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Optimal Allocation of Water Resources Based on GWAS Model in Handan, China

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Abstract: Optimal allocation of water resources is an effective way to solve the supply and demand contradiction between water resources and water users. Recently, the rapid economic and social development of Handan has significantly increased water demand in various industries. Superimposed on the reduction of incoming water in upstream rivers and the limitation of the total amount of groundwater extraction, a large number of water sources such as South-to-North Water Diversion, Yellow River Water Diversion, and Weihe River Water Diversion are used to replace domestic and industrial water. In support of Handan's dynamic supply and demand of water resources, the transported water was generalized as a virtual reservoir and introduced into the GWAS model. The allocation results show that the total water shortage volume and rate of Handan was 527.60 $\times$ 10^6 m^3 and 17.92% in 2025 at a P = 50%, respectively. Water shortage was concentrated in the primary industry. The allocation results align with actual water use conditions. The allocation of transported water is more reasonable than the conventional allocation scheme, and the domestic water is completely replaced by the South-to-North Water Diversion in the eastern plain of Handan. These research results can provide a technical reference for water resource allocation in Handan.

Keywords: water resource; supply versus demand; optimal allocation; GWAS model; Handan

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1. Introduction

China's total water resources are 2.8 trillion m^3, accounting for 6% of the global water resources, ranking fourth in the world. However, the per capita water resources are only 2300 m^3, which is only a quarter of the world average level, ranking 110th in the world, and listed by the United Nations as one of the 13 countries with the poorest per capita water resources in the world [1,2]. With the rapid development of China's economy and society, the demand for water in various industries has increased significantly. Simultaneously, with the frequent occurrence of water pollution incidents, the contradiction between the supply and demand of water resources has become increasingly prominent. Therefore, the rational and effective allocation of limited water resources and ensuring the normal development of the national economy to the greatest extent is an important issue in water resource research [3,4].

The optimal allocation of water resources is an important means of solving the contradiction between the production and life of human society and the supply and demand of water resources. Scholars have conducted research aimed at water resource problems that arise in different stages by studying water resource allocation methods and models under the framework of the theoretical system of water resource optimal allocation [5]. In 1962, Professor Maass systematically expounded on the connotation of water resources in his book *Design of Water Resource Systems* and explained the feasibility of using computer technology to construct a sub-model of a water resource system [6]. With the development of the mathematical programming theory, large-scale system decomposition, and coordination theory, many scholars have used the analytic hierarchy process, linear, stochastic, dynamic, and fuzzy programming, or a combination of multiple methods to establish optimal allocation models for water resources with different functions [7–14]. Multi-objective programming (MOP) is widely used in studying the optimal allocation of water resources to solve the problem of coordinated development of water resources and complex systems such as society and the economy. MOP is widely used in the ecological allocation of water resources [15–18]. In 1987, the concept of sustainable development was formally proposed by the United Nations World Commission on Environment and Development [19,20]. Since then, taking social, economic, and ecological benefits as objectives, and taking into account constraints such as regional geographic characteristics, climate change, demand for water resource management, water quantity, water quality, and water conservancy projects, the concept of sustainable development reflects the multi-objective allocation of water resources [21–24]. Wang et al. [25] proposed a theory for the optimal allocation of regional water resources based on macroeconomics. Furthermore, Chang et al. [26] used macroeconomic methods to study the rational allocation and optimal dispatch of water resources in the Yellow River Basin. This approach is based on the principles of sustainable development. In addition, Feng et al. [27,28] proposed a theoretical framework for sustainable utilization planning of new water resource systems. Huang et al. [29] established a deterministic multi-objective optimization model for the joint deployment of multiple water sources using systematic scientific methods and proposed solution ideas and methods for the multi-objective optimization model, laying a theoretical foundation for the optimal dispatching of urban water supply sources.

In terms of water resources optimal allocation models, scholars have developed models such as OOGIS, Waterware, Aquarius, ICMS, WMS, WROOM, MIKEBASIN, and WEAP [30]. Among them, MIKEBASIN and WEAP have been the most widely used. MIKEBASIN [31] is an integrated decision support software for basin water resources planning and management developed by the Danish Water and Environment Institute (DHI). MIKEBASIN takes the river system as the backbone, projects, users, and catchment points as nodes and corresponding hydraulic connections, constructs a watershed system diagram, and realizes dynamic simulation with the systems established by users and the corresponding attributes of select objects [32]. The model has been applied in water resource planning and management for several watersheds and regions [33–35]. While MIKEBASIN had achieved good results across many areas, it was not effective in areas with strong human activities [36,37]. The WEAP model [38] was developed by Raskin in 1992. Yates et al. [39] improved the WEAP model in 2005 and put forward the integrated water resource management model WEAP21. The reliable design principle and good GUI interface of the model provided convenience for researchers to construct a model network. Many researchers had applied it to river basins or regional water resource planning and management [40–44]. However, the WEAP model was demand-driven. If there were no crops in the winter farmland, the WEAP model could not directly generate irrigation water demand. This did not meet the requirements for winter irrigation in northern China. Although the latest version of the WEAP model had been adjusted to solve this problem, the setup process was tedious [45]. In addition, reservoirs operated according to water demand in the WEAP model, which may cause the simulated operation of the reservoir to be inconsistent with the actual situation [46,47].

In 2019, Sang et al. [48] developed a water resources simulation and allocation system model software platform, the GWAS model, where the second-generation non-dominated sorting genetic (NSGA-II-S) algorithm with elitist strategy is embedded in the model for model solving [49]. The GWAS model has the advantages of a high degree of interface visualization, strong operability, and convenient data management and has been used by many water resource researchers in studying water resource allocation in different regions and basins [50–58]. However, when dealing with water distribution through manual water diversion channels, GWAS cannot follow the water distribution principle of natural rivers from upstream to downstream and can only distribute water according to a fixed distribution scheme. The result of water distribution cannot be adjusted dynamically according to actual water demand.

With the rapid social and economic development in Handan, the demand for water resources in different industries has increased significantly, and the contradiction between the supply and demand of water resources in Handan is very prominent. Since 2014, a comprehensive control project for groundwater overexploitation has been implemented which has limited the scale of regional groundwater exploitation, and new construction of a water diversion project from the Yellow River was finished. Simultaneously, after 2018, the South-to-North Water Diversion gradually replaced domestic and industrial water in the eastern plains of Handan, and the form of the water supply has undergone major changes. Making good use of the South-to-North Water Diversion, flexible use of Yellow River transferred water, and limiting groundwater exploitation are new problems facing water resource management in Handan. Therefore, this study used the GWAS model to study the rational allocation of water resources in Handan in the new era. In the process of model construction, the conception of virtual reservoirs was added to the model, and the South-to-North Diversion Water, Yellow River Transferred Water, Weihe River Transferred Water, and Yuefeng Channel Transferred Water were generalized as virtual reservoirs, which made the transported water project have dynamic regulation characteristics and capacity.

2. Materials and Methods

2.1. The GWAS Model: Computational Unit Division

The establishment of the GWAS model [59] first requires the division of hydrological calculation units, which are mainly obtained by the nested division of water resources and administrative divisions. The model needs to input the reservoir, river system, water resources basin zoning, and administrative area layers. These layers must have the same projected coordinate system. The GWAS model automatically identifies the geographical information characteristics of the water resource and administrative divisions in the research area and then generates and extracts basic hydrological calculation units according to the principle of GIS superposition and division.

2.2. Establishing the Topological Relationship between Water Supply and Consumption

The GWAS model needs to manually establish the topological relationship of the water supply based on actual river reservoir conditions, water user distribution, and hydraulic engineering facilities in the study area. The topological relationship of water supply includes three parts: reservoir–reservoir, reservoir–unit, and unit–unit relationships. The reservoir–reservoir relationship indicates that the reservoir supplies water to another reservoir, and the water supply relationship is established according to whether there is a channel or an upstream–downstream connection relationship between the reservoirs. The reservoir–unit relationship indicates that the reservoir supplies water to the hydrological calculation unit and is established according to the actual water supply route and water supply objects of the reservoir. The unit–unit relationship represents the confluence relationship or drainage relationship between units in the study area and is established according to the upstream and downstream relationships of the river system and the connection relationship of the channel system in the study area.

2.3. Model Building

GWAS builds a multi-objective water resource optimal allocation model with a minimum load-balancing objective function and a spatial equilibrium objective function [48]. The load-balancing object is reflected by the minimum index of the industry water shortage rate, which can indicate the degree of satisfaction of industrial water demand within the calculated unit. The spatial equilibrium object is reflected by the variance index of the water scarcity rate in industrial spatial units, which is expressed as the fairness of water use in the different units of each industry. The smaller the final result of the model output, after the two objective function values are weighted by the fairness coefficient and the water shortage rate coefficient, the stronger the global optimization ability.

2.3.1. Objective Function

(1) Load-balancing object:

$$\min L(x_t) = \sum_{i=1}^{m} q_i \cdot SW(x_{it}) \tag{1}$$

$$SW(x_{it}) = \frac{1}{N} \cdot \sum_{n=1}^{N} \mid (x_{it}^n - Sob_{it}) \mid \tag{2}$$

where $L(x_{it})$ is the load balance target; $SW(x_{it})$ is the water supply stress function; q_i is the industry user penalty coefficient; x_{it} is the total water shortage rate of the unit i in the period t; x_{it}^n is the water shortage rate of the industry user i in the unit n in the period t, $0 \leq x_{it}^n \leq 1$; Sob_{it} is the ideal value of the water supply stress target of the regional industrial user i in the period t, $0 \leq Sob_{it} \leq 1 - B_i$; B_i is an empirical parameter representing the minimum water guarantee rate of the regional industrial user i, and B_i= 0.8; i is the type of regional industrial water user; m is the maximum number of regional industrial water user types; n is the regional unit; N is the maximum number of regional units; t is the calculation period.

(2) Spatial equilibrium object:

$$\min S(x_t) = \sum_{i=1}^{m} q_i \cdot GP(x_{it}) \tag{3}$$

$$GP(x_{it}) = \sqrt{\frac{1}{N} \cdot \sum_{n=1}^{N} (x_{it}^n - \overline{x}_{it})^2} \tag{4}$$

where $S(x_t)$ is the spatial balance function; $GP(x_{it})$ is the fairness function; $\overline{x}_{it}$ is the average water shortage rate of industry users of district and county in the period t;$0 \leq \overline{x}_{it} \leq 1$; and the remaining symbols are the same as above.

2.3.2. Restrictions

(1) Water supply capacity constraint: The allocated water volume of the water source should be less than or equal to the available water volume of the water source.

$$W_{hi}^n \leq Q_h^n \tag{5}$$

where W_{hi}^n is the water supply of industry users i from the water source h to unit n and Q_h^n is the available water resource from the water source h to the unit n.

(2) Water demand constraints. The water demand of each unit shall be between the corresponding maximum and minimum water demand.

$$Q_{i\,\min}^n \leq \sum_{h=1}^{u} W_{hi}^n \leq Q_{i\,max}^n \tag{6}$$

where $Q_{i\,\min}^n$ and $Q_{i\,max}^n$ are the maximum and minimum water demand of unit n in each industry i, respectively; u represents the total number of water source types.

(3) Water transport capacity constraints. The total water supply of each source shall not exceed the upper limit of the water transfer capacity of the source:

$$W_{hi}^n \leq Q_{h\,max}^n \tag{7}$$

where $Q_{h\,max}^n$ is the upper limit of the water transmission capacity of water source h to supply water to each unit n.

(4) Ecological flow constraints: River flow should meet the constraints of the river's ecological base flow:

$$Q_{r,t} \leq Q_{rob,t} \tag{8}$$

where $Q_{r,t}$ is the flow of the river course during the period t; $Q_{rob,t}$ is the minimum water consumption of the river course during the period t, that is, the ecological base flow of the river course.

2.3.3. Configuration Parameters

The allocation parameters of GWAS include the distribution ratio coefficient of water sources in the industry and the optimal allocation parameters. The distribution ratio coefficient of water sources in the industry is a ratio of the water supply quantity to the water demand quantity. It can represent how much of the total water demand of each industry belongs to this type of water source. Optimized allocation parameters include the industry weight coefficient, water shortage rate weight coefficient, and fairness weight coefficient. The numerical value of the industry weight coefficient reflects the degree of social and economic harm caused by water shortages for each industry. The water shortage rate weight coefficient and fairness weight coefficient are a medium to link the spatial equalization objective and the load equalization objective, and can be set according to the water resource manager's preference.

2.3.4. Solution Method

The model is solved using the second-generation non-dominated sorting genetic (NSGAII-S) algorithm with an elitist strategy. For multi-objective problems, the traditional genetic algorithm assumes that the importance weights of multiple engineering objectives are the same, which is inconsistent with reality. The NSGA-II algorithm is used to solve multi-objective problems. After the continuous evolution of the crossover and mutation mechanisms of the genetic algorithm, a non-dominated subset with a Pareto front can be obtained, but it easily falls into a local optimum. In this study, the expert experience was used to select the optimal genetic seed, intervening in the mating strategy of the genetic algorithm such that the genetic algorithm without a mechanism can be explained mechanically. It not only maintains the solution advantages of the NSGA-II algorithm but also shortens the calculation time, effectively solves the dimensionality problem, and improves the calculation efficiency.

2.4. Case Study

2.4.1. Study Area

Located in the south of Hebei Province, Handan has 18 administrative districts under its jurisdiction with a total area of 12,047 km^2 and a permanent population of 9.416 million. Handan is in a semi-humid and semi-arid continental monsoon climate zone in the warm temperate zone. The annual average temperature is 12.5–14.2 °C, the annual sunshine hours are 2300–2780 h, the frost-free period is 194–218 days, the annual average precipitation is 537.6 mm, and the annual average water surface evaporation is 1157.9 mm. The terrain of Handan is high in the west and low in the east, sloping from the southwest to the northeast. As shown in Figure 1, the main rivers in Handan are the Qingzhang, Zhang, Beiming, Ming, Fuyang, Liulei, Laosha, Wei, and Majia rivers. The main water conservancy engineering facilities include the two large-scale reservoirs Dongwushi Reservoir and Yuecheng Reservoir, and six medium-sized reservoirs, Qingta, Chegu, Maolingdi, Koushang, Siliyan, and Damingyuan. The main water supply channels are the Yuefeng, Minyou, Dongfeng, Mingyou, and Weixi channels. The middle route of the South-to-North Water Diversion Project runs through the junction of the western mountainous area and the eastern plain area of Handan. The Yellow River Water Diversion Project enters from Weixian and flows out from Quzhou.

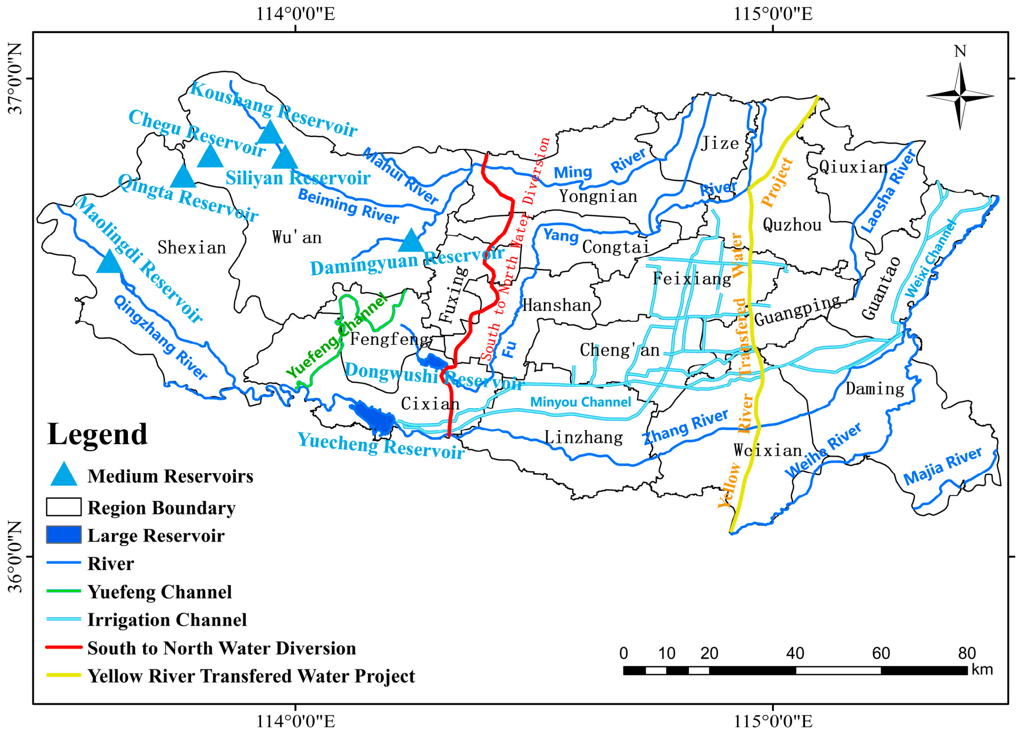

Figure 1. Distribution of water systems, water conservancy projects, and administrative divisions in Handan.

2.4.2. Water Demand Forecasting

This study takes 2019 as the base year; according to the Handan Statistical Yearbook [60], it is based on the long-term development plan of Handan and the water consumption quota of Hebei Province (DB 13/T 5448.1-2021), and uses the water quota forecasting method to predict the water demand of different industries in various administrative districts of Handan by 2025. The prediction results are presented in Table 1. Under the guaranteed rate of P = 50%, the total water demand in Handan is 2943.89 $\times$ 10^6 m^3, of which the total domestic water demand is 360.84 $\times$ 10^6 m^3, the total ecological water demand is 206.28 $\times$ 10^6 m^3, the total water demand for the primary industry is 1939.82 $\times$ 10^6 m^3, the total water demand of the secondary industry is 211.43 $\times$ 10^6 m^3, and the total water demand of the tertiary industry is 225.52 $\times$ 10^6 m^3.

Table 1. Forecast results of water demand of different industries in Handan in 2025 (P = 50%; 10^6 m^3).

Subregion	Domestic	Ecology	Primary Industry	Secondary Industry	Tertiary Industry	Total
Shexian	16.75	9.83	25.00	10.21	11.49	73.28
Wu'an	32.14	17.02	154.29	61.39	30.22	295.06
Cixian	18.32	9.70	60.07	3.64	6.32	98.05
Fengfeng	17.41	11.11	20.29	16.38	9.35	74.54
Hanshan	29.45	19.66	90.33	10.54	23.20	173.18
Fuxing	16.07	11.24	21.62	17.37	13.37	79.67
Congtai	33.49	25.31	33.33	19.76	35.32	147.21
Yongnian	31.80	16.84	188.05	14.18	12.82	263.69
Linzhang	21.34	10.64	173.66	6.78	9.47	221.89
Cheng'an	14.63	7.74	104.84	10.02	8.37	145.60
Weixain	28.91	15.31	228.10	10.91	11.13	294.36
Feixiang	13.73	7.27	136.86	5.16	11.41	174.43
Guangping	10.26	5.43	69.65	3.88	6.60	95.82
Quzhou	15.92	7.73	103.79	6.33	6.89	140.66
Daming	29.56	15.65	271.03	3.70	9.94	329.88
Guantao	11.97	6.34	92.77	2.48	8.05	121.61
Jize	10.21	4.76	83.55	4.62	5.85	108.99
Qiuxian	8.88	4.70	82.59	4.08	5.72	105.97
Total	360.84	206.28	1939.82	211.43	225.52	2943.89

2.4.3. Prediction of Available Water Supply

The water supply sources of Handan include groundwater, reclaimed water, water diversion from the South-to-North Water Diversion, Yellow River transferred water, Weihe River transferred water, the Yuefeng Channel, and reservoir water. The available supply of groundwater was taken from the Third Water Resources Evaluation in Handan [61,62]. The available supply of recycled water was predicted based on urban domestic and industrial water usage. The South-to-North Water Diversion Project was predicted based on the results of the Supporting Project Planning of Handan of Hebei Province's South-to-North Water Diversion Project (Middle Line) [63]. The available water supply of the Yellow River Diversion Project in Handan and the Yellow River Diversion Project in Hebei Province were used for the prediction. The available water supply of the Weihe River diversion, Yuefeng Channel diversion, and reservoir water was predicted by the distribution and utilization of surface water in Handan [64]. Table 2 shows the predicted results of the water supply with a P = 50% guarantee rate in different administrative regions of Handan in 2025. The total water supply in Handan is approximately 2646.53 × 10^6 m^3, including 928.40 × 10^6 m^3 groundwater, 359.23 × 10^6 m^3 recycled water, 352.02 × 10^6 m^3 water diverted from the South-to-North Water Diversion Project, 179.00 × 10^6 m^3 water diverted from the Yellow River, 87.00 × 10^6 m^3 diverted from the Weihe River, and 226.38 × 10^6 m^3 water diverted from the Yuefeng Channel; the reservoir water is approximately 514.5 × 10^6 m^3.

Table 2. Prediction results of the available water supply of different water sources in Handan in 2025 (P = 50%; 10^6 m^3).

Subunit	Ground Water	Recycled Water	South-to-North Water Diversion	Yellow River Transferred Water	Weihe River Transferred Water	Yuefeng Channel	Reservoir Water
Shexian	70.46	17.81					√
Wu'an	122.51	45.02					√
Cixian	60.64	13.23				√	√
Fengfeng	91.57	18.61				√	√
Hanshan	53.09	33.77					√
Fuxing	16.12	21.06					√
Congtai	36.79	45.15					√
Yongnian	75.09	25.51					√
Linzhang	79.53	16.64					√
Cheng'an	40.26	13.93	√				√
Weixain	63.58	22.51	√	√	√		√
Feixiang	16.86	14.65	√	√			√
Guangping	13.07	9.71	√	√			√
Quzhou	5.35	12.33	√	√			√
Daming	93.67	20.81	√	√	√		√
Guantao	43.09	11.20	√	√	√		√
Jize	29.62	8.76	√				√
Qiuxian	17.10	8.53	√	√			√
Total	928.40	359.23	352.02	179.00	87.00	226.38	514.50

The South-to-North Water Diversion Project supplies water through urban water supply networks and water plants, whereas the Yellow River Diversion Project, the Weihe River Diversion Project, and the Yuefeng Channel Diversion Project supply water through artificially constructed channels and pumping stations. They all have fixed water supply nodes, but they do not have the characteristics of natural river water supply, which is a process of strong human activities controlling water resources, making it difficult to establish the topological relationship between water supply and consumption in the GWAS model. Therefore, virtual reservoirs were constructed to represent the above four water diversion sources for optimal allocation of water resources. In addition, this study further generalized the other small reservoirs with water supply characteristics in the western mountainous area of Handan.

2.4.4. Determination of Topological Relationship and Model Parameters

Topological Relationship between Water Supply and Consumption

The study area was divided into 38 hydrological units, including 12 sub-computing units in the Handan west mountainous area and 26 sub-computing units in the eastern plain area. Among them, Wu'an, Shexian, and Fengfeng are all mountainous areas; a small part of Congtai, Fuxing, Yongnian, and Hanshan are mountainous; the rest are plains. The topological relationship between water supply and demand in Handan established in the GWAS model is shown in Figure 2, and the network diagram of the water supply relationship is shown in Figure 3.

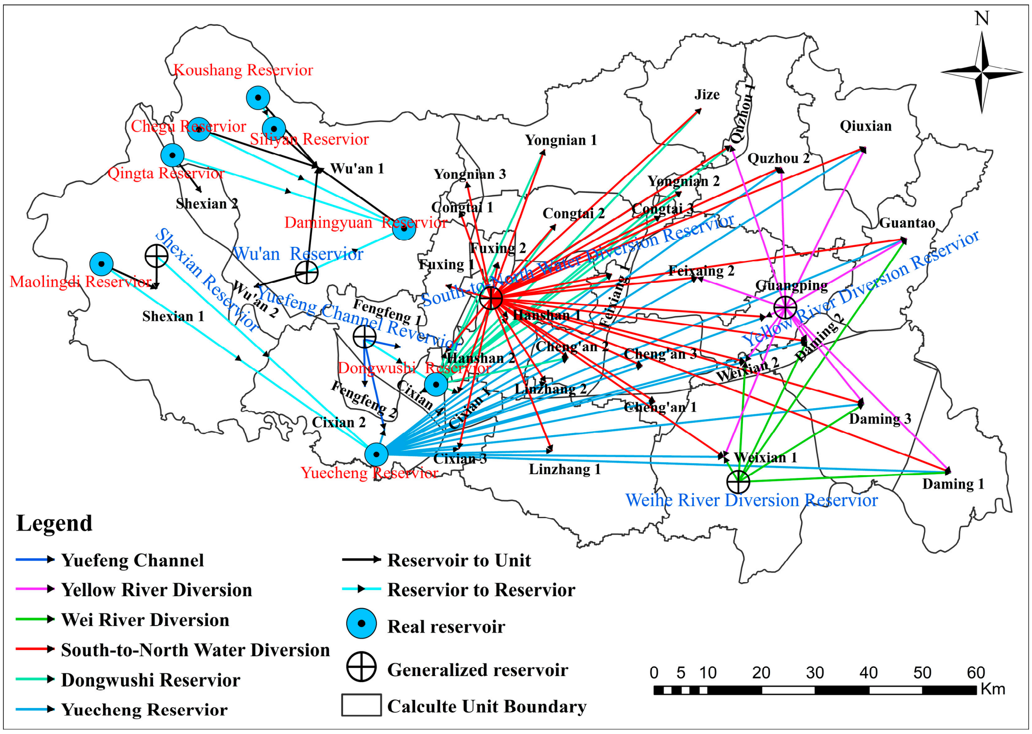

Figure 2. Topological diagram of water supply and consumption in the GWAS model.

Parameters Setting

The allocation ratio coefficient of water sources of the industry is set. According to the requirements of different water users for water supply sources, the water allocation ratio of different water sources to the corresponding industries for each calculation unit in Handan is determined. The industry weight coefficient is set to 1 for domestic and tertiary industry, 0.95 for ecology, 0.8 for primary industry, and 0.9 for second industry. Overall considering the actual situation of the socio-economic development and the characteristics of the distribution of water conservancy projects in Handan, the water shortage rate weights are as important as the fairness weights and are both set to 1. The NSGAII-S parameter settings are the following: the maximum number of running times is 1000, the population size is 50, the gene length is 0, the cross probability is 0.3, and the mutation probability is 0.05.

Reservoir Water Supply Characteristics

Table 3 represents the water supply characteristics of the reservoir, "$\surd$" indicates that the reservoir can supply water to corresponding industries; numbers 1 to 5 indicate the priority of water supply from the reservoir to different industries, where number 1 indicates the highest priority and number 5 indicates the least.

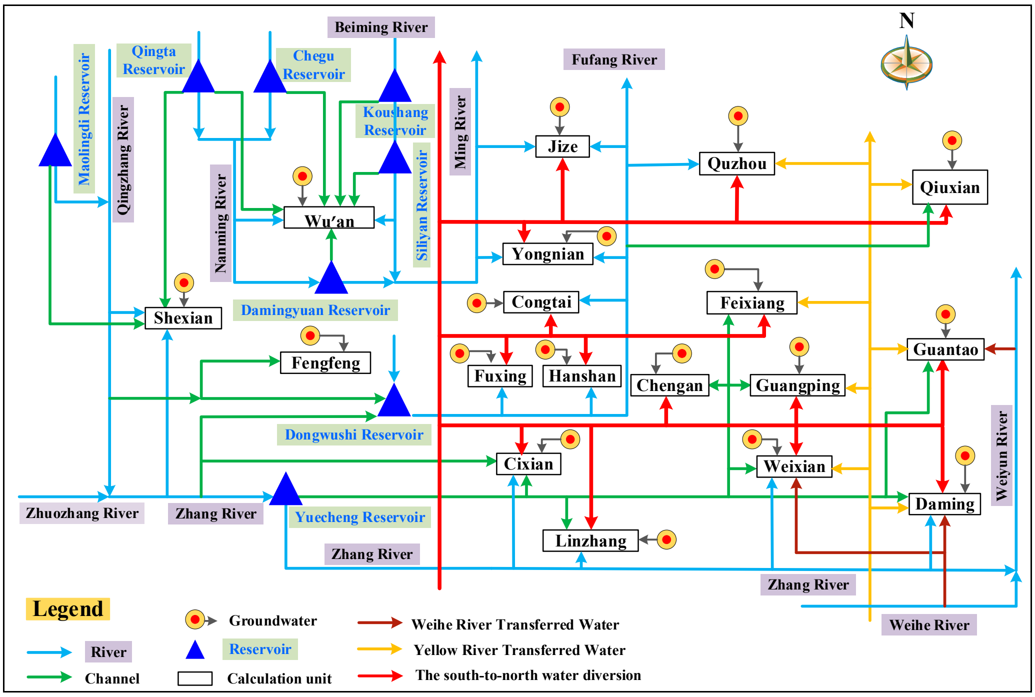

Figure 3. The network diagram of the water supply relationship in Handan.

Table 3. Water supply relationship and water supply level of the reservoir to industry.

Reservoir Name	Domestic		Ecology		Primary Industry		Secondary Industry		Tertiary Industry	
Maolingdi	√	1	√	2	√	5	√	3	√	4
Qingta	√	1	√	2	√	5	√	3	√	4
Chegu	√	1	√	2	√	5	√	3	√	4
Koushang		5	√	1	√	4	√	2	√	3
Siliyan	√	1	√	2	√	5	√	3	√	4
Damingyuan		5	√	1	√	3	√	2		4
Yuecheng		5	√	1	√	4	√	2	√	3
Dongwushi		5	√	1	√	4	√	2	√	3
Wu'an		5		4	√	2	√	1		3
Shexian		5		4	√	1		2		3
Yuefeng Channel		5	√	1	√	3	√	2		4
South-to-North Water Diversion	√	1		4		5	√	2	√	3
Weihe River Transferred		5		4	√	1		2		3
Yellow River Transferred		5	√	1	√	2		3		4

2.4.5. Model Validation

In order to validate the rationality of the model and the accuracy of the parameters, the actual water supply and water usage of Handan in 2019 were input into the model [65]. By comparing the simulated water supply volume with the actual water supply, the total error rate is 1.10%, and the error rate of each calculation unit is between 0–6%; among them, the highest rate is 5.51% in Daming, and the lowest rate is 0.12% in Yongnian, as shown in Figure 4a. Through the comparative analysis of the water supply of different industries and the simulated water supply, the error rate of different industrial water supplies for domestic (0.21%), ecological (0.75%), industrial (0.62%), and agricultural (1.88%) uses, respectively, is shown in Figure 4b. The Pearson correlation coefficient for simulated versus actual water supply in Handan was strong (0.9890). The error rate of simulation results and correlation coefficient are within the acceptable range. Therefore, the multi-objective optimal allocation model of water resources based on GWAS in Handan is reasonable and the model parameters are accurate.

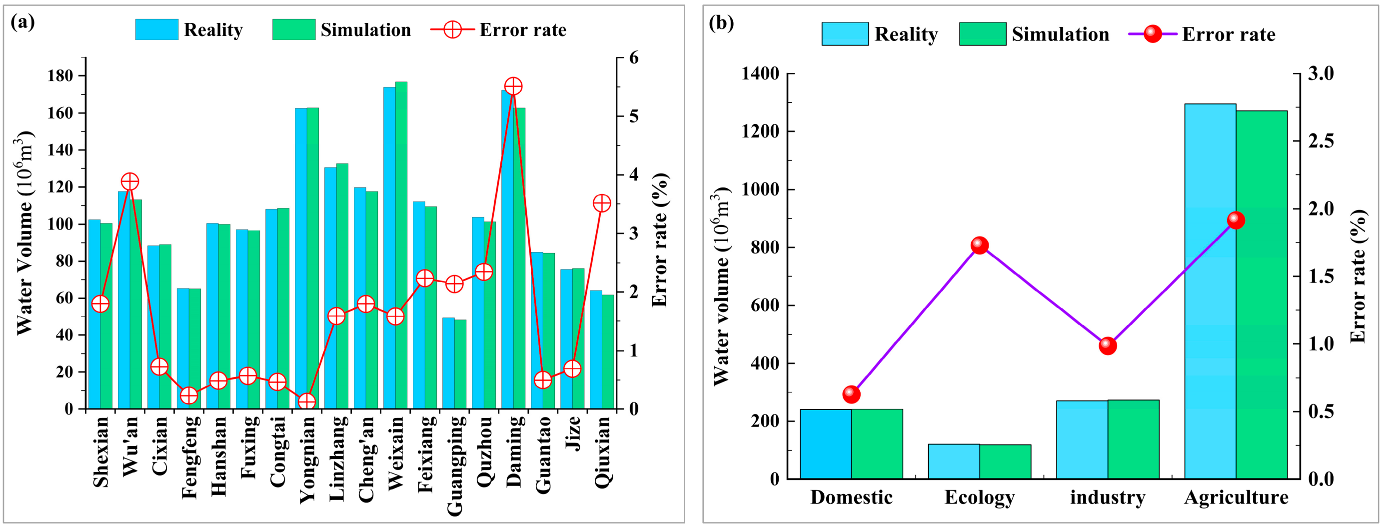

Figure 4. The comparative analysis of water supply between simulation and actual: (**a**) calculation units and (**b**) different industries.

3. Analysis of Results and Discussion

3.1. Results and Analysis

3.1.1. Analysis of Industry Water Shortage Rate

The results of the optimal allocation of water resources with a P = 50% guarantee rate for different industries in Handan by 2025 are shown in Table 4. The total water demand is predicted to be 2943.89 × 10^6 m^3, the total water allocation is 2416.92 × 10^6 m^3, the total water shortage is 527.60 × 10^6 m^3, and the total water shortage rate is 17.92%. Shexian, Cixian, Fengfeng, and Congtai are not short of water, while Linzhang has the largest water shortage of 76.62 × 10^6 m^3; the water shortage rate is 34.53%.

The domestic and ecological water needs of Handan were fully allocated. The total water demand of the primary industry is 1939.85 × 10^6 m^3, the total water distribution is 1416.42 × 10^6 m^3, the total water shortage is 523.43 × 10^6 m^3, the total water shortage rate is 26.98%, and the highest water shortage rate is 44.12%. The total water demand of the secondary industry is 211.43 × 10^6 m^3, the total water distribution is 211.30 × 10^6 m^3, the total water shortage is 0.13 × 10^6 m^3, the total water shortage rate is 0.10%, Wu'an is short of water (0.13 × 10^6 m^3), and the water shortage rate is 0.34%. The total water demand of the tertiary industry is 222.52 × 10^6 m^3, the total allocated water is 221.97 × 10^6 m^3, the total water shortage is 3.55 × 10^6 m^3, and the water shortage rate is 1.57%. Eight administrative districts of Wu'an, Cheng'an, Feixiang, Guangping, Daming, Quzhou, Guantao, and Qiuxian are short of water, among which Wu'an has the highest water shortage rate of 6.62%. Water shortage in the primary industry accounts for 99.21% of the total water shortage in the industry.

Table 4. Optimal allocation results and water shortage rate for water resources in different industries in Handan in 2025 (10^6 m^3, %).

Subunit	Domestic			Ecology			Primary Industry			Secondary Industry			Tertiary Industry			Total		
	Demand	Allocated	Shortage Rate	Demand	Allocated	Shortage Rate	Demand	Allocated	Shortage Rate	Demand	Allocated	Shortage Rate	Demand	Allocated	Shortage Rate	Demand	Allocated	Shortage Rate
Shexian	16.75	16.75	0	9.83	9.83	0	25.00	25.00	0	10.21	10.21	0	11.49	11.49	0	73.28	73.28	0
Wu’an	32.14	32.14	0	17.02	17.02	0	154.29	91.50	40.70	61.39	61.26	0.34	30.22	28.22	6.62	295.06	230.14	22.00
Cixian	18.32	18.32	0	9.70	9.70	0	60.07	60.07	0	3.64	3.64	0	6.32	6.32	0	98.05	98.05	0
Fengfeng	17.41	17.41	0	11.11	11.11	0	20.29	20.29	0	16.38	16.38	0	9.35	9.35	0	74.54	74.54	0
Hanshan	29.45	29.45	0	19.66	19.66	0	90.33	85.63	5.20	10.54	10.54	0	23.20	23.20	0	173.18	168.48	2.71
Fuxing	16.07	16.07	0	11.24	11.24	0	21.62	18.34	15.17	17.37	17.37	0	13.37	13.37	0	79.67	76.39	4.12
Congtai	33.49	33.49	0	25.31	25.31	0	33.33	33.33	0	19.76	19.76	0	35.32	35.32	0	147.21	147.21	0
Yongnian	31.80	31.80	0	16.84	16.84	0	188.05	147.48	21.57	14.18	14.18	0	12.82	12.82	0	263.69	223.12	15.39
Linzhang	21.34	21.34	0	10.64	10.64	0	173.66	97.04	44.12	6.78	6.78	0	9.47	9.47	0	221.89	145.27	34.53
Cheng’an	14.63	14.63	0	7.74	7.74	0	104.84	68.36	34.8	10.02	10.02	0	8.37	8.14	2.75	145.60	108.89	25.21
Weixain	28.91	28.91	0	15.31	15.31	0	228.1	164.97	27.68	10.91	10.91	0	11.13	11.13	0	294.36	231.23	21.45
Feixiang	13.73	13.73	0	7.27	7.27	0	136.86	87.10	36.36	5.16	5.16	0	11.41	11.02	3.42	174.43	124.28	28.75
Guangping	10.26	10.26	0	5.43	5.43	0	69.65	43.52	37.52	3.88	3.88	0	6.6	6.34	3.94	95.82	69.43	27.54
Quzhou	15.92	15.92	0	7.73	7.73	0	103.79	64.09	38.25	6.33	6.33	0	6.89	6.61	4.06	140.66	100.68	28.42
Daming	29.56	29.56	0	15.65	15.65	0	271.03	223.40	17.57	3.70	3.70	0	9.94	9.56	3.82	329.88	281.87	14.55
Guantao	11.97	11.97	0	6.34	6.34	0	92.77	69.84	24.72	2.48	2.48	0	8.05	7.74	3.85	121.61	98.37	19.11
Jize	10.21	10.21	0	4.76	4.76	0	83.55	61.73	26.12	4.62	4.62	0	5.85	5.85	0	108.99	87.17	20.02
Qiuxian	8.88	8.88	0	4.70	4.70	0	82.59	54.73	33.73	4.08	4.08	0	5.72	5.50	3.85	105.97	77.89	26.50
Total	360.84	360.84	0	206.28	206.28	0	1939.85	1416.42	26.98	211.43	211.30	0.10	225.52	221.45	1.80	2943.89	2416.29	17.92

3.1.2. Analysis of Water Allocation from Different Water Supply Sources

The allocation of water from different water supply sources to each administrative district of Handan is presented in Table 5. Figure 5 shows the water supply proportion of the water sources, representing the ratio of the total water distribution of a single water supply source to the total water distribution of all water supply sources. Because the Yuefeng Channel participates in the joint optimal operation of the reservoir, the independent water supply of the Yuefeng Channel and reservoir cannot be accurately calculated.

Table 5. Distribution of water from different water sources in Handan in 2025 (P = 50%; 10^6 m^3).

Subunit	Ground Water	Recycled Water	Reservoir Water	South-to-North Water Diversion	Yellow River Transferred Water	Weihe River Transferred Water	Yuefeng Channel	Total
Shexian	49.23	11.78	12.27	0	0	0	0	73.28
Wu'an	122.46	44.91	62.77	0	0	0	0	230.14
Cixian	58.37	10.65	2.01	12.59	0	0	14.43	98.05
Fengfeng	53.65	15.35	0	0	0	0	5.54	74.54
Hanshan	53.07	33.66	41.83	39.92	0	0	0	168.48
Fuxing	16.12	21.03	17.00	22.24	0	0	0	76.39
Congtai	35.34	40.37	32.93	38.57	0	0	0	147.21
Yongnian	75.08	24.52	87.85	35.67	0	0	0	223.12
Linzhang	79.53	16.64	16.52	32.58	0	0	0	145.27
Cheng'an	40.25	13.93	36.75	17.96	0	0	0	108.89
Weixain	63.57	22.51	25.81	40.47	35.88	42.99	0	231.23
Feixiang	16.86	14.65	40.93	16.28	35.56	0	0	124.28
Guangping	13.06	9.71	17.23	11.65	17.78	0	0	69.43
Quzhou	5.33	12.32	36.41	17.57	29.05	0	0	100.68
Daming	93.67	20.67	71.45	31.31	30.73	34.04	0	281.87
Guantao	43.09	10.34	12.77	13.24	9.05	9.88	0	98.37
Jize	29.62	8.18	37.39	11.98	0	0	0	87.17
Qiuxian	17.10	8.52	21.53	9.97	20.77	0	0	77.89
Total	865.40	339.74	573.45	352.00	178.82	86.91	19.97	2416.29

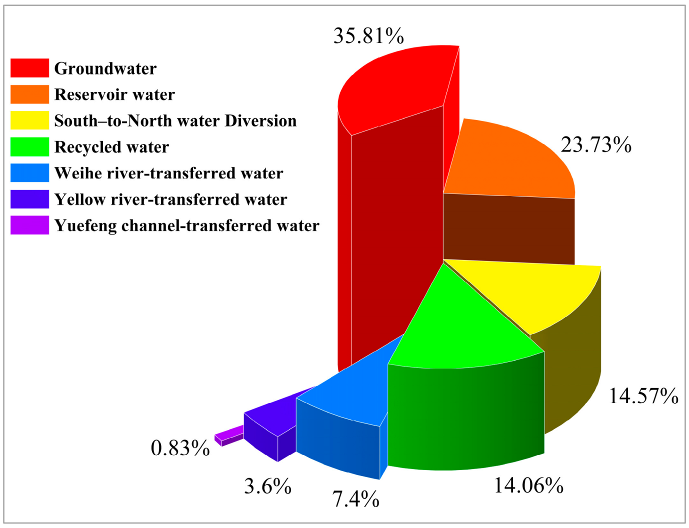

Figure 5. The proportion of water supply from different sources.

Therefore, the water supply proportion of the Yuefeng Channel shown in Figure 5 is only calculated using its allocation results in Fengfeng and Cixian; the total allocated water volume of different water supply sources in Handan is 2416.92 × 10^6 m^3, of which groundwater distribution is 865.40 × 10^6 m^3, accounting for 35.81%, and the water allocation rate is 93.22%. Recycled water distribution is 339.74 × 10^6 m^3, accounting for

14.06%, and the allocation rate is 94.58%. The allocation ratio is approximately 100% for the South-to-North, Weihe River, and Yellow River Water diversion projects with water distributions of 352.00 $\times$ 10^6 m^3, 86.91 $\times$ 10^6 m^3, and 178.82 $\times$ 10^6 m^3, respectively, and water supply accounting for 14.57, 7.40, and 3.60%, respectively. The Yuefeng Channel water supply is 19.97 $\times$ 10^6 m^3, accounting for 0.83%, and the reservoir water supply is 573.45 $\times$ 10^6 m^3, accounting for 23.73%.

3.1.3. Analysis of Reservoir Water Allocation

The allocated water volume of the reservoir shown in Table 6 is greater than the available water volume of the reservoir shown in Table 2, whereas the allocated water volume of the Yuefeng Channel is less than the available water volume. The main reason is that the Yuefeng Channel undertakes two tasks: supplying water to Cixian and Fengfeng as well as the Dongwushi Reservoir. When the water demands of Cixian and Fengfeng are met, the remaining water in the Yuefeng Channel flows into the Dongwushi Reservoir. Table 7 shows the results of the reservoir's optimal operation, and the total dispatching water volume of the reservoir is 210.94 $\times$ 10^6 m^3. The Koushang Reservoir supplies 12.00 $\times$ 10^6 m^3 of water to the Siliyan Reservoir, the Qingta Reservoir supplies 0.12 $\times$ 10^6 m^3 of water to the Damingyuan Reservoir, the Maolingdi and Shexian reservoirs supply water to the Yuecheng Reservoir 42.96 $\times$ 10^6 m^3 and 1.49 $\times$ 10^6 m^3, respectively, and the Yuefeng Channel supplies 154.37 $\times$ 10^6 m^3 of water to the Dongwushi Reservoir.

Table 6. Results of reservoir optimal operation in Handan (10^6 m^3).

Reservoirs Name	Koushang	Qingta	Maolingdi	Shexian	Yuefeng Channel	Total
Siliyan	12.00					12.00
Damingyuan		0.12				0.12
Yuecheng			42.96	1.49		44.45
Dongwushi					154.37	154.37
Total	12.00	0.12	42.96	1.49	154.37	210.94

Table 7. Results of reservoir optimal operation in Handan (10^6 m^3).

Subunit	South-to-North Water Diversion		Yellow River Transferred Water		Weihe River Transferred Water		Yuefeng Channel	
	GWAS	Tradition	GWAS	Tradition	GWAS	Tradition	GWAS	Tradition
Shexian								
Wu'an								
Cixian	12.59	30.74					14.43	15.00
Fengfeng							5.54	5.00
Hanshan	39.92	77.49						
Fuxing	22.24	44.56						
Congtai	38.57	71.68						
Yongnian	35.67	36.00						
Linzhang	32.58	7.38						
Cheng'an	17.96	6.74						
Weixain	40.47	21.00	35.88	36.24	42.99	40.00		
Feixiang	16.28	10.00	35.56	19.78		2.00		
Guangping	11.65	7.00	17.78	22.53				
Quzhou	17.57	5.53	29.05	24.02				
Daming	31.31	7.90	30.73	24.46	34.04	25.00		
Guantao	13.24	7.00	9.05	24.00	9.88	20.00		
Jize	11.98	6.00						
Qiuxian	9.97	13.00	20.77	27.93				
Total	352.00	352.02	178.82	178.96	86.91	87.00	19.97	20.00

3.1.4. Analysis of Water Distribution of Different Water Sources

Figure 6 shows the water supply of different water sources to different industries in each administrative district of Handan. Figure 6a shows that the total distribution of groundwater to different industries is 865.40 × 10^6 m^3. The distribution includes 72.73 × 10^6 m^3 supplied to domestic water, and the water supply areas are Wu'an, Cixian, Fengfeng, and Shexian counties. In addition, 4.61 × 10^6 m^3 is supplied to ecological water, and the water supply areas are Linzhang, Feixiang, Yongnian, and Daming. Water supply to primary and secondary industries is 664.48 × 10^6 m^3 and 111.38 × 10^6 m^3, respectively, and the scope of water supply is all areas of Handan. The water supply to the tertiary industry is 12.20 × 10^6 m^3, and the water supply areas are Wu'an, Fengfeng, and She counties.

Figure 6b shows the amount of water the reservoir supplies to different industries. The reservoir mainly supplies water to the primary and tertiary industries. The total water distribution of the reservoir is 556.11 × 10^6 m^3, the water supply in Yongnian is the largest, and no water is supplied to Fengfeng. The reservoir supplies 4.38 × 10^6 m^3 of domestic water to Shexian and Wu'an, 30.82 × 10^6 m^3 of ecological water supply, except for Wu'an and Fengfeng, and 371.40 × 10^6 m^3 of water supply to the primary industry, except for Shexian and Fengfeng. The secondary industrial water supply is 0.23 × 10^6 m^3, and that to the tertiary industry is 166.62 × 10^6 m^3.

Figure 6c shows the distribution of water resources in the South-to-North Water Diversion Project. The total allocated water volume of this water source is 352.00 × 10^6 m^3, of which the water supply for domestic use is 283.73 × 10^6 m^3, 25.64 × 10^6 m^3 for the secondary industry, and 42.63 × 10^6 m^3 for the tertiary industry. Its water supply is largest in Weixian, and it does not supply water to Shexian, Wu'an, or Fengfeng, nor does it supply water to ecological areas and primary industries.

Figure 6d shows the distribution of recycled water, which had the largest water supply in Wu'an and the smallest in Jize. The total distribution of recycled water is 351.97 × 10^6 m^3, of which 102.84 × 10^6 m^3 is supplied to the primary industry, 71.10 × 10^6 m^3 to the secondary industry, and 165.80 × 10^6 m^3 to ecological regions.

Figure 6e shows the allocation of water resources transferred from the Yellow River. This water source supplies water only to the primary industry. The total allocated water volume is 178.80 × 10^6 m^3. The water supply areas include Weixian, Feixiang, Guangping, Quzhou, Daming, Guantao, and Qiuxian, among which the largest amount of water is supplied to Weixian.

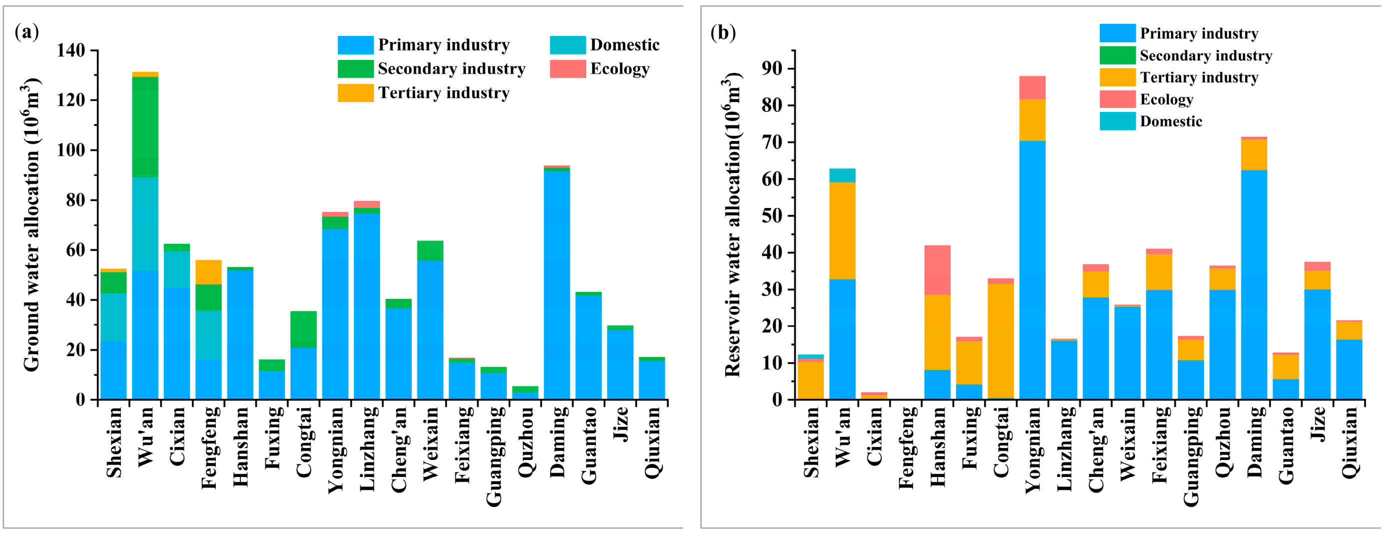

Figure 6. *Cont.*

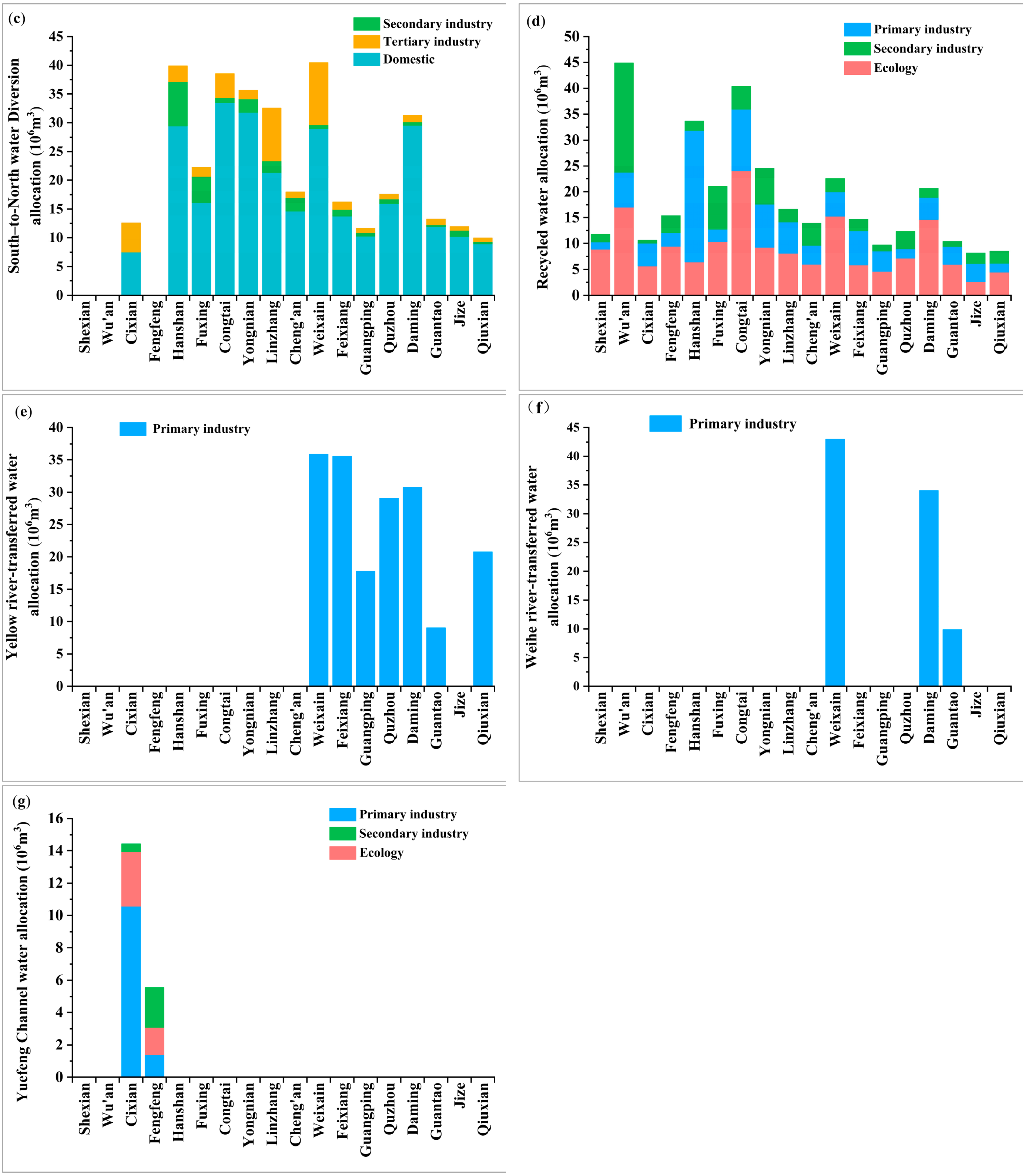

Figure 6. Allocation of different water supply sources in Handan. (**a**) Groundwater, (**b**) Reservoir water, (**c**) South-to-North Water Diversion, (**d**) Recycled water, (**e**) Yellow river-transferred water, (**f**) Weihe river-transferred water, and (**g**) Yuefeng channel water.

Figure 6f shows the allocation of the water resources diverted from the Weihe River. This water source only supplies water to the primary industry; the total allocated water volume is 86.91×10^6 m^3. Of this, 42.99×10^6 m^3 is supplied to Weixian, 32.28×10^6 m^3 to Daming, and 10.23×10^6 m^3 to Guantao.

Figure 6g shows the distribution of the water resources diverted from the Yuefeng Canal, which supplies water to ecological regions and primary and secondary industries in Cixian and Fengfeng. The total allocated water volume is 19.97×10^6 m^3, of which 5.05×10^6 m^3 is supplied to ecological regions, 11.97×10^6 m^3 is supplied to the primary industry, and 2.95×10^6 m^3 is supplied to the secondary industry.

3.1.5. Analysis of the Water Supply Ratio from Water Sources to Industry

Figure 7 shows the proportions of water supply from different water sources to different industries in each administrative area of Handan. Figure 7a shows the proportions of different water sources in the domestic water supply. Water supply sources include groundwater, reservoir water, and South-to-North Water Diversion. Groundwater and reservoir water jointly supply the domestic water needs of Shexian and Wu'an, with groundwater accounting for 94.81 and 89.08% and reservoir water accounting for 5.19 and 10.92%, respectively. Cixian's domestic water needs are supplied by both groundwater (59.01%) and South-to-North Water Diversion (40.99%). All domestic water in Fengfeng is supplied by groundwater, and all domestic water in other administrative regions is supplied by South-to-North Water Diversion.

Figure 7b shows the proportions of different water sources to the ecological water supply. Water supply sources include groundwater, recycled water, reservoir water, and water diversions from the Yuefeng Channel. The ecological regions are mainly supplied by reclaimed water and reservoirs. Reservoirs account for the largest proportion (67.19%) of the ecological water supply in Hanshan, and the rest of the area had the largest proportion of recycled water supply. Wu'an's ecology is entirely supplied by recycled water. Cixian's ecological water demand is jointly supplied by recycled water, water diversion from the Yuefeng Channel, and reservoir water, which account for 58.35, 34.74, and 6.91% of the water supply, respectively. Fengfeng's water demand is supplied by recycled water and water diversion from the Yuefeng Channel, accounting for 84.88 and 15.12% of the water supply, respectively. The ecological areas of Yongnian, Linzhang, Feixiang, and Daming are jointly supplied by groundwater, recycled water, and reservoir water, while the ecological water needs of other areas are jointly supplied by reclaimed and reservoir water.

Figure 7c shows the proportion of water supply for the primary industry. Water supply sources include groundwater, recycled water, reservoir water, Yellow River water, Weihe River water, and Yuefeng Channel water. Reservoir water accounts for 47.76, 46.84, and 48.76% of the water supply in Yongnian, Quzhou, and Jize, respectively. The proportion of water diverted from the Yellow River to the Feixiang, Guangping, and Qiu counties is 40.83, 40.86, and 45.33%, respectively. In the rest of the region, the proportion of groundwater supply was the largest, among which Shexian had the largest proportion (94.56%).

Figure 7d shows the proportion of water supply for the secondary industry. Water supply sources include groundwater, recycled water, reservoir water, the South-to-North Water Diversion, and Yuefeng Canal water. The South-to-North Water Diversion accounts for 73.15% of the water supply in the Hanshan area. Groundwater accounts for the largest proportion of water supply in Shexian, Wu'an, Fengfeng, Cixian, Congtai, Weixian, Guangping, and Guantao, while recycled water supplies the largest proportion in other areas, and reservoir water only supplies a small amount of water resources.

Figure 7e shows the proportion of water supply for the tertiary industry. Water supply sources include South-to-North Water Diversion, groundwater, and reservoir water. Wu'an and Shexian are supplied by groundwater and reservoirs, accounting for the largest proportions at 91.04 and 93.55%, respectively. Fengfeng is supplied by groundwater, while the rest of the area is jointly supplied by reservoirs and the South-to-North Water Diversion. The South-to-North Water Diversion Project contributed the largest proportion of water supply to Cixian, Linzhang, and Weixian, accounting for 80.38, 97.36, and 97.30%, respectively, and the reservoir water supply proportion in other units was the largest.

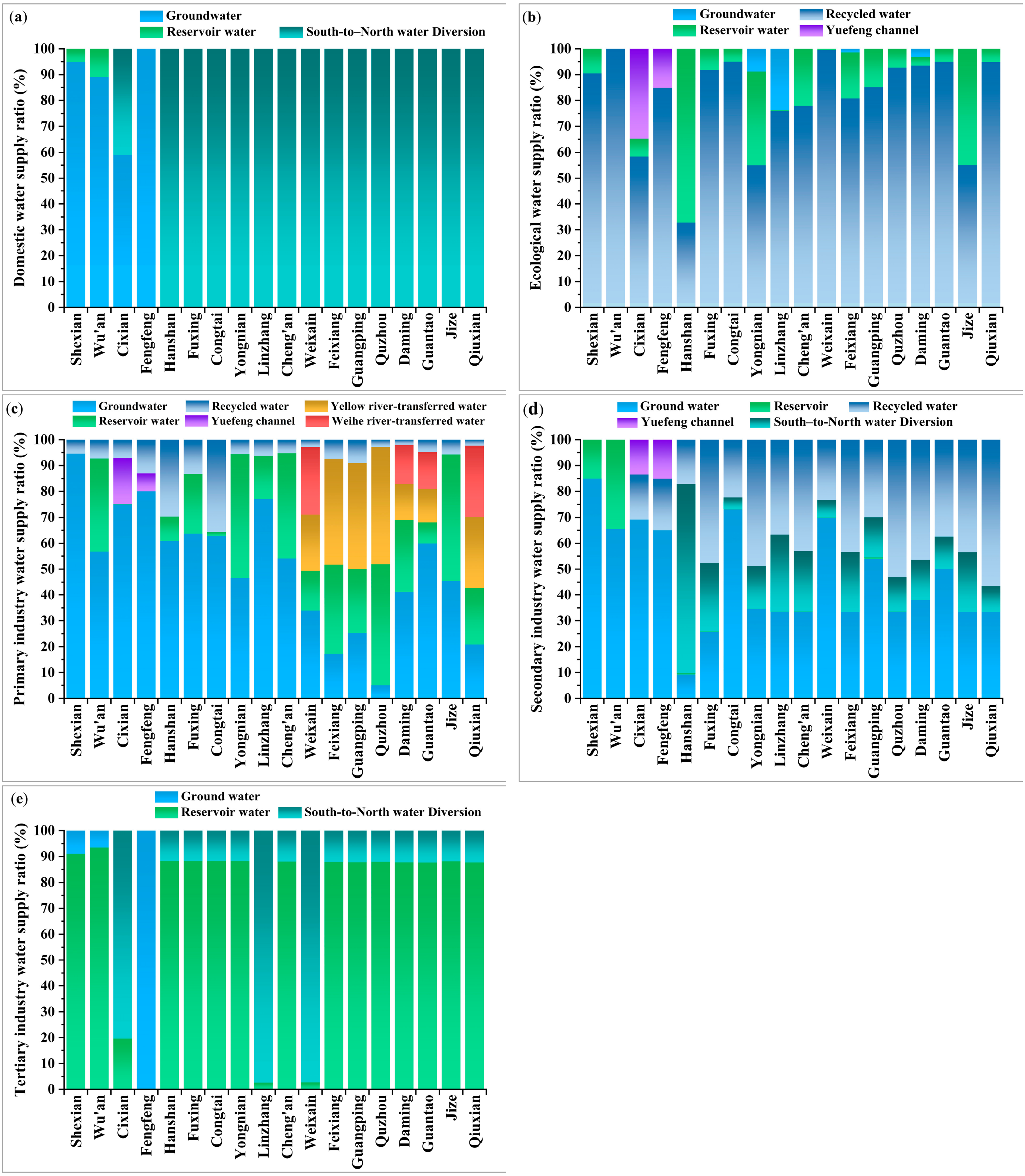

Figure 7. The proportion of water supply from different industries in each administrative district of Handan. (**a**) Domestic, (**b**) Ecological, (**c**) Primary industry, (**d**) Secondary industry, (**e**) Tertiary industry.

3.2. Discussion

The transported water includes South-to-North Water Diversion, Yellow River diversion, Weihe River diversion, and Yuefeng Channel diversion. In the conventional water resources allocation, the water supply amount of the four types of water sources to each unit was determined according to the fixed distribution water indicators [66]. However, in this study, the four types of water sources were generalized into virtual reservoirs with dynamic regulation characteristics for optimal allocation. The GWAS model allocation results were compared with the traditional method distribution results, as shown in Table 7. The results show that the total amount of transported water allocation based on the GWAS model was the same as that of the traditional method. However, in different calculation units, the allocation of transported water volume was very different; the main reason is that the GWAS model not only considers the load-balancing object of the minimum water shortage rate of each calculation unit, but also considers the spatial balance of water shortage between each calculation unit. The allocation results of the GWAS model avoided the large difference in water shortage rate between each calculation unit, and effectively coordinate the balanced allocation of various water sources between regions and water users.

A comparative analysis with other research was also carried out. Ma et al. [67] treated transported water as a uniform source without subdivision. Suo et al. [68] used a fuzzy-interval dynamic programming (FIDP) model to allocate water resources in Handan without subdividing the sources of external transferred water. Yan et al. [69] also allocated the transported water according to a fixed water distribution scheme without dynamic adjustments. This study introduced virtual reservoirs into the model to enable each transported water source to dynamically adjust to demand from the calculation units, which assisted in the later development of transported water schemes.

4. Conclusions

According to the characteristics of water resources and the distribution characteristics of water conservancy projects and the transported water projects in Handan, this study, based on forecasts of water resource supply and demand, used GWAS to construct an optimal allocation model of water resources in Handan. The model introduced the concept of the virtual reservoir and generalized the South-to-North Water Diversion, Yellow River Transferred Water, Weihe River Transferred Water, and Yuefeng Channel Transferred Water as virtual reservoirs, which are jointly allocated with local surface water, groundwater, and recycled water. The results show that in 2025, the total water demand of Handan at a P = 50% guarantee rate is 2943.89×10^6 m^3, the total allocated water is 2416.92×10^6 m^3, the total water shortage is 527.60×10^6 m^3, and the water shortage rate is 17.92%. There was no water shortage in some calculation units, such as Shexian, Cixian, Fengfeng and Congtai. The highest water shortage rate was in Linzhang, at 34.53%. For the different industry sectors, no water shortage occurred in domestic and ecological water users. Water scarcity was mainly concentrated in the primary industry where the water shortage rate was 26.98%. Only Wu'an has a certain shortage of water in the secondary industry, mainly due to the large water usage of the steel industry.

One challenge in the present modeling process was that the GWAS parameters required manual adjustment, which is cumbersome and inconvenient and needs to be improved in future research. Secondly, the model cannot input the water demand data of the tertiary industry. In this study, the water demand of the tertiary industry was added to the domestic water demand. This may lead to an increase in the water supply from the South-to-North Water Diversion for domestic uses, indirectly affecting the accuracy of the allocation results and compromising the realization of the delicate management of regional water resources in Handan. Finally, due to the many small rainwater interception and storage projects in Handan, it was impossible to generalize them in the model; this paper did not consider the water supply of small rainwater storage projects, and these sources should be added to subsequent research.

Overall, the GWAS model had strong applicability in Handan, and the allocation results were reliable. In the GWAS model, the transported water is not allocated according to a fixed water distribution scheme but is dynamically adjusted according to the water demand of different calculation units, which can provide a technical reference for the management of transported water.

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