tons, and the effluent is finally discharged into the Fuyang River. The reclaimed water utilization mainly includes more than 20,000 tons of landscape water.

## 2.3 Problems in development and utilization of water resources

At present, the main problems of water resource development and utilization in Hengshui City are as follows.

### 2.3.1 Shortage of water resources

Hengshui City is located in the south of the Haihe River Basin. Since the origin of the People's Republic of China, after years of construction and development, the average annual water supply in the Haihe River Basin has been increased to 37.2 billion m<sup>3</sup>, the development and utilization rate has reached 81%, the actual water use has reached 43.2 billion m<sup>3</sup>, and the total local water resources have reached 37.2 billion m<sup>3</sup>. Due to the over-exploitation of water resources, upstream reservoir construction, and interception of runoff, it resulted in a sharp reduction in downstream rivers or cut off, which seriously affected the downstream areas of domestic, industrial, and agricultural water usage.

### 2.3.2 Serious over-exploitation of groundwater

The domestic and agricultural water in Hengshui City is dominated by groundwater. After years of exploitation, the groundwater level continues to decline, the salt-fresh water interface moves down, and the groundwater quality deteriorates.

### 2.3.3 Low utilization of water resources: an imperfect water-saving mechanism

Hengshui City is a large agricultural city, and agricultural irrigation water accounts for approximately 83% of the city's water supply. Its traditional agricultural planting structure is mainly wheat, corn, and other crops with high water consumption and low efficiency. Field irrigation is mainly flood irrigation, and the utilization rate of flood irrigation water is only approximately 45%.

### 2.3.4 Low utilization rate of unconventional water resources

The utilization rate of reclaimed water, such as the water used for farmland irrigation, urban ecology, family life, and urban

landscaping, in Hengshui is still very low. It is mainly used in urban landscaping and shows great potential for excavation. The overall utilization of rainwater in Hengshui is in the early stages of development. In addition to the demonstration collection and utilization projects built by individual units in Hengshui City, most of them are still in the blank stage, and the understanding of rainwater as a resource is not enough. With the development of urban construction, the city's hardening area is increasing and the city's permeable area is shrinking, so surface water cannot infiltrate into the ground to increase the groundwater composition. Underground pipe network construction is seriously lagging behind. Most of the pipe network construction still follows the traditional direct discharge and dredging mode, resulting in the loss of rainwater resources. The city lacks systematic rainwater utilization planning, and there are no relevant laws and regulations to provide support and guarantee for the systematic utilization of rainwater (Shadeed et al., 2020; Ge et al., 2022; Wang et al., 2022; Wu M et al., 2021). The use of brackish water in Hengshui City is relatively extensive, but it is mainly used for direct irrigation with 2~3 g/L brackish water, and 3~10 g/L brackish water and salt water still show great development potential.

## 3 Co-ordinated allocation of conventional and unconventional water resources in Hengshui City

In order to make use of the limited unconventional and conventional water resources, both the water resources can be scientifically allocated between different water use sectors of agriculture, industry, construction, tertiary industry, domestic usage, and ecological usage. This chapter uses the basic connotation of the coordinated allocation of unconventional and conventional water resources, comprehensively considering the economic development status and planning of the study area, and focuses on the following principles when incorporating unconventional water resources into the unified allocation of water resources.

### 3.1 Principles of collaborative optimal allocation of water resources

#### 3.1.1 Principles of water supply by quality

Although it is currently technically feasible to purify unconventional water resources to drinking water, considering other issues, such as production costs, potential risks, and social acceptance, unconventional water resources need to be used for other purposes other than drinking water, such as urban ecology, industry, and agriculture (Jodar-Abellan et al., 2019; Ge et al., 2020a; Zhang Y et al., 2022). Therefore, according to the water demand of different users, it is necessary to carry out targeted quality water supply, high quality and excellent use.

#### 3.1.2 Principles of water safety

The water security principle is mainly reflected in two aspects: one is to give priority to meet the domestic and ecological water demands, on this basis, considering the rational allocation of

construction, tertiary industry, and industrial and agricultural water. Second, considering the stability and efficiency of the water supply guarantee rate, surface water is preferentially supplied for domestic, industrial, and agricultural usage, followed by the exploitation of groundwater (Ge et al., 2020b). The treatment cost of unconventional water resources is also much smaller than the corresponding water transfer cost. Therefore, the principle of controlling groundwater exploitation and expanding the scale of unconventional water resource utilization is adhered to, and the water supply order of each water source is defined as follows: reclaimed water, mine drainage water, surface water, and groundwater (Kim et al., 2022; Mu and Wang, 2020).

## 3.2 Establishment of the collaborative optimal allocation model of water resources

### 3.2.1 Objective function

For optimal allocation of water resources, the minimum relative water shortage rate is generally selected as the objective function, but the objective is a cumulative value, which cannot reflect the depth of water supply damage and the quality of the water supply process. According to the uniformity of water distribution in time and space, the storage capacity of water conservancy projects can be fully exerted. In the calculation period T, the water supply process with time and space uniformity is selected as the objective function of water supply scheduling, that is, the maximum water shortage rate in a certain period of the water supply process is the minimum. The objective function is

$$f(x) = \min \max_t [(Q_t - G_{0,t} - X_t)/Q_t]. \tag{1}$$

In the formula,  $Q_t$  is the water demand of the water supply area in the period  $t$ ;  $G_{0,t}$  is the conventional water supply of the water supply area in the period  $t$ ;  $X_t$  is the water supply of unconventional water in the period  $t$ ;  $t = 1, 2, \dots, T$ , where T is the number of water supply periods.

The model of the minimum–maximum water shortage rate can make the water supply process and water shortage loss in the water supply area uniform so that the water shortage in a certain period is not very serious in order to meet the water demand of the previous period, which can reduce the damage depth of water shortage, improve the uniformity of the water supply process, and effectively reduce the maximum damage depth (Li et al., 2018).

### 3.2.2 Constraint conditions

#### 3.2.2.1 Water supply condition constraints

The supply of water resources shall not exceed the total supply of water resources; the expressible formula is

$$\sum_{k=1}^{\sigma} \sum_{i=1}^m \sum_{j=1}^n x_{ij}^k \leq W_s. \tag{2}$$

In this formula,  $W_s$  is the total supply of water resources, 10,000 m<sup>3</sup>;  $x_{ij}^k$  is the water supply of the  $i$  water source to  $j$  users in  $k$  area;  $k$  is the water supply area, a total of  $\sigma$ ;  $i$  is the source of water supply, including surface water, groundwater, reclaimed water, mine drainage water, and brackish water, a total of  $m$ ;  $j$  for different users,

including life, tertiary industry, industry, agriculture, construction, and ecology, a total of  $n$ . Because the surface water and groundwater in the available water resources are conventional water resources, it is necessary to pay attention to conservation. The total amount of available surface water and groundwater cannot exceed the red line of the total amount control of surface water and groundwater in Hengshui while not exceeding the calculated available water.

#### 3.2.2.2 Unconventional water supply constraints

$$h^k \leq \frac{x_{3j}^k + x_{4j}^k + x_{5j}^k}{\sum_{i=1}^m x_{ij}^k} \leq H^k. \tag{3}$$

In this formula,  $x_{3j}^k$ ,  $x_{4j}^k$ , and  $x_{5j}^k$  are the water supply of reclaimed water, mine drainage water, and brackish water to  $j$  users, respectively. Taking into account the principle of water supply and water supply network constraints, domestic water and tertiary industry water do not consider unconventional water;  $h^k$  and  $H^k$  are the minimum and maximum water supply ratios of unconventional water resources of  $j$  users in  $k$  area, respectively.

#### 3.2.2.3 Contamination carrying capacity constraints

COD emissions should not be greater than the regional COD capacity; the expressible formula is

$$\sum_{j=1}^n 0.01d_j p_j \sum_{i=1}^m x_{ij}^k \leq \theta^k COD. \tag{4}$$

In this formula,  $\theta^k COD$  is the maximum COD capacity in  $k$  region,  $t$ .

#### 3.2.2.4 Effective irrigation area constraint

The water consumption of the irrigation area in the same level year should be higher than the predicted water consumption of the low scheme but lower than the predicted water consumption of high scheme; the expressible formula is

$$N_1^k C^k \leq x_g^k \leq N_2^k C^k. \tag{5}$$

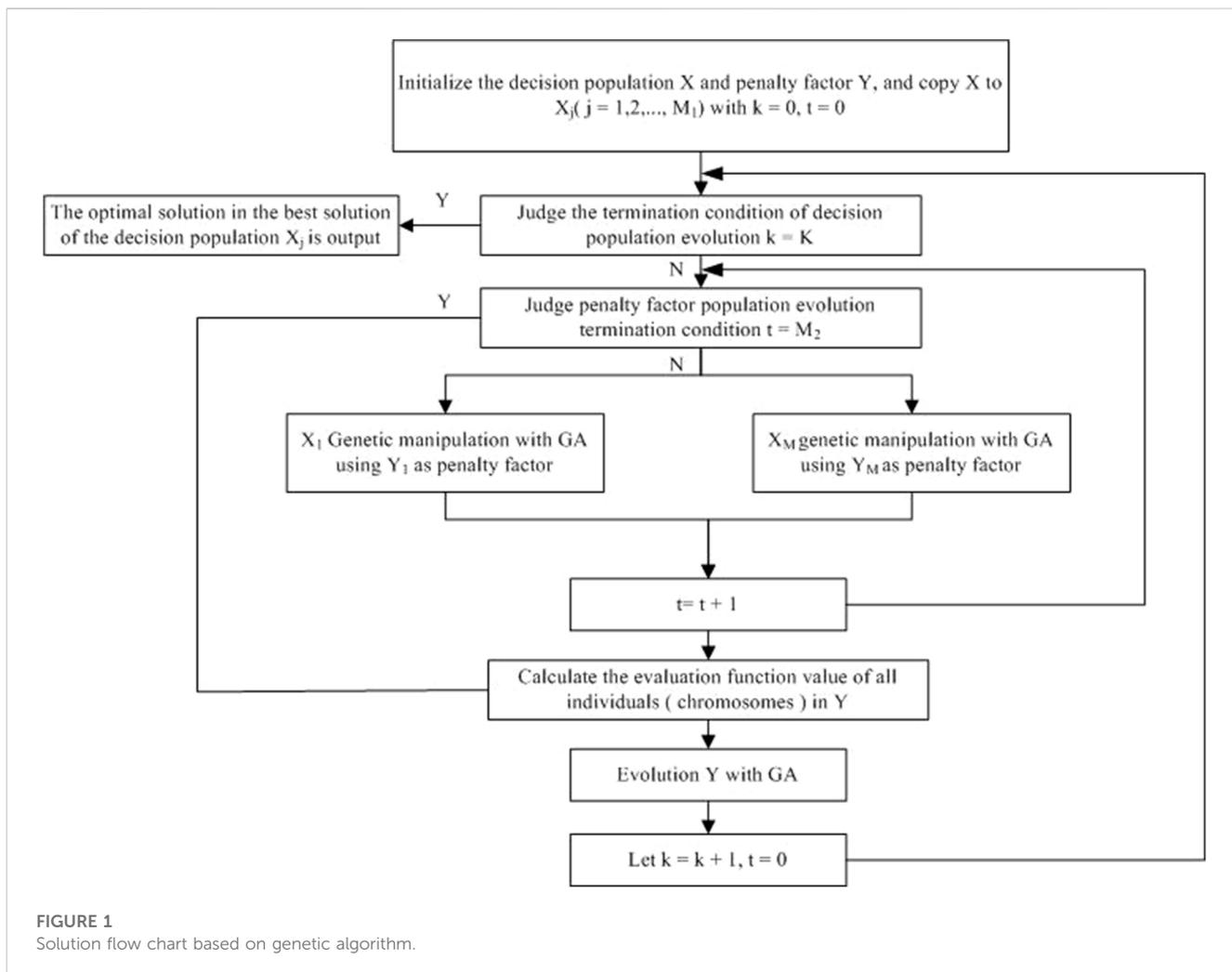
In this formula,  $N_1^k$  and  $N_2^k$  are the predicted values of the effective irrigation area of low scheme and high scheme in the  $k$  region, respectively, km<sup>2</sup>;  $C^k$  is the water requirement per unit effective irrigation area in the  $k$  region, 0.01m, referencing to the Gansu Province water quota value;  $x_g^k$  is the irrigation water consumption to  $k$  area, 10,000 m<sup>3</sup>, and  $x_g^k$  is contained in agricultural water.

#### 3.2.2.5 Tertiary industry output value constraint

The output value of the tertiary industry in the planning year should be greater than the planning value target; the expressible formula is

$$\sum_{k=1}^{\sigma} \sum_{i=1}^m x_{i3}^k \cdot \alpha_{i3}^k \geq 10^4 Z_3. \tag{6}$$

In this formula,  $x_{i3}^k$  is the water supply of the tertiary industry in the  $k$  region, 10000 m<sup>3</sup>;  $\alpha_{i3}^k$  is the economic output value of unit water resources of the tertiary industry in the  $k$  region, yuan/m<sup>3</sup>;  $Z_3$  is the tertiary industry output value planning target, 100 million yuan.



### 3.2.2.6 Non-negative constraint

Water supply is non-negative; the expressible formula is

$$x_{ij}^k \geq 0. \quad (7)$$

## 4 Model solution of collaborative optimal allocation of water resources

The genetic algorithm (GA) was first proposed by Professor Holland of Michigan University in 1975. The basic idea was based on Darwin's theory of evolution and Mendel's theory of genetics. The recombination and mutation operators were the two most important components of GA, and they were repeatedly applied to the chromosomes formed by encoding the solution of the problem. This is a new global optimization search algorithm, simple and universal, robust, and suitable for parallel processing; based on the fitness function, the genetic operation is applied to the individuals in the group to realize the reorganization of the individual structure in the group so that the individuals in the group can be optimized and gradually approach the global optimal solution. It can calculate multidimensional problems in optimal allocation of water resources.

In this paper, a set of basic feasible decoding of the problem is expressed as a set of binary strings. Each string contains multiple substrings. The combination of one or more bits of each substring is called a gene, also known as a chromosome. Then, some operations are carried out on these genes (chromosomes) to gradually realize parameter optimization and achieve the purpose of optimal allocation of water resources.

At the beginning of the genetic algorithm, some individuals (initial solutions) are randomly generated; each individual is evaluated according to the predetermined objective function (1), and the fitness value of the individual is given. Based on the fitness value, the individual is selected to copy the next generation. The selection operation embodies the "survival of the fittest" principle, in which "good" individuals are selected for replication and "bad" ones are eliminated. Then, the selected individuals are recombined by exchange and mutation operators to generate a new generation. This new group of individuals inherits some of the good traits of the previous generation and is therefore superior in performance. The genetic algorithm realizes the process of optimal allocation of water resources by simulating the three ways of replication, exchange, and mutation of biological genes. The specific process is shown in Figure 1. The specific steps are as follows:

**TABLE 1** Statistics on water supply in counties and districts of the Hengshui City in 2020 unit: 10<sup>4</sup> m<sup>3</sup>.

County name	Groundwater				Surface water				External water diversion	Waste water reuse	Total
	Deep well	Shallow well	Brackish water	Subtotal	Water diversion project	Electro mechanical site	Water storage project	Subtotal			
Taocheng District	1762.15	73.05	78.49	1913.69	1549.84	0.00	1778.17	3328.01	7221.13	306.32	12769.15
Jizhou City	2461.57	319.58	89.09	2870.24	2239.46	3951.40	982.04	7172.90	2434.12	334.27	12811.52
Zaoqiang County	3550.94	1934.27	0.00	5485.21	5741.55	0.00	0.00	5741.55	3702.11	0.00	14928.87
Wuyi County	3446.85	761.19	152.96	4361.00	1411.98	0.00	5660.63	7072.61	991.39	727.11	13152.11
Shenzhou City	3931.07	1950.99	0.00	5882.06	24302.7	0.00	0.00	24302.71	811.33	323.97	31320.07
Wuqiang County	3667.01	0.00	0.00	3667.01	1493.24	0.00	4195.47	5688.71	293.19	88.74	9737.65
Raoyang County	3167.32	667.83	0.00	3835.15	5456.48	0.00	653.24	6109.72	351.66	169.04	10465.57
Anping County	3019.41	2732.15	59.69	5811.25	77.56	0.00	5191.62	5269.18	310.37	0.00	11390.81
Gucheng County	1622.96	1598.84	308.47	3530.27	4573.24	0.00	1239.99	5813.23	1842.97	1016.76	12203.23
Jing County	5251.99	874.29	0.00	6126.28	5949.23	0.00	0.00	5949.23	5367.03	1010.61	18453.15
Fucheng County	5860.25	493.47	0.00	6353.72	7825.15	0.00	1243.85	9069.00	1776.72	605.69	17805.13
New industrial district	85.27	22.65	21.97	129.89	0.00	0.00	0.00	0.00	1745.02	901.49	2776.40
Lakeside new district	385.82	19.68	11.01	416.51	0.00	165.80	189.80	355.60	735.76	0.00	1507.87
Whole city	38212.60	11447.9	721.68	50382.26	60620.4	4117.20	21134.8	85872.45	27582.79	5484.00	169321.50

**TABLE 2** Statistical table of water supply in counties and districts of Hengshui City in 2022 unit:  $10^4 \text{ m}^3$ .

County name	Groundwater				Surface water				External water diversion	Waste water reuse	Total
	Deep well	Shallow well	Brackish water	Subtotal	Water diversion project	Electro mechanical site	Water storage project	Subtotal			
Taocheng District	2321.88	71.27	262.70	2655.85	2570.03	0.00	2078.16	4648.19	9448.26	365.35	17117.6
Jizhou City	1584.46	274.28	271.40	2130.14	2637.53	4511.66	800.83	7950.02	4583.22	398.69	15062.1
Zaoqiang County	2285.66	1660.06	0.00	3945.72	5534.36	0.00	0.00	5534.36	9021.24	0.00	18501.3
Wuyi County	2211.76	636.12	449.75	3297.63	6861.26	0.00	2629.96	9491.22	1835.78	867.17	15491.8
Shenzhou City	1530.41	1686.64	0.00	3217.05	21054.12	0.00	876.45	21930.57	9227.59	388.88	34764.1
Wuqiang County	2060.38	0.00	0.00	2060.38	1985.22	0.00	6066.78	8052.00	875.12	105.83	11093.3
Raoyang County	2038.73	573.15	0.00	2611.88	7513.17	0.00	868.46	8381.63	688.83	201.60	11883.9
Anping County	784.91	2173.18	0.00	2958.09	6941.12	0.00	2482.28	9423.40	607.96	0.00	12989.4
Gucheng County	1044.66	1372.18	643.90	3060.74	6079.98	0.00	775.19	6855.17	4317.84	1212.65	15446.3
Jing County	3380.59	750.35	0.00	4130.94	7254.04	0.00	0.00	7254.04	10512.99	1205.32	23103.3
Fucheng County	4093.95	423.51	0.00	4517.46	8475.56	0.00	3522.06	11997.62	3480.26	722.36	20717.7
New industrial district	376.72	19.44	184.22	580.38	226.91	0.00	0.00	226.91	1570.71	1075.16	3453.16
Lakeside new district	248.34	16.89	42.15	307.38	0.00	189.32	900.01	1089.33	695.10	0.00	2091.82
Whole city	23962.47	9657.08	1854.12	35473.67	77133.29	4700.98	21000.2	102834.4	56864.89	6543.00	201716

TABLE 3 List of unconventional water resource growth in 2025 unit:  $10^4 \text{ m}^3$ .

	Year 2020	Year 2025	Increment
Brackish water	721.68	1854.12	1132.44
Sewage reuse	5484	6543	1059
Total	6205.68	8397.12	2191.44

- Step 1: Individual coding: Taking the amount of water distributed to each user as the decision variable  $Z$ , the decision variables are coded and a feasible solution set is formed.
- Step 2: Initializing the decision population and penalty factor population: The algorithm parameters are assigned, several sets of initial water resources pre-allocation schemes are randomly generated, and some relatively better allocation schemes are selected as the initial scheme set for the next optimization. The population size is  $L_1$ , and  $L_2$  copies are  $M$  populations. Taking  $w_1$  and  $w_2$  as penalty factors, the population  $Y$  with  $L_2$  penalty factors is randomly generated, where  $Y_j = (w_{1j}, w_{2j}) (j = 1, 2, \dots, L_2)$ .
- Step 3: Formula (1) is used as the fitness function to evaluate the advantages and disadvantages of each individual in the population.
- Step 4: Genetic operations of decision population and penalty factor population: For each sub-population  $Z$  in the decision population  $M$ , the individuals with the same number in the population  $Y$  are used as penalty factors, and the GA algorithm is used to evolve until the number of iterations is set. The GA algorithm is used to evolve the next generation of population  $Y$  so as to obtain a new penalty factor population  $Y$ .
- Step 5: Iterations of the algorithm: After the end of the first generation co-evolution, Step 4 is repeated, until the convergence criterion of the algorithm is reached.
- Step 6: Output of the optimal solution. By comparing all the historically best solutions obtained in the population  $M$ , the optimal solution is output as the final solution and the optimal individual in the population  $Y$  is the optimal penalty factor.

## 5 Calculation results and analysis

Based on the present situation of water resource development and utilization in counties and cities of Hengshui City, the conventional and unconventional water resources between 2020 and 2025 are allocated accordingly. Among them, the water supply situation of counties and districts in Hengshui City in 2020 is as shown in Table 1; the water supply of each county in Hengshui in 2025 is shown in Table 2. Among them, the basic data from 2020 are derived from the “Hengshui City Water Resources Bulletin,” and the basic data for 2025 are predicted based on a large amount of data. Due to the limited space, this paper does not elaborate on the prediction model.

The growth of unconventional water resources in 2025 is shown in Table 3; the proportion of conventional and unconventional water resources between 2020 and 2025 level years is shown in Figures 2, 3.

Analysis of water supply and water use in counties and cities of Hengshui City in the 2025 level year shows that according to the configuration results in Table 2, from the perspective of each user, it can be seen that the water supply and demand in counties and cities of Hengshui City in the 2025 level year is relatively balanced. Compared with other water use sectors, the agricultural sector has the largest water demand. In order to avoid the contradiction between supply and demand of water resources, strengthening agricultural water conservation will be the focus of future work.

From the perspective of water supply sources, the water supply ratio of groundwater, surface water, external water transfer, and unconventional water will be 29%, 51%, 16%, and 4% after the allocation of counties and districts in Hengshui City in 2020 (Figure 2); In 2025, the proportion of groundwater, surface water, external water transfer, and unconventional water supply in each county of Hengshui City is 17%, 51%, 28%, and 4%, respectively (Figure 3). Compared with the 2020 level year, surface water will still remain the largest source of water supply in Hengshui City; by 2025, groundwater consumption will continue to decrease, and the amount of water supply for external water transfer will increase. According to Table 3, compared with the 2020 level year, the total amount of unconventional water resources in Hengshui City will increase by the 2025 level year, with an

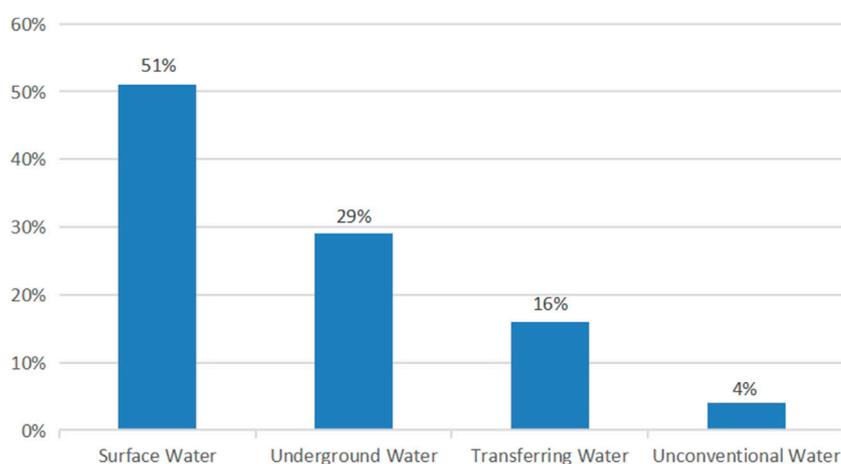
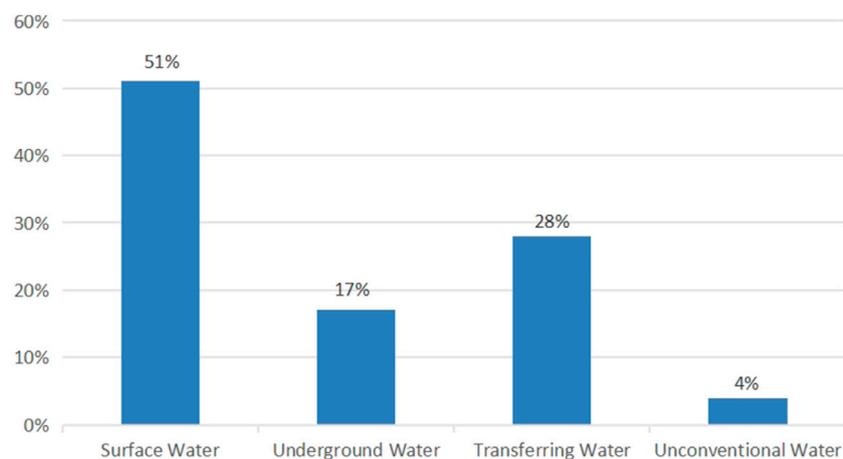


FIGURE 2  
Proportion of water resources allocation in Hengshui City in 2020.



**FIGURE 3**  
Proportion of water resources allocation in Hengshui City in 2025 level year.

increase of 21.9144 million  $m^3$ , of which the increase in brackish water consumption would be 11.3244 million  $m^3$ , and the increase in sewage reuse water consumption will be 10.59 million  $m^3$ .

## 6 Conclusion

The North China Plain is an important grain, cotton, fruit, and vegetable production base in China. The grain production accounts for 29.6% of the total grain production in the country, and the vegetable production accounts for 42.7% of the national vegetable production. The area uses less than 1/2 of its total arable land to produce 80% of vegetables, 65% of grain, and 60% of economic crops. However, the climate in this area is dry and rainy, and the water resources are scarce. The *per capita* water resources are 523  $m^3$ , and the average water resources are 309  $m^3$ , which are 1/4 and 1/5 of the national average, respectively. The combination of water resources, population, and cultivated land is extremely unbalanced, making this area a serious water shortage area in China. Long-term groundwater over-exploitation has formed a groundwater “funnel group” consisting of a series of funnels with an area of 40,000  $km^2$  in the Hebei Plain, causing a series of ecological and geological hazards, such as land subsidence and collapse. The shortage of water resources has become an important bottleneck, restricting the economic and social development of the North China Plain and national food security. Therefore, this study takes Hengshui City as an example to study the coordinated allocation of water resources between conventional and unconventional water resources. The results show that from the perspective of each user, the water demand of each county and city in Hengshui City will be guaranteed in 2025, and there will be no water shortage. From the perspective of each user, the water supply and demand of each county and city in Hengshui City will be relatively balanced by 2025. Compared with other water use sectors, the agricultural sector has the largest water demand. In order to avoid the contradiction between supply and demand of water resources, strengthening agricultural water saving and inhibiting water demand will be the focus of future work. The planned use of unconventional water resources, such as reclaimed

water and rainwater, is a good way to turn waste water and sewage into resources, which is a feasible way to effectively alleviate the imbalance between supply and demand of water resources; the coordinated allocation of conventional water and unconventional water resources can maximize the comprehensive benefits of society, economy, and ecological environment.

## Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

## Author contributions

Conceptualization: QC and WH; methodology: QC; software, WH; validation: WH, ZD, and FW; formal analysis: ZD; investigation: FW and ZD; data curation and writing—original draft preparation: FWu; writing—review and editing: WH; supervision: FWu. All authors contributed to the article and approved the submitted version.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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