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Study on the Optimization of Multi-Objective Water Resources Allocation in the Henan Yellow River Water Supply Zone

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Abstract: With the continuous growth in the global population, rapid socioeconomic development, and the impacts of factors like climate change, we are facing increasingly severe challenges regarding water scarcity. The scientific and rational allocation of water resources has become a key factor in ensuring sustainable development. The Henan Yellow River water supply zone occupies a crucial position in the socioeconomic development of Henan Province. Currently, there is a shortage of water resources with relatively low utilization rates. To alleviate the contradiction between water supply and demand, a study on the optimization of water resources (with $p = 90\%$) for the years 2025 and 2030 was conducted. In this study, we constructed a multi-objective optimization model with the objectives of maximizing economic benefits, minimizing total water shortage, and maximizing water use efficiency. The second-generation non-dominated sorting genetic algorithm (NSGA-II) was utilized to solve this model. The results indicate that by 2025, the optimized allocation of water resources will correspond to 17.663 billion m^3, reducing the average water shortage rate in the research area to 9.69%. By 2030, the optimized allocation of water resources will further increase to 18.363 billion m^3, bringing down the average water shortage rate to 8.34%. Concurrently, the supply structure of the research area will significantly improve after optimization. This is manifested through an increase in the proportion of surface water supply and a substantial rise in the proportion of supply from other water sources, while the proportion of groundwater supply noticeably decreases. These research findings can serve as a reference for the rational utilization and distribution of water resources in the future and can also offer insights for optimizing water resource allocation in other regions.

Keywords: water resources optimization allocation; second-generation non-dominated sorting genetic algorithms; multi-objective; Yellow River supply area in Henan Province

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1. Introduction

Water, as a fundamental component of Earth's natural resources, is intricately linked to all facets of human social development [1,2]. However, due to the combined effects of human activities and climate change, the dynamics of the regional water cycle have undergone some alterations. This, in turn, has resulted in notable shifts in the quality, quantity, and spatial-temporal distribution of water resources [3,4]. At the same time, with the rapid development of much of the global economy and the increase in the level of urbanization, the limited water resources currently available cannot adequately satisfy the needs of human production and life, and the problems of water pollution and the low utilization of water resources also undoubtedly exacerbate the mismatch between the supply and demand of water resources [5–9]. For this reason, considering the sustainable utilization of water resources, the Chinese government has advocated for reinforcing stringent controls on water resources. Emphasis has been placed on steadfastly upholding the principle of "water for the city, water for the land, water for the people, water for production" [10,11]. Consequently, achieving efficient and rational allocation of water resources is a prominent issue that requires immediate attention [12].

Water resource allocation, a pivotal approach for the efficient management of regional water resources, holds paramount theoretical significance and practical applicability in addressing water resource challenges [13]. The study of rational water resource allocation traces back to the 1940s, evolving from initial single-reservoir optimal scheduling to today's multidimensional, multi-objective, and all-encompassing water resource allocation schemes considering various factors [14,15]. Efforts ranging from small-scale water resource regulation to large-scale planning in watersheds and inter-basin and urban agglomerations [16–18] and from single mathematical optimization to the computer simulation of multi-level, multi-objective, and complex mega-systems have collectively propelled substantial advancements in water allocation technology.

However, due to the complexity of water allocation, it is often necessary to use mathematical analytical models to integrate different categories of information for calculation and comprehensive evaluation in order to obtain programmatic results that can be used as a reference for decision making. Traditional approaches to solving mathematical planning models include linear programming methods, nonlinear programming, stochastic linear programming, and dynamic programming [19–22]. However, with the multi-objective and multi-variable nature and high dimensionality of current water resources allocation models, the traditional optimization algorithms are not very effective in terms of convergence, computational efficiency, parameter sensitivity, etc. For the water resources optimization and allocation of large and complex systems, the resulting dimensionality usually makes it difficult to solve the optimization methods, or the optimization results are not in line with the reality, so the application of intelligent heuristic algorithms to the allocation of water resources is gradually becoming more and more widespread. For example, Qi et al. [23] constructed a water resources optimization allocation model for economic–social–environmental benefits in Harbin City and used genetic algorithms (GAs) to solve the corresponding problem and determine the water resources allocation scheme in the forecasted year. Yan et al. [24] constructed a water resources optimal allocation model with the objectives of attaining maximum economic benefits and minimum total water shortage and applied it in Xingtai City; the model was solved using the Whale Optimization Algorithm (WOA), yielding reasonable and accurate results. Wang et al. [25] selected Yinchuan as a study area, constructed a water resources optimal allocation model with the objective of maximizing the comprehensive benefits for society, and used the annealed particle swarm algorithm (SA-PSO) to solve the corresponding problem and obtain the optimal water resources allocation scheme. Ma et al. [26] constructed a model with the objectives of achieving optimal equity and a minimum water shortage rate and used a simulation model (GWAS) to optimize the allocation of water resources in Handan City in 2025 and 2035. Davijani et al. [27] constructed a bi-objective socio-economic optimization model, using Iran as a study area, and used a genetic algorithm (GA) and a particle swarm algorithm (PSO) to determine the allocation of water resources among different sectors. Zeng et al. [28] used the artificial fish swarm algorithm (FSA) to solve the optimal allocation model of water resources in Guangdong province with the objective of achieving optimal economic and social benefits, and the results showed that the water shortage problem was significantly improved after the allocation scheme was applied. All of the above algorithms provide basic ideas for solving optimization problems, and the results have shown the applicability and accuracy of heuristic algorithms.

In summary, most of the current studies on the optimal allocation of water resources focus on the dual objective, i.e., considering the optimal social and economic benefits, and this paper, based on this approach, sets the benefit as the objective function, which can maximally satisfy the water demand regarding human life and socio-economic development. Heuristic optimization algorithms have strong practicality in the optimal allocation of water resources, and the second-generation non-dominated sorting genetic algorithm

(NSGA-II), as a recently proposed heuristic algorithm, is gradually being increasingly used in engineering applications due to its advantages, i.e., high efficiency, high accuracy, etc.; therefore, it was selected in this paper for model solving.

Based on this, in this paper, we selected the 13 prefecture-level cities of the Henan Yellow River Water Supply Zone as the study area and considered the overall optimization of economic benefits, total water shortage, and water use efficiency. We constructed a multi-objective water resource optimization model and used NSGA-II to determine a water resources allocation scheme for the 2025 and 2030 planning-level years in the Henan Yellow River Water Supply Zone so as to solve the water resources allocation problems in the study area and make water resources allocation more efficient and reasonable. By applying our scheme, water resources in the study area will be utilized more efficiently and rationally to meet the needs of different water-using industries to the greatest extent possible. The results of this study will provide a scientific basis for future water resource management decisions in the study area and promote the sustainable development of the region.

2. Overview of the Study Area and Data Sources

2.1. Overview of the Study Area

The Yellow River flows into Henan Province upon departing Tongguan in Shaanxi Province, traversing from Lingbao City in the west to Taizian County in the east. It stands as the largest transit river in Henan Province, boasting a total length of 711 km and a basin area of 36,200 km^2, constituting approximately 21.7% of Henan Province's total area [29]. The water supply region of the Henan Yellow River lies in the north-central part of the province, forming a "butterfly" shape on both banks of the Yellow River. This region encompasses an aggregate area of approximately 104,000 km^2, accounting for 62.3% of the province's total area [30]. The population in the water supply area accounts for 72.8% of the total population of the province, and the water-saving irrigation area accounts for 86.8% of the province's water-saving irrigation area, contributing 80% of the province's gross domestic product and 66% of its total grain production, with an average of 5216 million m^3 of surface water in the Yellow River from 2010 to 2020 and a consumption of 4907 million m^3, accounting for 67.2% of the surface water supply of the Yellow River water supply area [31]. It can be seen that the Yellow River basin occupies an important position in the socio-economic development of Henan Province, especially in the region along the Yellow River.

Currently, the water resources within the Henan Yellow River water supply area are inadequate, marked by an uneven spatial and temporal distribution. The per capita water resources stand at a mere 381 m^3, amounting to only one-fifth of the national per capita level. Moreover, the average multi-year runoff of the Yellow River has seen a decrease from 53.5 billion m^3 (1956–2000) to 46.6 billion m^3 (2000–2019), reflecting a 13% reduction [30]. The over-exploitation of groundwater is a serious issue, with low efficiency in the utilization of water resources and constituting an overall grim situation [32]. Hence, it is necessary to optimize the allocation of water resources within the Yellow River water supply zone in Henan. In this paper, according to the principle of sub-district division, the study area is divided by prefecture-level cities, namely, Zhengzhou City, Kaifeng City, Luoyang City, Pingdingshan City, Anyang City, Xinxiang City, Jiaozuo City, Puyang City, Xuchang City, Sanmenxia City, Shangqiu City, Zhoukou City, and Jiyuan City, and the scope of the study is shown in Figure 1.

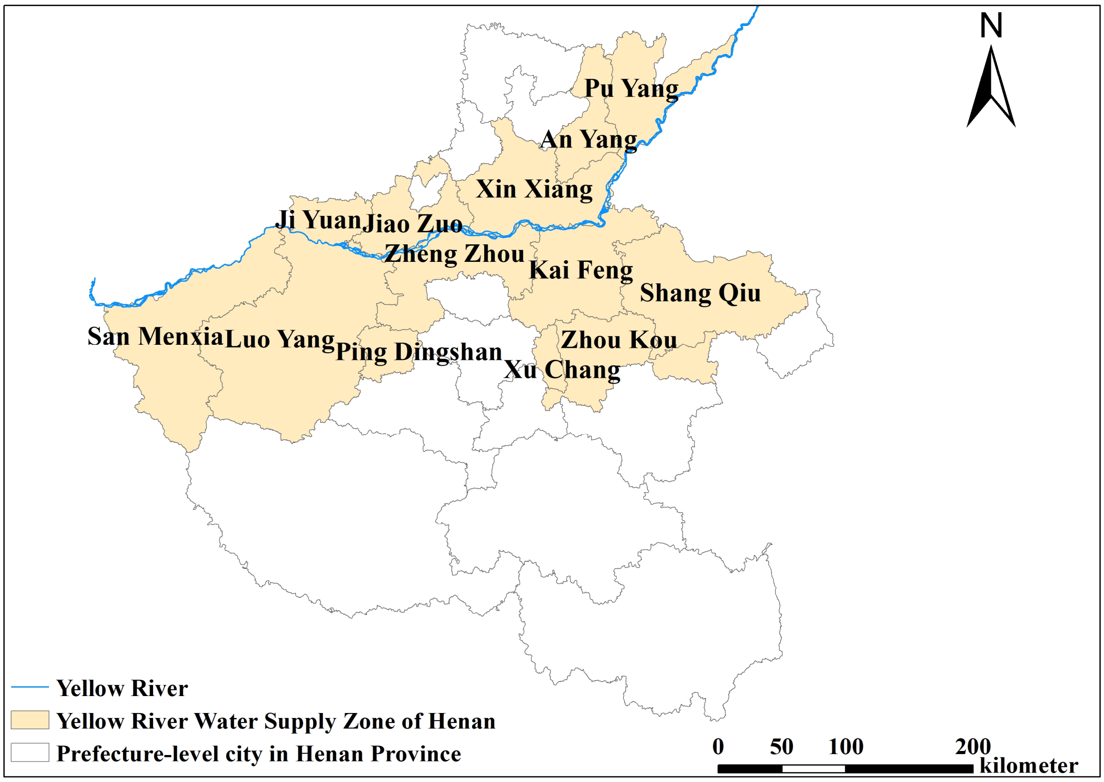

Figure 1. Geographic scope of the Yellow River water supply zone in Henan.

2.2. Data Sources

The data in this paper were taken from the Henan Provincial Statistical Yearbook (2016–2021), the Henan Provincial Water Resources Bulletin (2011–2020), Local Standard Urban Industrial Water Use Quotas (DB41/T 385-2020), Local Standard Agricultural and Rural Water Use Quotas (DB41/T 958-2020), the Henan Provincial Four Waters and the Same Governance Plan (2021–2035), and the development plans of various municipalities, among other sources.

3. Water Resources Optimization Model

3.1. Objective Function

The goal of this optimal allocation scheme is to maximize the combined benefits of economic efficiency, total water deficit, and water use efficiency in the study area, i.e.,

$$F(x) = \max\{f_1(x), f_2(x), f_3(x)\} \tag{1}$$

(1) The objective of our scheme is maximizing the overall economic benefits generated by various industries within the study area, denoted as $f_1(x)$:

$$\max f_1(x) = \sum_{k_1=1}^{13} \sum_{k_2=1}^{13} \sum_{i=1}^{3} \sum_{j=1}^{4} g_{k_2,j} a_{i,j} r_j x_{k_1,k_2,i,j} \tag{2}$$

where k denotes the sub-area, in which $k = 1, 2, \ldots, 13$ for 13 prefecture-level cities; i denotes water source, with $i = 1, 2, 3$ for surface water (including external water transfer), groundwater, and other water sources; j denotes water user, in which $j = 1, 2, 3, 4$ for life, agricultural, industrial, and ecological environments; $x_{k_1,k_2,i,j}$ denotes the amount of water supplied by water source i in sub-area k_1 to the water supply from water source i in subarea k_2 to water user j in subarea k_2, that is, 10^8 m^3; $g_{k_2,i}$ denotes the benefit generated per unit of water for user j in subarea k_2, amounting to 10^4 CNY/m^3 (400 USD/m^3); $a_{i,j}$ denotes the coefficient of order in which water is supplied from source i to water user j; and r_j denotes the coefficient of equity in water use for user j.

(2) The following equation was developed with the objective of minimizing the total water scarcity in the study area, denoted as $f_2(x)$:

$$\min f_2(x) = \sum_{k_2=1}^{13}\sum_{j=1}^{4}\left(D_{k_2,j} - \sum_{k_2=1}^{13}\sum_{i=1}^{3} x_{k_1,k_2,i,j}\right) \tag{3}$$

where $D_{k_2,j}$ denotes the water demand of user j in subarea k_2, amounting to 10^8 m^3.

(3) The following equation was developed with the objective of maximizing water use efficiency in the study area, denoted as $f_3(x)$:

$$\max f_3(x) = \frac{GDP}{\sum\limits_{k_1=1}^{13}\sum\limits_{k_2=1}^{13}\sum\limits_{i=1}^{3}\sum\limits_{j=1}^{4} x_{k_1,k_2,i,j}} \tag{4}$$

where *GDP* denotes the *GDP* gross product for all sub-districts for the forecasted year, equal to CNY 10^8 (USD 1.4×10^7).

3.2. Constraints

(1) Capacity constraints for water supply from water sources

$$\sum_{k_2=1}^{13}\sum_{j=1}^{4} x_{k_1,k_2,i,j} \le W_{k_1,i}, \text{ for all } k_1, i \tag{5}$$

Here, $W_{k_1,i}$ denotes the maximum available water supply from source i in subarea k_1, equal to 10^8 m^3.

(2) User water demand constraints

$$D_{j\min} \le \sum_{k_1=1}^{13}\sum_{i=1}^{3} x_{k_1,k_2,i,j} \le D_{j\max}, \text{ for all } k_2, i \tag{6}$$

Here, D_{jmin} denotes the lower limit of water demand for user j, 10^8 m^3, and D_{jmax} denotes the upper limit of water demand for user j, 10^8 m^3.

(3) Variable non-negative constraints

$$x_{k_1,k_2,i,j} \ge 0, \text{ for all } k_1, k_2, i, j \tag{7}$$

3.3. Model Parameter

(1) Economic efficiency coefficient

The industrial economic efficiency coefficient was determined as the reciprocal of water consumption per CNY 10,000 of added industrial value. Similarly, the agricultural economic efficiency coefficient was calculated as the reciprocal of water consumption per CNY 10,000 of added agricultural value. There is a lack of relevant data for the calculation of the coefficient of living and ecological efficiency, as priority should be given to life-related and ecological water use, and the coefficients of economic efficiency of various industries should be combined, and the maximum value should be taken as the coefficient of economic efficiency of living and ecological efficiency [33]. The economic efficiency coefficients for the sub-areas for the forecasted year are shown in Table 1.

Table 1. Economic efficiency coefficients for sub-areas in the forecasted year. Unit: 10^4 CNY/m^3 (1400 USD/m^3).

Subarea	**Economic Efficiency Factor for 2025**						**Economic Efficiency Factor for 2030**					
	Life	**Agriculture**			**Industry**	**Ecology**	**Life**	**Agriculture**			**Industry**	**Ecology**
		p = 75%	p = 90%	p = 97%				p = 75%	p = 90%	p = 97%		
Zhengzhou	0.1042 (145.88)	0.0029 (4.06)	0.0026 (3.64)	0.0025 (3.50)	0.1042 (145.88)	0.1042 (145.88)	0.1250 (175.00)	0.0031 (4.34)	0.0028 (3.92)	0.0027 (3.78)	0.1250 (175.00)	0.1250 (175.00)
Kaifeng	0.0546 (76.44)	0.0053 (7.42)	0.0047 (6.58)	0.0045 (6.30)	0.0546 (76.44)	0.0546 (76.44)	0.0617 (86.38)	0.0067 (9.38)	0.0060 (8.40)	0.0057 (7.98)	0.0617 (86.38)	0.0617 (86.38)
Luoyang	0.0452 (63.28)	0.0072 (10.08)	0.0065 (9.10)	0.0063 (8.82)	0.0452 (63.28)	0.0452 (63.28)	0.0483 (67.62)	0.0081 (11.34)	0.0072 (10.08)	0.0070 (9.80)	0.0483 (67.62)	0.0483 (67.62)
Pingdingshan	0.0541 (75.74)	0.0042 (5.88)	0.0037 (5.18)	0.0036 (5.04)	0.0541 (75.74)	0.0541 (75.74)	0.0578 (80.92)	0.0051 (7.14)	0.0045 (6.30)	0.0044 (6.16)	0.0578 (80.92)	0.0578 (80.92)
Anyang	0.0588 (82.32)	0.0028 (3.92)	0.0026 (3.64)	0.0025 (3.50)	0.0588 (82.32)	0.0588 (82.32)	0.0629 (88.06)	0.0033 (4.62)	0.0030 (4.20)	0.0029 (4.06)	0.0629 (88.06)	0.0629 (88.06)
Xinxiang	0.0541 (75.74)	0.0032 (4.48)	0.0029 (4.06)	0.0028 (3.92)	0.0541 (75.74)	0.0541 (75.74)	0.0578 (80.92)	0.0040 (5.60)	0.0037 (5.18)	0.0035 (4.90)	0.0578 (80.92)	0.0578 (80.92)
Jiaozuo	0.0541 (75.74)	0.0031 (4.34)	0.0028 (3.92)	0.0027 (3.78)	0.0541 (75.74)	0.0541 (75.74)	0.0578 (80.92)	0.0035 (4.90)	0.0032 (4.48)	0.0031 (4.34)	0.0578 (80.92)	0.0578 (80.92)
Puyang	0.0541 (75.74)	0.0049 (6.86)	0.0044 (6.16)	0.0043 (6.02)	0.0541 (75.74)	0.0541 (75.74)	0.0578 (80.92)	0.0074 (10.36)	0.0067 (9.38)	0.0065 (9.10)	0.0578 (80.92)	0.0578 (80.92)
Xuchang	0.1136 (159.04)	0.0034 (4.76)	0.0030 (4.20)	0.0029 (4.06)	0.1136 (159.04)	0.1136 (159.04)	0.1724 (241.36)	0.0035 (4.90)	0.0031 (4.34)	0.0030 (4.20)	0.1724 (241.36)	0.1724 (241.36)
Sanmenxia	0.0541 (75.74)	0.0131 (18.34)	0.0118 (16.52)	0.0114 (15.96)	0.0541 (75.74)	0.0541 (75.74)	0.0578 (80.92)	0.0168 (23.52)	0.0150 (21.00)	0.0146 (20.44)	0.0578 (80.92)	0.0578 (80.92)
Shangqiu	0.0541 (75.74)	0.0042 (5.88)	0.0037 (5.18)	0.0036 (5.04)	0.0541 (75.74)	0.0541 (75.74)	0.0578 (80.92)	0.0056 (7.84)	0.0050 (7.00)	0.0048 (6.72)	0.0578 (80.92)	0.0578 (80.92)
Zhoukou	0.0541 (75.74)	0.0050 (7.00)	0.0044 (6.16)	0.0042 (5.88)	0.0541 (75.74)	0.0541 (75.74)	0.0578 (80.92)	0.0062 (8.68)	0.0055 (7.70)	0.0053 (7.42)	0.0578 (80.92)	0.0578 (80.92)
Jiyuan	0.0690 (96.60)	0.0054 (7.56)	0.0049 (6.86)	0.0047 (6.58)	0.0690 (96.60)	0.0690 (96.60)	0.0826 (115.64)	0.0073 (10.22)	0.0066 (9.24)	0.0064 (8.96)	0.0826 (115.64)	0.0826 (115.64)

Note: Values in parentheses indicate USD.

(2) Water supply sequencing factor

The coefficient of the order of water supply indicates the priority of water sources in relation to other water sources. According to the principle of the optimal allocation of water resources and taking into account the specific development model of Henan Province, the order of water supply was determined: first, use surface water; then, use groundwater; and lastly, use other water sources. The water supply sequencing factor was calculated using the following formula:

$$a_i^k = \frac{1 + n_{\max}^k - n_i^k}{\sum\limits_{i=1}^{3} (1 + n_{\max}^k - n_i^k)} \tag{8}$$

where a_i^k denotes the water supply order coefficient for source i in subarea k; $n_{\max}^k$ denotes the maximum value of the water supply order for source i in subarea k; and n_i^k denotes the water supply order for source i in subarea k.

After the calculations were made, the water supply sequence coefficients for each water source for each water user were determined, and these are presented in Table 2.

Table 2. Order coefficients of water supply from various sources for different water users in the forecasted year.

Water User	Life	Agriculture	Industry	Ecology
Surfacewater	0.67	0.33	0.33	0.33
Groundwater	0.33	0.17	0.17	0.00
Other Water Sources	0.00	0.50	0.50	0.67

(3) Water use equity coefficient

In determining the importance of water for water users within the Yellow River Water Supply District in Henan Province, it is important to first ensure that residents have access to water for their daily use, as this has a direct impact on their quality of life. It is equally important to ensure ecological water use, as this has a significant impact on the overall well-being of a community. Next, attention should be paid to meeting the water needs of the industrial sector, followed by agriculture. Therefore, the order of priority should be as follows: domestic, ecological, industrial, and agricultural water.

When employing Equation (4) to compute the water use equity coefficient, the resulting coefficients were determined to be 0.4 for domestic water use, 0.3 for ecological water use, 0.2 for industrial water use, and 0.1 for agricultural water use.

(4) Upper and lower constraints on water demand

Given the paramount importance of meeting the domestic water demand, both the upper and lower limits were constrained to the predicted value of domestic water demand, emphasizing its high priority. In alignment with the advancement of economic and social development, coupled with an enhancement in living standards, there are heightened aspirations for an enhanced ecological environment. Therefore, the upper limit for ecological water demand was set at the predicted value, highlighting the significance of this aspect. Additionally, considering the valuable ecological benefits, the lower limit was conservatively established at 90% of the predicted value of ecological water demand. Considering the dynamics of agricultural development in Henan Province, the upper constraint for agricultural water demand was set at its predicted value, while the lower constraint was set at 60% of the predicted value. Taking into account the distinctive characteristics of industrial water use in Henan Province, the upper constraint for industrial water demand was defined by its predicted value. In recognition of the substantial economic benefits derived from the industrial sector, the lower constraint was prudently set at 70% of the predicted value. This ensured a balanced approach, considering both economic gains and sustainable water management.

(5) Gross Domestic Product

The 2015–2020 GDP of the 13 prefecture-level cities in the statistical study area was determined to have an average annual growth rate of approximately 6.8 percent, and the forecasted year GDP was calculated using the following equation:

$$P_n = P_0 \times (1 + r)^n \tag{9}$$

where P_n denotes forecasted year GDP, amounting to CNY 10^8 (USD 1.4 × 10^7); P_0 denotes base year GDP, amounting to CNY 10^8 (USD 1.4 × 10^7); r denotes the annual growth rate in GDP, expressed as a %; and n denotes the number of years in the forecast.

The calculations for the years 2025 and 2030 in the study area yielded gross product values of CNY 5.95 trillion (USD 8.33 × 10^{11}) and CNY 8.12 trillion (USD 1.14 × 10^{12}), respectively.

3.4. Model Solution

In this paper, the optimal allocation model of water resources in the Henan Yellow River water supply area was optimized and solved using MATLAB R2017b software. The model used was a nonlinear multi-objective optimization model due to the great size of the problem to be solved, so the original problem was split into a two-layer planning model to attain a solution. For the upper layer, only water allocation within each subregion was considered, and for cities with sufficient water sources, priority was given to meeting the lower limit of water demand, and excess water data were recorded. Conversely, for cities incapable of meeting the lower limit, data regarding water shortage were recorded. The problem was addressed using the NSGA-II algorithm. The lower-level model addresses the distribution of water resources among subzones, emphasizing self-allocation and focusing solely on the outward transfer of surface water, making use of water quantity and shortage data recorded in the upper model. Given that the purpose of inter-city dispatching is to meet water constraints, the objective of maximizing economic efficiency was chosen. At this stage, the model was linearly constrained, so it was solved using the linprog solver. The final water distribution scheme was derived by combining the results of the two components.

Kalyanmoy et al. [34] proposed the second-generation Elitist Non-Dominated Sorting Genetic Algorithm (NSGA-II), a fast non-dominated sorting algorithm that introduces an elite retention strategy and congestion distance, solving the non-dominated genetic algorithm's (NSGA) [35] problems of non-dominated sorting computational complexity, lack of elite strategy, and the need to specify shared parameters. NSGA-II consists of two selection operators, one crossover operator, and one mutation operator [36].

The basic idea of the algorithm is as follows: First, initialize the population, randomly generate a parent population with a size of N, and then obtain the first generation of the offspring population through the three basic operations of a genetic algorithm, namely, selection, crossover, and mutation, after carrying out non-dominated sorting. Then, merge the parent population with the offspring population (at this time, the size of the population is 2N); carry out rapid non-dominated sorting while, at the same time, carrying out the crowding calculation for the individuals in each non-dominated layer; and select suitable individuals according to the non-dominance relationship and the size of the congestion distance to select the appropriate individuals with which to form a new parent population with a size of N. Finally, the basic process of the genetic algorithm is used to generate a new offspring population, and this step is executed repeatedly until the conditions for initiating the end of the program are met. A flowchart of the algorithm is shown in Figure 2.

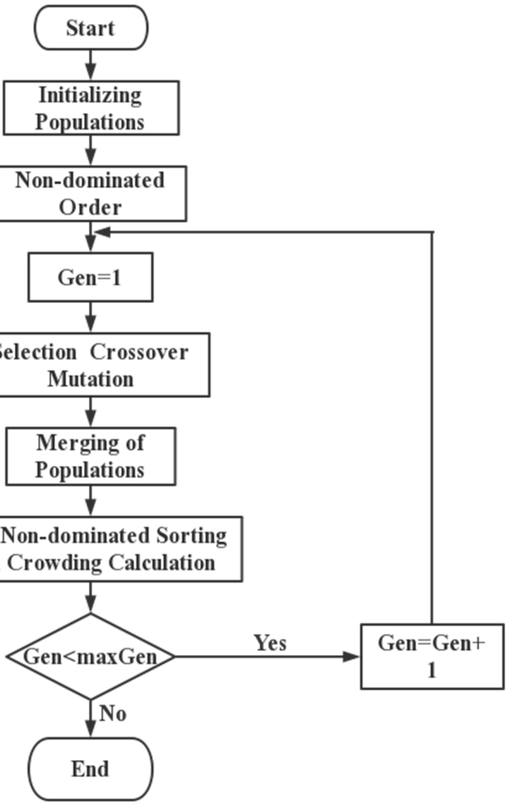

Figure 2. NSGA-II flowchart.

4. Results and Discussion

4.1. Analysis of Water Resource Supply and Demand Balance

Taking the year 2020 as the baseline year and considering the years 2025 and 2030 as forecasted years, a quota-based approach was employed to forecast the water demand for four water users in the Henan Yellow River water supply zone, namely, the domestic, agricultural, industrial, and ecological sectors, under different water inflow frequencies (p = 75%, p = 90%, and p = 97%). This analysis was based on the current state of hydraulic engineering, water sources, and supply potential. Additionally, it incorporates the results from the "Henan Province Integrated Water Management Plan (2021–2035)". Forecasts for available water resources were conducted considering surface water (including inter-basin transfers), groundwater, and other water sources. Building upon the water demand forecasts, a water resource supply–demand balance analysis was conducted for the Henan Yellow River water supply zone. The results of this analysis considering varying water inflow frequencies are presented in Figure 3.

As shown in Figure 3, overall, the Henan Yellow River water supply zone will face severe water shortages. Taking p = 90% as an example, in 2025, the average water shortage in various sub-regions will affect an area of 173 million m^3. In 2030, the average water shortage area decreases to 142 million m^3. There is a slight improvement in the water shortage situation in 2030 compared to that in 2025. The eastern part of the study area will experience more severe water scarcity compared to the western part. Among the regions, Shangqiu City will face the most severe water shortages, with predicted annual water shortages of 1.034 billion m^3 and 1.065 billion m^3 in 2025 and 2030, respectively. In 2025, Shangqiu, Zhoukou, and Pingdingshan will be subject to water shortages exceeding 510 million m^3, while Puyang, Xinxiang, Anyang, and Kaifeng will face water shortages ranging from 230 million m^3 to 510 million m^3. The remaining sub-regions will experience water shortages below 230 million m^3. In 2030, Shangqiu will face a water shortage exceeding 540 million m^3, while Zhoukou and Pingdingshan will experience water shortages ranging from 230 million m^3 to 540 million m^3. The remaining sub-regions will be subject to water shortages below 230 million m^3. In the eastern part of the study area, cities like Shangqiu and Zhoukou will consume significant amounts of water for agriculture, aligning with the research findings of Xu et al. [37] regarding the proportion of agricultural water usage in the Henan Yellow River basin. At different water inflow frequencies, the available water supply gradually decreases, while water usage increases, exacerbating water scarcities. The increase in the available water supply in 2030 will help alleviate the pressure on water supply to some extent, even with the growing water demand. Therefore, the water shortage in 2030 is expected to be somewhat alleviated compared to 2025.

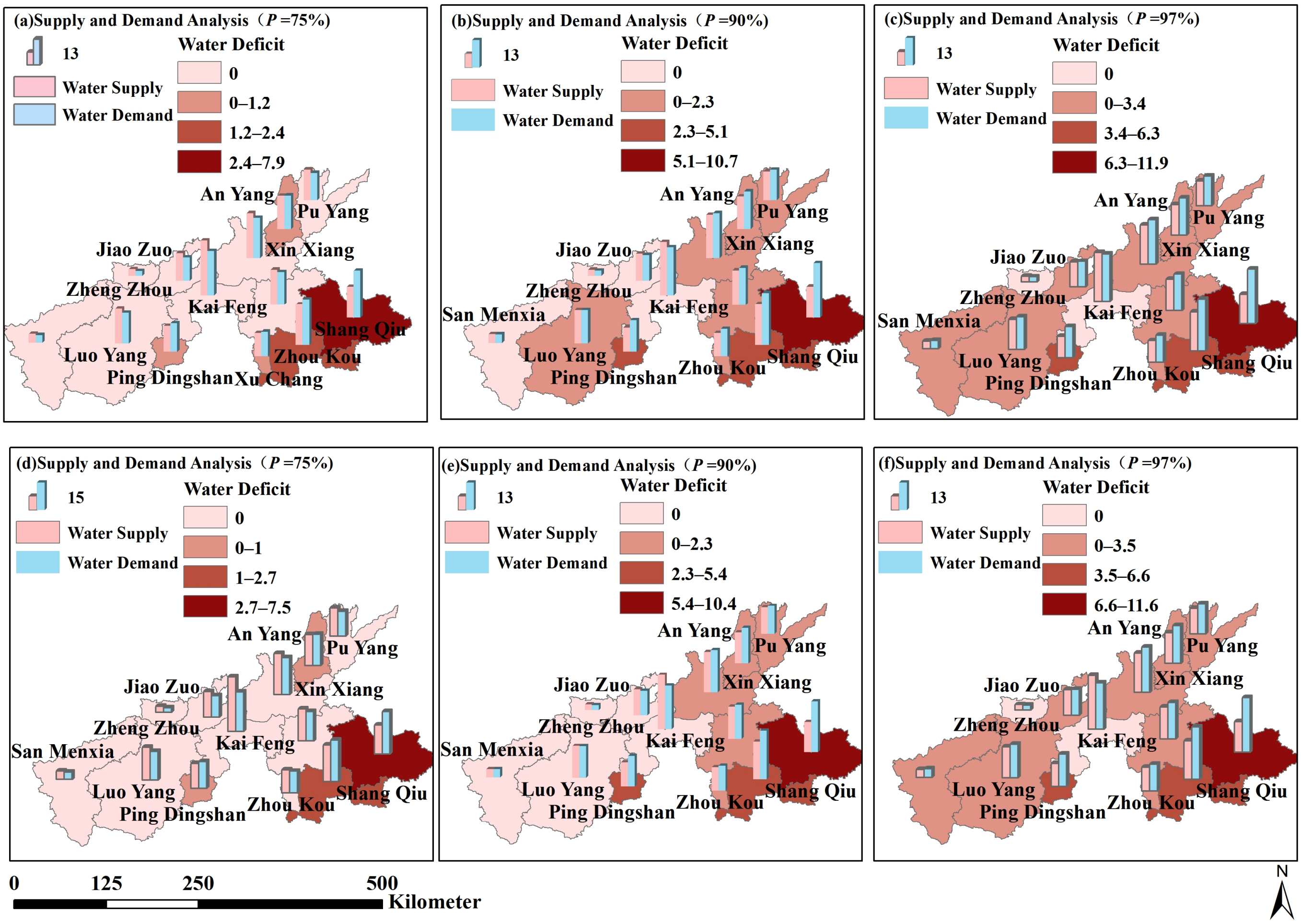

Figure 3. Spatial map of supply and demand balance analysis of Henan Yellow River water supply zone in the forecasted year: (**a**–**c**) represent the results of the 2025 supply-and-demand balance analysis, while (**d**–**f**) represent the results of the 2030 supply-and-demand balance analysis.

4.2. Water Resource Optimization Allocation Plan

In this section, taking p = 90% as an example, we analyze the allocation results. After running the simulation, the benefits of the economic goals, total water shortage targets, and water use efficiency targets for the years 2025 and 2030 are shown in Table 3. From Table 3, it can be observed that the economic benefits in the study area increase year by year, while the total water shortage significantly decreases, and water use efficiency also notably improves. The results of water resource optimization allocation are presented in Table 4. In 2025, the surface water supply will be 7.605 billion m^3, the groundwater supply will be 8.203 billion m^3, and the supply of other water sources will be 1.854 billion m^3. By 2030, the surface water supply will increase to 8.092 billion m^3, the groundwater supply will be 7.875 billion m^3, and the supply of other water sources will increase to 2.395 billion m^3. In 2025, the total domestic water supply in the study area will amount to 3.108 billion m^3.

Among the areas analyzed, Zhengzhou City has the highest domestic water usage, while Jiyuan City has the lowest. The agricultural water allocation is 9.100 billion m^3, with Shangqiu City utilizing the most and Jiyuan City using the least. Industrial water allocation amounts to 2.605 billion m^3, with Luoyang City consuming the most and Jiyuan City consuming the least. Regarding ecological environment water allocation, it amounts to 2.850 billion m^3, with Zhengzhou City utilizing the most and Sanmenxia City using the least. In 2030, the total water allocations for the four water users will be 3.238 billion m^3, 9.300 billion m^3, 2.736 billion m^3, and 3.088 billion m^3, respectively. The water resource optimization allocation results for each sub-region are presented in Table 5.

Table 3. Targeted benefits of the Yellow River water supply zone in Henan in the forecasted year.

Forecasted Year	**Economic Benefits (CNY 10^{12} (USD 1.4×10^6))**	**Water Deficit (10^8 m^3)**	**Water Efficiency (CNY/m^3 (1.4×10^8 USD/m^3))**
2025	0.89 (1.25)	22.63	337.04 (4.72)
2030	1.11 (1.55)	20.25	442.18 (6.19)

Note: Values in parentheses indicate USD.

Table 4. Results of optimal allocation of water resources in the Yellow River water supply zone of Henan in the forecasted year. Unit: 10^8 m^3.

Forecasted Year	**Headwater**	**Life**	**Agriculture**	**Industry**	**Ecology**
2025	Surfacewater	21.77	24.51	11.46	18.31
	Groundwater	9.31	64.47	8.25	0.00
	Other water sources	0.00	2.01	6.34	10.19
2030	Surfacewater	21.53	26.73	13.77	18.89
	Groundwater	10.85	60.71	7.19	0.00
	Other water sources	0.00	5.56	6.40	11.99

Table 5. Results of optimal allocation of water resources in the zones for the forecasted year. Unit: 10^8 m^3.

Subarea	**2025 Sub-User Configuration Results**					**2030 Sub-User Configuration Results**				
	Life	**Agriculture**	**Industry**	**Ecology**	**Total**	**Life**	**Agriculture**	**Industry**	**Ecology**	**Total**
Zhengzhou	5.83	6.42	3.73	5.67	21.65	6.09	6.68	3.83	6.13	22.73
Kaifeng	2.08	9.16	1.47	3.15	15.86	2.18	9.44	1.40	3.41	16.42
Luoyang	3.16	4.82	4.62	2.54	15.14	3.32	4.81	4.87	2.77	15.77
Pingdingshan	2.15	4.87	2.14	3.13	12.29	2.25	6.30	2.49	3.38	14.41
Anyang	2.34	8.30	1.34	2.31	14.29	2.45	9.19	1.40	2.51	15.55
Xinxiang	2.68	11.12	2.34	2.08	18.22	2.81	9.76	2.67	2.27	17.52
Jiaozuo	1.45	6.33	1.64	1.95	11.37	1.51	6.04	1.78	2.12	11.46
Puyang	1.50	7.94	1.09	2.52	13.05	1.54	6.14	1.28	2.71	11.68
Xuchang	1.78	4.63	1.66	2.47	10.54	1.84	5.75	1.27	2.66	11.52
Sanmenxia	0.83	1.29	1.13	0.33	3.58	0.85	1.48	1.21	0.35	3.89
Shangqiu	3.33	13.22	1.90	0.88	19.33	3.46	14.80	2.03	0.97	21.26
Zhoukou	3.66	12.06	2.34	0.92	18.98	3.79	11.82	2.49	1.01	19.12
Jiyuan	0.29	0.82	0.65	0.55	2.31	0.29	0.79	0.64	0.59	2.30
Total	31.08	91.00	26.05	28.50	176.63	32.38	93.00	27.36	30.88	183.63

4.3. Analysis of Water Resource Optimization Allocation Results

4.3.1. Water Shortage Analysis

The water shortage situations in different sub-regions of the Henan Yellow River water supply zone for various upcoming years are illustrated in Figure 4. In 2025, the average water shortage rate in each sub-region of the study area will be 9.69%. Among the studied areas, Shangqiu City and Zhoukou City face the most severe water shortages, with water shortage rates of 22.67% and 20.41%, respectively. The water shortage rates for Pingdingshan City, Anyang City, Xinxiang City, and Xuchang City range between 10% and 20%. The remaining sub-regions have water shortage rates below 10%. In 2030, the average water shortage rate in each sub-region of the study area will be 8.34%, marking a decrease of 1.35% compared to 2025. This indicates a slight alleviation of the water shortage situation. Specifically, Shangqiu City's water shortage rate will decrease from 22.67% in 2025 to 15.94%, signifying an improvement. Zhoukou City, on the other hand, will continue to face a severe water shortage, with a water shortage rate of 20.88%. The water shortage rates for Xinxiang, Anyang, and Puyang range between 10% and 20%. The remaining sub-regions will maintain a water shortage rate below 10%.

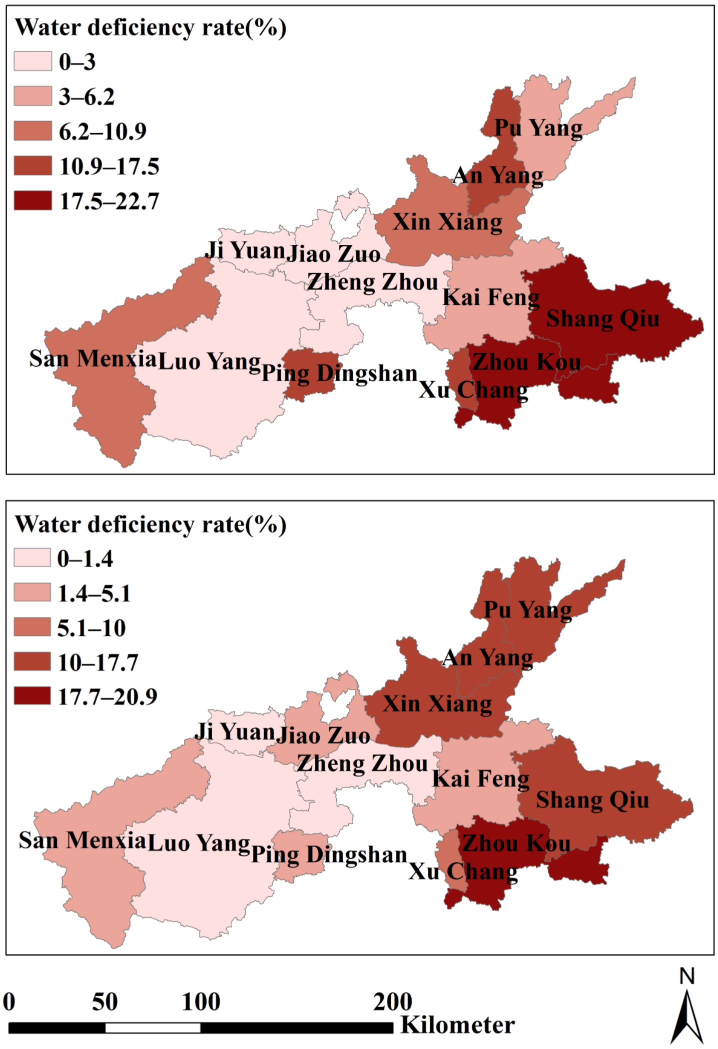

Figure 4. Spatial map of water shortage in the Yellow River water supply zone of Henan in the forecasted years.

The water shortage situations in the different forecasted years are predominantly reflected in agriculture (Figure 5). The total agricultural water shortages amount to 22.62 billion m^3 and 20.23 billion m^3 for the respective years. The average water shortage rates are 16.19% and 13.55% for 2025 and 2030. In 2025, Shangqiu City will face the most severe agricultural water shortage, with a rate of 30.00%. Conversely, in 2030, Zhoukou City will experience the most severe agricultural water shortage, with a rate of 29.90%. Upon analyzing the reasons behind this, it can be noted that, on the one hand, agriculture corresponds to the lowest priority for water allocation. Coupled with its comparatively lower economic benefits in the pursuit of maximizing economic gains and considering its limited water resources, priority in this region is given to fulfilling the water requirements for domestic use, industry, and the ecological environment. This leads to a reduction in the allocation of water for agriculture, resulting in unmet agricultural water demands. This aligns with the research findings of Jiang et al. [38] and Fang et al. [18]. On the other hand, due to different water fee collection standards, excessively low water fees may result in insufficient public awareness of water conservation, leading to wasteful practices. This issue can be addressed by implementing relevant tariff policies to reduce water resource wastage. For example, Macchiaroli et al. [39] employed an approach consisting of implementing an Increasing Block Tariff (IBT) to price water supply services and utilized optimization models to determine the optimal fee structure. This approach can effectively safeguard the sustainable development of water resources. Therefore, in the future, the study area should vigorously promote water-saving agricultural practices, continue to improve water-saving irrigation systems, make necessary adjustments to the agricultural structure, and enhance the efficiency of its use of irrigation water in agriculture. Simultaneously, specific tariff policies can be employed to alter the fee structure in order to reduce water resource wastage.

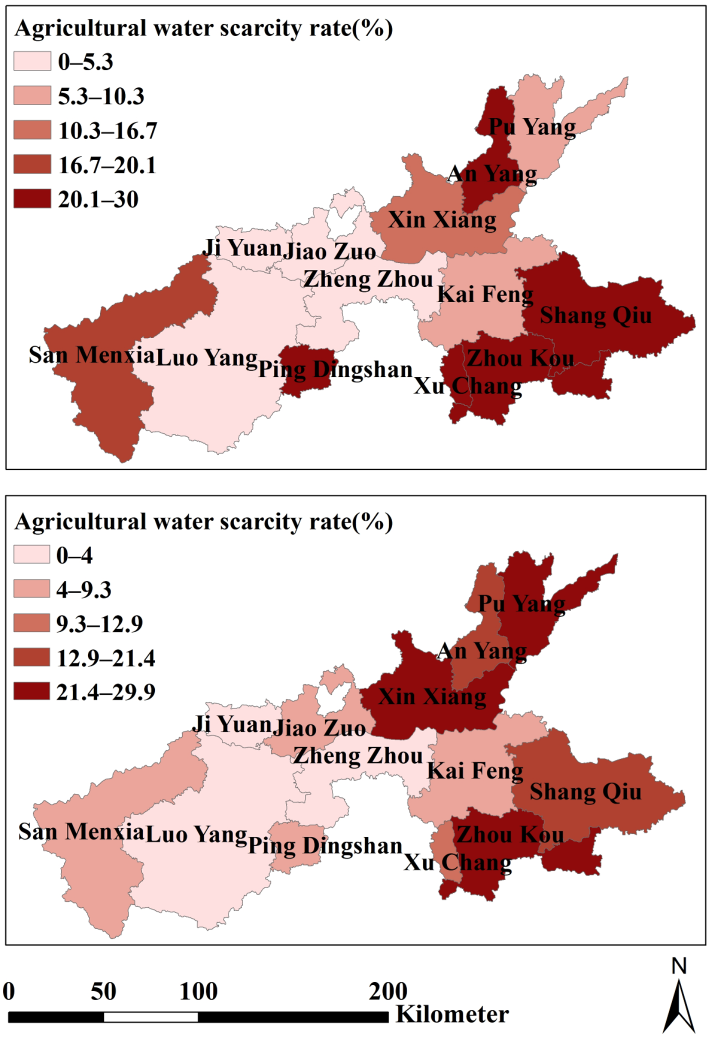

Figure 5. Spatial map of agricultural water shortages in the Yellow River water supply zone of Henan in the forecasted years.

4.3.2. Analysis of Water Supply and Demand Structure

The water supply structure in the study area for the different forecasted years is illustrated in Figure 6, and the water usage structure is shown in Figure 7. Looking at the water supply aspect, for the base year 2020, the proportions of surface water, groundwater, and other water sources in the Henan Yellow River water supply zone are 39.57%, 54.28%, and 6.15%, respectively. For 2025, these proportions will change to 43.06%, 46.44%, and 10.50%, respectively. In 2030, the proportions for each water source supply are 44.07%, 42.89%, and 13.04%, respectively.

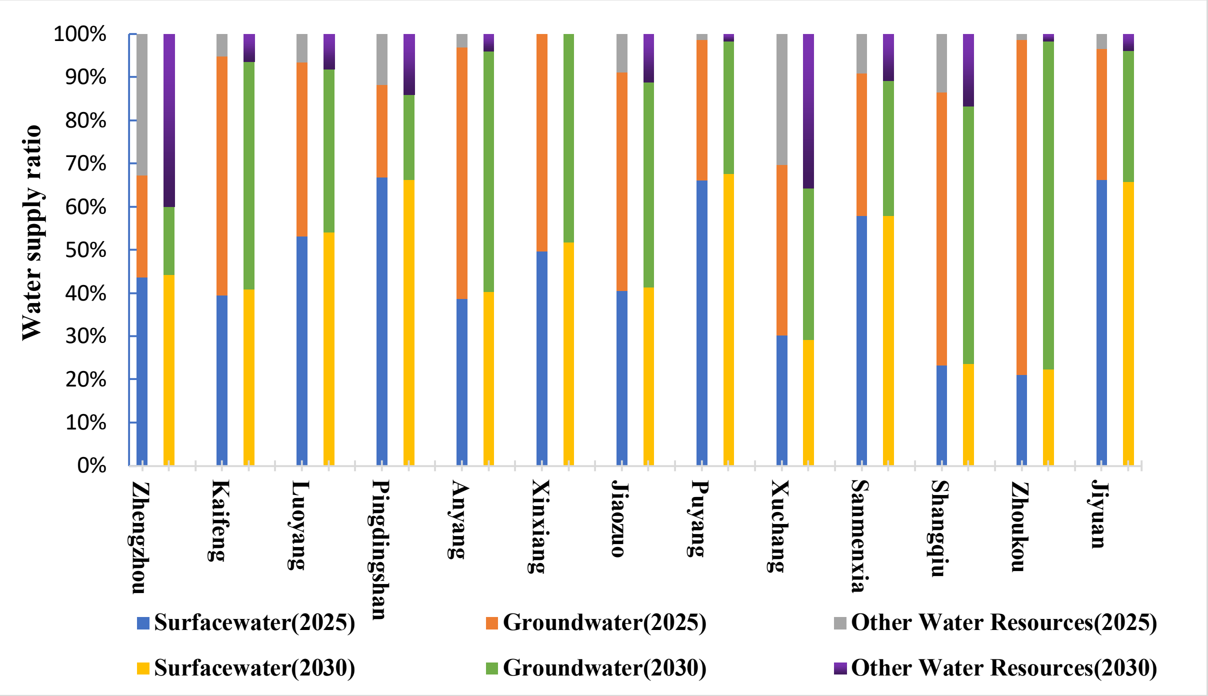

Figure 6. Changes in the water supply structure of water sources in the Yellow River water supply zone in Henan in the forecasted years.

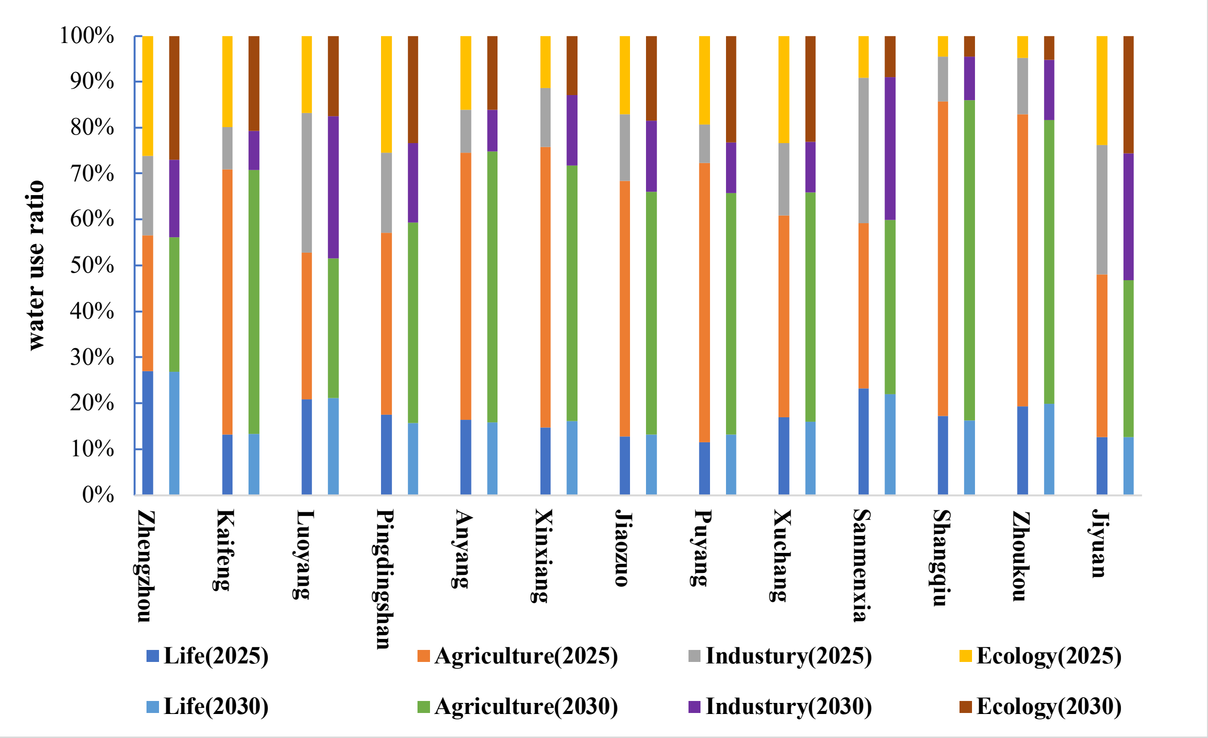

Figure 7. Changes in the proportion of sectoral water use in the Yellow River water supply zone in Henan in the forecasted years.

The proportion of groundwater supply has significantly decreased, while the proportions of surface water and the supply of other water sources have been increasing year by year. This gradual shift suggests the occurrence of water source substitution and an optimization of the water supply structure. This aligns with the research findings reported by Tao et al. [40].

In Figure 6, it can be observed that the main water source for water supply in Kaifeng, Anyang, Shangqiu, and Zhoukou is groundwater. In 2025, the proportions of groundwater supply for these cities will be 55.39%, 58.22%, 63.41%, and 77.78%, respectively. In 2030, these proportions are 52.74%, 55.78%, 59.54%, and 76.11%, respectively. Among these cities, Zhoukou has the highest proportion of groundwater supply (77.78% in 2025 and 76.11% in 2030). Zhengzhou, Luoyang, Pingdingshan, Sanmenxia, and Jiyuan mainly rely on surface water for water supply. In 2025, the proportions of surface water supply for these cities will be 43.71%, 53.21%, 66.85%, 57.98%, and 66.24%, respectively. In 2030, the proportions of surface water supply for these cities will be 44.37%, 54.16%, 66.32%, 57.98%, and 65.80%, respectively. Among the studied cities, Pingdingshan has the highest proportion of surface water supply (66.85% in 2025 and 66.32% in 2030). Conversely, Xinxiang city has relatively similar proportions of surface water and groundwater supply, with values of 49.82% and 50.18% in 2025 and 51.92% and 48.08% in 2030. Zhengzhou and Xuchang have relatively high utilization rates of other water sources, reaching 32.73% and 30.19% in 2025 and increasing to 40.04% and 35.64% in 2030, respectively.

Regarding water demand, for the base year 2020, the proportions of water usage for living, agriculture, industry, and the ecological environment in the Henan Yellow River water supply zone are 14.46%, 54.01%, 16.80%, and 14.74%, respectively. For 2025, these proportions change to 17.60%, 51.52%, 14.75%, and 16.14%, respectively. In 2030, the proportions for each sector's water usage will be 17.63%, 50.65%, 14.90%, and 16.83%, respectively.

Due to the rapid socio-economic development in the research area, overall water usage is on the rise. When considering different user segments, water usage for domestic and industrial purposes is increasing. The trends in total water demand for the forecasted years in Henan province are consistent with the predictions made by Ji et al. [41]. As shown in Figure 7, Zhengzhou has the highest level of domestic water usage, with proportions of 26.92% and 26.79% for the different forecasted years. Conversely, Jiyuan has the lowest domestic water usage percentages, with proportions of 12.55% and 12.58%. Luoyang exhibits the highest level of industrial water usage, with proportions of 30.52% and 30.87% for the different forecasted years. The cities with the lowest industrial water usage proportions are Puyang (8.35% in 2025) and Kaifeng (8.52% in 2030). The ecological environment is closely related to residents' livelihoods, and people are increasingly pursuing ecological benefits. The proportion of water usage for the ecological environment is also on the rise. This is consistent with the results obtained by Zhang et al. [42], who analyzed the trend of ecological water use in Chongqing. Among the analyzed areas, Zhengzhou has the highest levels of ecological water usage, with proportions of 26.18% and 26.95% for the different forecasted years. Conversely, Shangqiu has the lowest levels of ecological water usage, with proportions of 4.55% and 4.56%. With the improvement of agricultural water-saving measures, the proportion of water used in agriculture is decreasing. However, being an agricultural powerhouse, agriculture still remains the dominant sector with respect to water usage in Henan Province. Among the studied cities, Shangqiu has the highest proportion of water usage for agriculture, with percentages of 68.40% and 69.62%. Conversely, Zhengzhou has the lowest proportion of water usage for agriculture, with percentages of 29.67% and 29.38%. With the improvement of agricultural water-saving measures, the proportion of water used in agriculture is decreasing. However, being an agricultural powerhouse, agriculture still remains the dominant sector in terms of water usage in Henan Province. Among the cities, Shangqiu has the highest proportion of water usage for agriculture, with percentages of 68.40% and 69.62%. Conversely, Zhengzhou has the lowest proportion of water usage for agriculture, with percentages of 29.67% and 29.38%.

5. Conclusions

Water resource allocation is an effective means of alleviating regional water scarcity issues and holds significant importance for the sustainable development of water resources. This paper focuses on the Henan Yellow River supply area, a resource-scarce region, and we selected the years 2025 and 2030 as planning horizons. Based on the analysis of supply and demand relationships during drought years (p = 90%), a multi-objective water resource optimization allocation model was constructed. The NSGA-II algorithm was employed to obtain solutions, and the results are as follows:

a. In 2025, the optimized allocation of water resources will amount to 176.63 billion m^3, with water allocations for various sectors as follows: 31.08 billion m^3 for domestic use, 91.00 billion m^3 for agriculture, 26.05 billion m^3 for industry, and 28.5 billion m^3 for ecological and environmental purposes. The water usage proportions for each sector are 17.60%, 51.52%, 14.75%, and 16.14%, respectively. In 2030, the optimized allocation of water resources will be 183.63 billion m^3, with sectoral water allocations as follows: 32.38 billion m^3 for domestic use, 93.00 billion m^3 for agriculture, 27.36 billion m^3 for industry, and 30.88 billion m^3 for ecological and environmental purposes. The water usage proportions for each sector are 17.63%, 50.65%, 14.90%, and 16.83%, respectively.

b. In 2025, the average water scarcity rate in the study area will be 9.69%, while in 2030, it will decrease to 8.34%. Water resource allocation for the different forecasted years can adequately meet the demands of domestic, industrial, and ecological and environmental use. The primary issue is related to water scarcity in agriculture. There is still substantial potential for water conservation in agriculture, which can be achieved through implementing measures such as enhancing irrigation system infrastructure, optimizing crop planting structures, and improving irrigation methods.

c. The optimized water supply structure has improved. This is mainly manifested in an increase in the proportion of surface water supply, a significant increase in the proportion of other water sources, and a more pronounced effect pertaining to utilizing unconventional water sources. The proportion of groundwater supply has significantly decreased, and the process of substituting water sources has gradually been completed, resulting in relief from groundwater over-extraction issues.

The configuration study conducted in this study involved only one decision-making subject, namely, the decision-making needs of the water use sector. However, water resource allocation systems are complex systems involving multiple stakeholders. Neglecting the decision requirements of any party is detrimental to the fairness and rationality of water resource allocation. Subsequent research will further consider the decision requirements of water resource management departments and investigate water resource allocation problems in consideration of both water resource management and water use sectors.

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References

1. Cosgrove, W.J.; Loucks, D.P. Water management: Current and future challenges and research directions. *Water Resour.* **2015**, *51*, 4823–4839. [CrossRef]
2. Li, R.H.; Chang, Y.L.; Wang, Z.C. Study of optimal allocation of water resources in Dujiangyan irrigation district of China based on an improved genetic algorithm. *Water Supply* **2021**, *21*, 2989–2999. [CrossRef]
3. Moghadam, S.H.; Ashofteh, P.S.; Loáiciga, H.A. Optimal Water Allocation of Surface and Ground Water Resources Under Climate Change with WEAP and IWOA Modeling. *Water Resour. Manag.* **2022**, *36*, 3181–3205.
4. Li, C.L.; Zhou, J.Z.; Ouyang, S.; Wang, C.; Liu, Y. Water Resources Optimal Allocation Based on Large-scale Reservoirs in the Upper Reaches of Yangtze River. *Water Resour. Manag.* **2015**, *29*, 2171–2187. [CrossRef]
5. Hong, X.J.; Guo, S.L.; Wang, L.; Yang, G.; Liu, D.D.; Guo, H.J.; Wang, J. Evaluating Water Supply Risk in the Middle and Lower Reaches of Hanjiang River Basin Based on an Integrated Optimal Water Resources Allocation Model. *Water* **2016**, *8*, 364.
6. Guan, H.P.; Chen, L.H.; Huang, S.P.; Yan, C.; Wang, Y. Multi-objective optimal allocation of water resources based on 'three red lines' in Qinzhou, China. *Water Policy* **2020**, *22*, 541–560.
7. Kerachian, R.; Karamouz, M. A stochastic conflict resolution model for water quality management in reservoir-river systems. *Adv. Water Resour.* **2007**, *30*, 2866–2882.
8. Jan, E. The rising pressure of global water shortages. *Nature* **2015**, *517*, 6.
9. Ye, Q.L.; Li, Y.; Zhuo, L.; Zhang, W.L.; Xiong, W.; Wang, C.; Wang, P.F. Optimal allocation of physical water resources integrated with virtual water trade in water scarce regions: A case study for Beijing, China. *Water Resour.* **2018**, *129*, 264–276.
10. Liu, Y. Reasonable allocation of water resources under the strictest water resource management system. *Henan Water Resour. South-North. Water Divers.* **2013**, *5*, 3–4.
11. Wang, R.Y.; Zhao, Z.X.; Huang, C.S.; Sha, H.F.; Geng, L.H. Research progress on water resources management theory of "basing four aspects on water resources". *Water Resour. Prot.* **2023**, *39*, 111–117.
12. Li, X.N.; Wang, X.S.; Guo, H.Y.; Ma, W.M. Multi-Water Resources Optimal Allocation Based on Multi-Objective Uncertain Chance-Constrained Programming Model. *Water Resour. Manag.* **2020**, *34*, 4881–4899.
13. Li, Y.; Xie, J.C.; Jiang, R.G.; Yan, D.F. Application of edge computing and GIS in ecological water requirement prediction and optimal allocation of water resources in irrigation area. *PLoS ONE* **2021**, *16*, e0254547.
14. Li, M.S.; Yang, X.H.; Wu, F.F.; Pius, B. Spatial equilibrium-based multi-objective optimal allocation of regional water resources. *J. Hydrol. Reg. Stud.* **2022**, *44*, 101219. [CrossRef]
15. Xu, J.; Tu, Y.; Zeng, Z. Bilevel Optimization of Regional Water Resources Allocation Problem under Fuzzy Random Environment. *Water Res. Plan. Man.* **2013**, *139*, 246–264. [CrossRef]
16. Yan, B.W.; Jiang, H.N.; Zou, Y.X.; Liu, Y.; Mu, R.; Wang, H. An integrated model for optimal water resources allocation under "3 Redlines" water policy of the upper Hanjiang river basin. *J. Hydrol. Reg. Stud.* **2022**, *42*, 101167. [CrossRef]
17. Fu, J.S.; Zhong, P.A.; Zhu, F.L.; Chen, J.; Wu, Y.N.; Xu, B. Water Resources Allocation in Transboundary River Based on Asymmetric Nash–Harsanyi Leader–Follower Game Model. *Water* **2018**, *10*, 270. [CrossRef]
18. Fang, G.H.; Zhao, W.C.; Li, X.; Wen, X.; Zhuo, B.S. Study on water resources dispatching and allocation in Jiangsu Section of Eastern Route Project of South-to-North Water Diversion Project. *Water Resour. Prot.* **2023**, *39*, 1–8.
19. Jin, L.; Fu, H.Y.; Younggy, K.; Long, J.X.; Huang, G.H. A Bi-Objective Pseudo-Interval T2 Linear Programming Approach and Its Application to Water Resources Management Under Uncertainty. *Water* **2018**, *10*, 1545.
20. Ahmed, A.; Larry, M.; Peter, F. Optimization Model for Agricultural Reclaimed Water Allocation Using Mixed-Integer Nonlinear Programming. *Water* **2018**, *10*, 1291.
21. Higgins, A.; Archer, A.; Hajkowicz, S. A stochastic non-linear programming model for a multi-period water resource allocation with multiple objectives. *Water Resour. Manag.* **2008**, *22*, 1445–1460.
22. Suo, M.Q.; Xia, F.; Fan, Y.R. A Fuzzy-Interval Dynamic Optimization Model for Regional Water Resources Allocation under Uncertainty. *Sustainability* **2022**, *14*, 1096. [CrossRef]
23. Qi, S.; Wan, L.; Fu, B. Multisource and multiuser water resources allocation based on genetic algorithm. *J. Supercomput.* **2018**, *76*, 3222–3230. [CrossRef]
24. Yan, Z.H.; Wang, S.Q.; Liu, B.; Li, X.D. Application of Whale Optimization Algorithm in Optimal Allocation of Water Resources. *E3S Web Conf.* **2018**, *53*, 04019. [CrossRef]
25. Wang, Z.P.; Tian, J.C.; Feng, K.P. Optimal allocation of regional water resources based on simulated annealing particle swarm optimization algorithm. *Energy Rep.* **2022**, *8*, 9119–9126. [CrossRef]
26. Ma, J.; Liu, H.L.; Wu, W.F.; Zhang, Y.Q.; Dong, S. Research on Optimal Allocation of Water Resources in Handan City Based on the Refined Water Resource Allocation Model. *Water* **2022**, *15*, 154.
27. Davijani, H.M.; Banihabib, E.M.; Anvar, N.A.; Hashemil, S.R. Multi-Objective Optimization Model for the Allocation of Water Resources in Arid Regions Based on the Maximization of Socioeconomic Efficiency. *Water Resour. Manag.* **2016**, *30*, 927–946.
28. Zeng, M.; Wang, F.; Zhang, Y.P.; Yu, S. Research on of the optimal allocation of water resources in Guangdong Province Based on fish swarm algorithm. *J. Northwest Univ. (Nat. Sci. Ed.)* **2020**, *50*, 733–741.
29. Jia, Y.Z.; Shen, J.Q.; Wang, H.; Dong, G.H.; Sun, F.H. Evaluation of the Spatiotemporal Variation of Sustainable Utilization of Water Resources: Case Study from Henan Province (China). *Water* **2018**, *10*, 554. [CrossRef]

30. Liu, X.H.; Ai, R.X.; Yan, Y. Realization Path of Saving and Intensive Utilization of Yellow River Water Resources in Henan from the Perspective of GEP. *Yellow River* **2022**, *44*, 55–56+59.
31. Qiao, Y. Discussion on Establishing a Rigid Constraint System for Yellow River Water Resources in Henan. *Yellow River* **2022**, *44*, 80–82.
32. Guo, Y.R.; Hu, Y.; Shi, K.; Bilan, Y. Valuation of Water Resource Green Efficiency Based on SBM–TOBIT Panel Model: Case Study from Henan Province, China. *Sustainability* **2020**, *12*, 6944. [CrossRef]
33. Lei, X. Optimal allocation of water resources in Yangling Demonstration Zone based on multi-objective programming. *J. Water Resour. Water Eng.* **2009**, *20*, 96–100+103.
34. Kalyanmoy, D.; Samir, A.; Amrit, P. A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Trans. Evol. Comput.* **2002**, *6*, 182–197.
35. Srinivas, N.; Deb, K. Muiltiobj ective Optimization Using Nondominated Sorting in Genetic Algorithms. *Evol. Comput.* **1994**, *2*, 221–248. [CrossRef]
36. Gao, P.C.; Wang, H.Y.; Song, C.Q.; Cheng, C.X.; Shen, S. NSGA multi-objective optimization algorithms and geographic decision-making: Principles, state of the art, and the future. *J. Geo-Inf. Sci.* **2023**, *25*, 25–39.
37. Xu, F.Y.; Shi, J.H.; Han, Y.P.; Zhao, H.; Wang, F.Q. Evolution of water use structure and evaluation of spatial equilibrium in the Yellow River basin of Henan Province. *J. North China Univ. Water Resour. Electr. Power (Nat. Sci. Ed.)* **2023**, *44*, 41–48.
38. Jiang, Q.X.; He, X.L.; Wang, Z.L.; Wu, Y.X.; Liao, H.Y. A model for optimal allocation of water resources based on interval multistage stochastic programming and its application. *Adv. Sci. Technol. Water Resour.* **2022**, *42*, 1–7.
39. Macchiaroli, M.; Dolores, L.G.; Mare, G.H.D. Design the Water Tariff Structure: Application and Assessment of a Model to Balance Sustainability, Cost Recovery and Wise Use. *Water* **2023**, *15*, 1309. [CrossRef]
40. Tao, J.; Wang, P.L.; Wang, H.; Yuan, J.W.; Zuo, Q.T. Research on the optimal allocation of water resources in the Henan section of the Yangtze River to Huaihe River water transfer project based on A-NSGA-III algorithm. *Adv. Sci. Technol. Water Resour.* **2023**, *43*, 1–13.
41. Ji, J.T.; Qu, X.N.; Zhang, Q.; Tao, J. Predictive analysis of water resource carrying capacity based on system dynamics and improved fuzzy comprehensive evaluation method in Henan Province. *Environ. Monit. Assess.* **2022**, *194*, 500. [CrossRef] [PubMed]
42. Zhang, W.J.; Yu, Y.; Zhou, X.Y.; Yang, S.; Li, C. Evaluating Water Consumption Based on Water Hierarchy Structure for Sustainable Development Using Grey Relational Analysis: Case Study in Chongqing, China. *Sustainability* **2018**, *10*, 1538. [CrossRef]