An Integrated Method for Interval Multi-Objective Planning of a Water Resource System in the Eastern Part of Handan

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Abstract: In this study, an integrated solving method is proposed for interval multi-objective planning. The proposed method is based on fuzzy linear programming and an interactive two-step method. It cannot only provide objectively optimal values for multiple objectives at the same time, but also effectively offer a globally optimal interval solution. Meanwhile, the degree of satisfaction related to different objective functions would be obtained. Then, the integrated solving method for interval multi-objective planning is applied to a case study of planning multi-water resources joint scheduling under uncertainty in the eastern part of Handan, China. The solutions obtained are useful for decision makers in easing the contradiction between supply of multi-water resources and demand from different water users. Moreover, it can provide the optimal comprehensive benefits of economy, society, and the environment.

Keywords: joint scheduling; multi-objective; satisfaction degree; uncertainty

1. Introduction

At present, there are a great number of contradictions in the water resources management system. First of all, different from pure pursuit of economic benefit in the past [1,2], social and environmental benefits are being paid more and more attention with the enhancement of the public's consciousness on environmental protection [3]. Secondly, as a results of the implementation of South-to-North water diversion project, how to use the transferred water and local water effectively has become a difficult issue in many parts of China [4–7]. Thirdly, there have been serious contradictions between water supply and demand, water shortage and water pollution, as well as the competition among water users [8]. In addition, water resources systems can be complex with uncertainties which may exist in technical, social, environmental, political, and financial factors [9,10]. For example, there are serious water resource problems in the eastern part of Handa, China: (a) the distribution of water resources is uneven since the main surface water of Handan (Yuecheng and Dongwushi reservoirs) are located in the western part of Handan [11]; (b) the groundwater is seriously over-exploited because it is the most important source for agriculture which is the main industry [12]; (c) transferred water and local water conservancy projects cannot be organically combined, and thus cannot realize the maximum benefit of transferred water [13]; (d) there is a serious competition among different water users [14,15]. Therefore, it is desired to develop effective multi-objective optimization methods for water resource management under such contradictions and uncertainties.

Multi-objective linear programming (MOLP) is an effective method for problems with many goals. In the past decades, MOLP was developed and applied in many water resources management

systems [16–22]. Han et al. demonstrated a reasonable allocation model for urban multi-source water to multi-user in Dalian city through using the step method [23]. Su et al. presented a multi-objectives allocation model of water resources and applied it in the Shiyang River basin [24]. Yang et al. improved a multi-objective evolutionary optimization algorithm and applied for hydropower reservoir operations in the California Oroviille-Thermalito complex [25]. However, in actual problems, there are many uncertain factors in water resources systems, such as rainfall events, inflow of river, benefit of water use, and the quantity of water demand [8,13,26–28]. All these uncertain factors influence the parameters definition of a system model. Therefore, a great number of uncertain multi-objective linear programming models were proposed to handle different uncertainties [16,29–36]. Among them, interval multi-objective linear programming model was an effective technique for problems with conflicts among the objectives and interval uncertainty [8]. For MOLP, there are many solving methods, such as the weighted sum method [37], ε-constraint method [38], objective programming method [39], interactive methods [40], pareto-dominated methods [41], and new dominance methods [42]. Fuzzy programming is one of the new dominance methods and has been widely studied [43,44]. It can effectively convert MOLP into single objective linear programming by introducing the flexible index [37]. The advantage of fuzzy programming is that the transform process is objective without subjective information, and it is an analytical method without iteration error. However, it is difficult to solve interval multi-objective linear programming models with interval coefficients in both objectives and constraints [8,16,29]. Previously, several scholars made great efforts to develop solutions methods for the interval linear programming models [45–50]. Among them, the improved two-step method (ITSM) proposed by Wang and Huang was proved to be a simple and effective method for interval linear programming without violation [50].

Therefore, the aim of this paper is to present an integrated approach for interval multi-objective planning by coupling the fuzzy programming and ITSM. The decision makers can make tradeoffs among a more valid range of multi-objectives, and then a viable solution with interval form can be obtained. The proposed model is applied to multiple water resources joint scheduling in the eastern part of Handan, China. The rational scheduling model pursues the maximum integration benefits of economy, society, and environment under uncertainty. At last, the comparison between the integrated approach and weighted sum method is provided to prove objectivity and stability of the proposed method in this paper. It is an effective method to promote the sustainable utilization of water resources and social development in the study area.

2. Methodology

2.1. IMOLP Model

According to Wu et al. [16], a general interval multi-objective planning problem can be formulated as follows:

$$\text{Max } f_1^{\pm} = C_1^{\pm} X^{\pm} \tag{1a}$$

$$\text{Min } f_2^{\pm} = C_2^{\pm} X^{\pm} \tag{1b}$$

Subject to:

$$A^{\pm} X^{\pm} \leq B^{\pm} \tag{1c}$$

$$X^{\pm} \geq 0 \tag{1d}$$

where $f_1^{\pm}$ and $f_2^{\pm}$ are the interval objective functions. $A^{\pm} \in \{R^{\pm}\}^{m \times n}$, $B^{\pm} \in \{R^{\pm}\}^{m \times 1}$, $C_1^{\pm} \in \{R^{\pm}\}^{1 \times n}$, $C_2^{\pm} \in \{R^{\pm}\}^{1 \times n}$, and $X^{\pm} \in \{R^{\pm}\}^{n \times 1}$ ($R^{\pm}$ means a set of interval data).

2.2. Integrated Solving Method

Before solving model (1), it is necessary to introduce the improved two-step method (ITSM) for interval linear programming (ILP) [50]. According to Huang et al. [45], a general ILP problem can be formulated as follows:

$$\text{Max } f^{\pm} = C^{\pm} X^{\pm} \tag{2a}$$

Subject to:

$$A^{\pm} X^{\pm} \leq B^{\pm} \tag{2b}$$

$$X^{\pm} \geq 0. \tag{2c}$$

Based on ITSM, model (2) can be converted into two deterministic sub-models, which correspond to the upper and lower bounds of objective function value, respectively. Since the objective function is to be maximized, the sub-model corresponding to f^{+} should first be calculated, and then the lower bound sub-model (corresponding to f^{-}) can be formulated on the basis of the result of the upper bound sub-model. Specifically, the two sub-models (3) and (4) for f^{+} and f^{-} individually are:

$$\text{Max } f^{+} = \sum_{j=1}^{k} c_j^{+} x_j^{+} + \sum_{j=k+1}^{n} c_j^{+} x_j^{-} \tag{3a}$$

Subject to:

$$\sum_{j=1}^{k} |a_{ij}|^{-} Sign(a_{ij}^{\pm}) x_j^{+} + \sum_{j=1}^{k} |a_{ij}|^{+} Sign(a_{ij}^{\pm}) x_j^{-} \leq b_i^{+}, \ \forall i \tag{3b}$$

$$x_j^{+} \geq 0, \ j = 1, \ 2, \ \ldots, \ k \tag{3c}$$

$$x_j^{-} \geq 0, \ j = k+1, \ \ldots, \ n \tag{3d}$$

$$\text{Max } f^{-} = \sum_{j=1}^{k} c_j^{-} x_j^{-} + \sum_{j=k+1}^{n} c_j^{-} x_j^{+}. \tag{4a}$$

Subject to:

$$\sum_{j=1}^{k} |a_{ij}|^{+} Sign(a_{ij}^{\pm}) x_j^{-} + \sum_{j=1}^{k} |a_{ij}|^{-} Sign(a_{ij}^{\pm}) x_j^{+} \leq b_i^{-}, \ \forall i \tag{4b}$$

$$\sum_{j=1}^{n} a_{ij}^{-} x_j' \leq b_i^{+}, \ x_j' = \begin{cases} x_j^{-} & if \ sign(a_{ij}^{\pm}) = sign(c_j^{\pm}), \ j = 1, \ 2, \ \ldots, \ k \\ x_{jopt}^{+} & if \ sign(a_{ij}^{\pm}) \neq sign(c_j^{\pm}), \ j = 1, \ 2, \ \ldots, \ k \\ x_j^{+} & if \ sign(a_{ij}^{\pm}) = sign(c_j^{\pm}), \ j = k+1, \ k+2, \ \ldots, \ n \\ x_{jopt}^{-} & if \ sign(a_{ij}^{\pm}) \neq sign(c_j^{\pm}), \ j = k+1, \ k+2, \ \ldots, \ n \end{cases} \tag{4c}$$

$$x_{jopt}^{+} \geq x_j^{-} \geq 0, \ j = 1, \ 2, \ \ldots, \ k \tag{4d}$$

$$x_j^{+} \geq x_{jopt}^{-} \geq 0, \ j = k+1, \ \ldots, \ n. \tag{4e}$$

where $c_j^{\pm}(j = 1, \ 2, \ \ldots, \ k)$ means the former k coefficients in the objective function are positive, while $c_j^{\pm}(j = k+1, \ \ldots, \ n)$ means the rest $n - k$ coefficients are negative. Through solving the above two sub-models successively, the values of f_{opt}^{+}, $x_{jopt}^{+}(j = 1, \ 2, \ \ldots, \ k)$ and $x_{jopt}^{-}(j = k+1, \ \ldots, \ n)$ can be obtained based on model (3), while the values of f_{opt}^{-}, $x_{jopt}^{-}(j = 1, \ 2, \ \ldots, \ k)$ and $x_{jopt}^{+}(j = k+1, \ \ldots, \ n)$ should be taken based on model (4). Thus, the solution of model (2) can be obtained by integrating the results of models (3) and (4), which are shown as follows:

$$f_{opt}^{\pm} = [f_{opt}^{-}, \ f_{opt}^{+}] \tag{5a}$$

$$x_{jopt}^{\pm} = [x_{jopt}^{-}, \; x_{jopt}^{+}], \; \forall j. \tag{5b}$$

It is known that the single objective has a unified and simple solution. So the solution of multi-objective programming is generally on the basis of the single objective programming algorithm. According to Wang [37] and Huang et al. [45], model (1) can be transformed into an interval fuzzy linear planning problem (IFLP) by coupling the fuzzy programming. The IFLP model can be shown as follows:

$$Max\lambda^{\pm} \tag{6a}$$

Subject to:

$$C_1^{\pm}X^{\pm} \geq f_{1l}^{-} + \lambda^{\pm}(f_{1u}^{+} - f_{1l}^{-}) \tag{6b}$$

$$C_2^{\pm}X^{\pm} \leq f_{2u}^{+} - \lambda^{\pm}(f_{2u}^{+} - f_{2l}^{-}) \tag{6c}$$

$$A^{\pm}X^{\pm} \leq B^{\pm} \tag{6d}$$

$$X^{\pm} \geq 0 \tag{6e}$$

$$0 \leq \lambda^{\pm} \leq 1. \tag{6f}$$

where $\lambda^{\pm}$ is the decision variable that relates to the satisfaction degree for the fuzzy decision; $f_{1u}^{+} = \max(f_{11}^{+}, f_{12}^{+})$, $f_{1l}^{-} = \min(f_{11}^{-}, f_{12}^{-})$, $f_{2u}^{+} = \max(f_{21}^{+}, f_{22}^{+})$, and $f_{2l}^{-} = \min(f_{21}^{-}, f_{22}^{-})$ mean the upper and lower bounds of $f_1^{\pm}$ and $f_2^{\pm}$ individually, and the values of $f_{1u}^{+} - f_{1l}^{-}$, and $f_{2u}^{+} - f_{2l}^{-}$ are the flexible indexes for $f_1^{\pm}$ and $f_2^{\pm}$ respectively. In detail, f_{11}^{+}, f_{11}^{-}, f_{21}^{+}, and f_{21}^{-} are the solutions of the single objective function (1a) with constraints (1c) and (1d); f_{12}^{+}, f_{12}^{-}, f_{22}^{+}, and f_{22}^{-} are the solutions of the single objective function (1b) with constraints (1c) and (1d). Under this condition, it can be known that model (6) is actually an interval single objective linear programming. Therefore, its solution can be calculated by ITSM and shown as follows:

$$\lambda_{opt}^{\pm} = [\lambda_{opt}^{-}, \; \lambda_{opt}^{+}] \tag{7a}$$

$$x_{jopt}^{\pm} = [x_{jopt}^{-}, \; x_{jopt}^{+}], \; \forall j. \tag{7b}$$

And thus, the values of $f_{1opt}^{\pm}$ and $f_{2opt}^{\pm}$ can be obtained by calculating the Equations (1a) and (1b) based on Equation (7b), which are shown as follows:

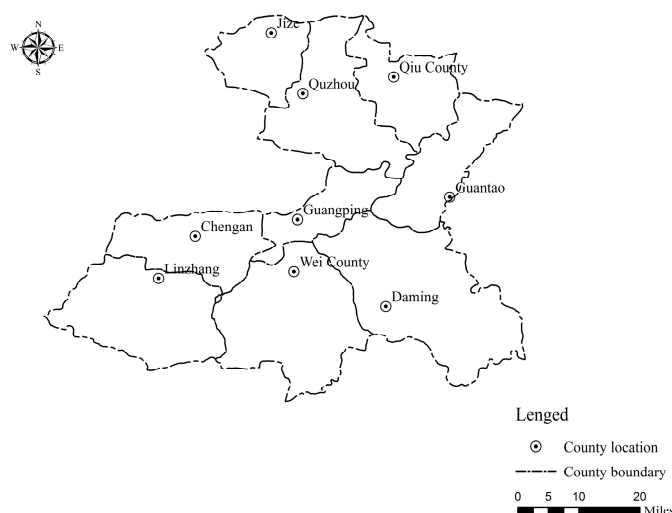$$f_{1opt}^{\pm} = [f_{1opt}^{-}, \; f_{1opt}^{+}] \tag{7c}$$

$$f_{2opt}^{\pm} = [f_{2opt}^{-}, \; f_{2opt}^{+}]. \tag{7d}$$

3. Application

3.1. The Study Area Profile

The eastern part of Handan is 4271 square kilometers, accounting for 36% of the total area of Handan, and the geographical position is 36°6′–36°57′ in north latitude, longitude 114°24′–115°29′. Administrative division includes Linzhang County, Cheng'an County, Guangping County, Quzhou County, Jize County, Daming County, Wei Country, Guantao County, and Qiu County, which is shown in Figure 1.

The Adminstrative Map of Eastern Handan

Figure 1. The administrative map of eastern Handan.

In the study area, the water resources include surface water, transferred water, groundwater, and recycled water. The surface water includes Yuecheng reservoir water, Dongwushi reservoir water, and Wei River. Yuecheng reservoir is located in the western mountainous area of Ci County, mainly supplying to provinces of Hebei and Henan. The project affords domestic water, agricultural water, industrial water, and ecological water for each region of Handan. Dongwushi reservoir is located in the western mountainous area of Ci County. It provides industrial water, agricultural water, and ecological water for each region in the eastern part of Handan every year. Wei River belongs to level one in the river level, with a total length of 70 km. It originates in the Taihang Mountain foothills of Xinxiang, and flows through Wei County and Daming County, importing Fuyang River into Guantao County. The transferred water includes the South-to-North water and Yellow River water.

3.2. Forecast of Water Demand and Supply under Uncertainty

Based on the development planning of the eastern part of Handan, the water demand includes municipality, industry, agriculture and ecology, in which the domestic water demand contains urban and rural domestic water demands. In this paper, the first three water demands are predicted by the quota method, and the ecological water demand is forecasted by direct method [51]. In planning level year, the upper and lower water demands for each water user take 80% and 120% of the planning water demand respectively in every administrative region, which are shown in Table 1.

Table 1. Upper and lower limit of water demand (10^6 m^3).

Administrative Division	Domestic Water		Ecological Water		Industrial Water		Agricultural Water	
	Lower	Upper	Lower	upper	Lower	Upper	Lower	Upper
Daming	[34.51, 38.15]	[39.78, 41.02]	[1.80, 1.98]	[1.80, 1.98]	[7.40, 8.18]	[11.10, 12.26]	[124.07, 137.13]	[174.33, 192.69]
Wei County	[25.59, 28.29]	[29.39, 32.49]	[1.92, 2.12]	[1.92, 2.12]	[6.27, 6.93]	[9.41, 10.40]	[247.19, 273.21]	[316.53, 349.85]
Quzhou	[7.79, 8.61]	[9.69, 10.71]	[0.82, 0.90]	[0.82, 0.90]	[7.62, 8.42]	[11.42, 12.62]	[77.36, 79.56]	[142.46, 157.46]
Qiu County	[7.55, 8.35]	[9.45, 10.45]	[0.53, 0.59]	[0.53, 0.59]	[1.72, 1.90]	[2.57, 2.85]	[53.76, 59.42]	[70.40, 77.81]
Jize	[8.98, 9.92]	[10.88, 12.02]	[0.65, 0.71]	[0.65, 0.71]	[5.37, 5.93]	[8.05, 8.89]	[51.07, 56.45]	[68.16, 75.34]
Guang Ping	[3.10, 3.42]	[5.00, 5.52]	[0.64, 0.70]	[0.64, 0.70]	[2.48, 2.74]	[3.71, 4.11]	[42.11, 44.70]	[66.57, 73.57]
Cheng'an	[8.08, 8.94]	[9.98, 11.04]	[0.88, 0.98]	[0.88, 0.98]	[7.93, 8.77]	[11.90, 13.16]	[88.29, 97.59]	[112.19, 123.99]
Linzhang	[18.20, 20.12]	[22.00, 24.32]	[1.41, 1.55]	[1.41, 1.55]	[2.13, 2.35]	[3.19, 3.53]	[111.06, 122.75]	[147.34, 162.84]
Guantao	[7.08, 7.82]	[8.98, 9.92]	[0.72, 0.80]	[0.72, 0.80]	[6.05, 6.69]	[9.08, 10.04]	[58.02, 64.12]	[75.17, 83.09]

The precipitation, surface water resources, groundwater resources, transferred water resources, and the total volume of water resources were analyzed for Handan city by Wang and Li [52]. Accordingly, the amount of available water supply in the eastern part of Handan can be obtained and is shown in Table 2.

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

Water Resources	Supply Water
Surface water	[499.17, 550.19]
Groundwater	[450.51, 505.30]
Recycled water	[89.10, 105.82]
Transferred water	[85.60, 96.17]

3.3. Application Model

Based on the current relevant national policies and local water resources planning, the proposed interval multi-objective planning model regards 2013 as present level year and regards 2020 as planning level year in the study area. The water resources in this model will refer to surface water, groundwater, diversion, and recycled water. Targets will include economic, social, and environmental benefits. Constraints will contain the water supply capacity, water requirement, water conveyance capacity, pollution emission of chemical oxygen demand (COD), and variable nonnegative constraint. Then collected data are imported into the model, through the model operation and debugging, the specific optimization results are obtained. The proposed model is as follows:

3.3.1. Objective Function

Economic benefit target (with the goal of maximizing the net benefit of water supply).

$$\max f_1^{\pm}(x) = \sum_{k=1}^{9} \sum_{i=1}^{4} \sum_{j=1}^{4} e_{kj}^{\pm} R_{kij} x_{kij}^{\pm} \tag{8a}$$

Social benefit target (minimizing water resources shortage used to indirectly reflect the social benefit).

$$\min f_2^{\pm}(x) = \sum_{k=1}^{9} \sum_{j=1}^{4} \sum_{i=1}^{4} (D_{kj}^{\pm} - R_{kij} x_{kij}^{\pm}) \tag{8b}$$

Environmental target (with target of minimizing the sum of chemical oxygen demand that is main pollution emission area).

$$\min f_3^{\pm}(x) = \sum_{k=1}^{9} \sum_{j=1}^{4} \sum_{i=1}^{4} q d_{kj}^{\pm} w_{kj} R_{kij} x_{kij}^{\pm} \tag{8c}$$

3.3.2. Constraints

Water supply capacity constraints:

$$\sum_{k=1}^{9} R_{kij} x_{kij}^{\pm} \le s_{ij}^{\pm}, \ \forall i, j. \tag{8d}$$

Water demand constraints:

$$D_{kj\min}^{\pm} \le \sum_{i=1}^{4} R_{kij} x_{kij}^{\pm} \le D_{kj\max}^{\pm}, \ \forall t, k, j. \tag{8e}$$

Carrying capacity constraints:

$$\sum_{j=1}^{4} R_{kij} x_{kij}^{\pm} \le Q_{ki}^{\pm}, \ \forall k, i. \tag{8f}$$

COD pollution emissions constraints:

$$\sum_{i=1}^{4} q d_{kj}^{\pm} w_{kj} R_{kij} x_{kij}^{\pm} \le DQ_{kj}^{\pm}, \ \forall k, j. \tag{8g}$$

Variable nonnegative constraints:
$$x_{kij}^{\pm} \ge 0. \tag{8h}$$

where:

k: The research regions, k = 1 (Daming County), 2 (Wei County), 3 (Quzhou County), 4 (Qiu County), 5 (Jize County), 6 (Guangping County), 7 (Cheng'an County), 8 (Linzhang County), 9 (Guantao County);

i: Headwaters, i = 1 (surface water), 2 (transferred water), 3 (groundwater), 4 (recycled water);

j: Water users, j = 1 (industrial water), 2 (domestic water), 3 (agricultural water), 4 (ecological water);

$e_{kj}^{\pm}$: The net benefit coefficient of every water sector in each region;

$x_{kij}^{\pm}$: Each user's water allocation;

$D_{kj}^{\pm}$: Each user's water demand;

$d_{kj}^{\pm}$: The content of pollutants that each user emissions sewage;

w_{kj}: The coefficient of sewage;

q: The content of COD in the pollutants;

R_{kij}: Water distribution relationship;

$s_{ij}^{\pm}$: Supply amount;

$D_{kj\min}^{\pm}$: The minimized water requirement;

$D_{kj\,\max}^{\pm}$: Rated water demand;

$Q_{ki}^{\pm}$: The biggest water conveyance capacity of the water conveyance project;
$DQ_{kj}^{\pm}$: The provisions of the COD emissions.

Based on the solving method depicted in Section 2, model (8) can be converted into an IFLP model with one objective. And then the IFLP model is decomposed into two deterministic submodels and solved sequentially by ITSM to obtain the interval solutions [50]. The specific solution process can be summarized as follows.

Step 1. Solve ILP models with the objective being (8a) and constraints being (8d–h), the objective being (8b) and constraints being (8d–h), objective being (8c) and constraints being (8d–h) by ITSM individually, in order to obtain the flexible indexes for each objective and formulate IFLP model for model (8).
Step 2. Transform IFLP model into two submodels, where the upper bound (λ^+) is first solved because the objective is to maximize $\lambda^{\pm}$.
Step 3. Solve the λ^+ submodel and obtain solutions of $x_{kij\ opt}^+$ and λ_{opt}^+.
Step 4. Formulate the objective function and relevant constraints of the λ^- submodel based on ITSM.
Step 5. Solve the λ^- submodel and obtain solutions of $x_{kij\ opt}^-$ and λ_{opt}^-.
Step 6. Obtain the values of all objectives by calculating (8a–c) based on $x_{kij\ opt}^+$ and $x_{kij\ opt}^-$.
Step 7. Integrate solutions of the two submodels and all objectives' values, and the optimal results can be expressed as $\lambda_{opt}^{\pm} = [\lambda_{opt}^-, \lambda_{opt}^+]$, $f_{1opt}^{\pm} = [f_{1opt}^-, f_{1opt}^+]$, $f_{2opt}^{\pm} = [f_{2opt}^-, f_{2opt}^+]$, $f_{3opt}^{\pm} = [f_{3opt}^-, f_{3opt}^+]$, and $x_{kij\ opt}^{\pm} = [x_{kij\ opt}^-, x_{kij\ opt}^+]$.
Step 8. Stop.

4. Results and Discussion

4.1. Results Analysis

Through solving the interval multi-objective programming model by the above depicted integrated method, both of the objective function values and water resources allocation schemes can be obtained by solving model (8), which can be seen in Tables 3–7 and Figures 2–5. Table 3 shows the results of objective function values, it is noted that the upper bound of λ is corresponding to the upper bound of model (8), meaning higher degree of satisfaction and higher risk of violating the constraints. And the lower bound of λ is corresponding to the lower bound of model (8), meaning lower degree of satisfaction and lower risk of violating the constraints. Specifically, the value of λ^+ for model (8) is 0.986, and the corresponding values for economic, social, and environmental are 434.01 $\times$ 10^6 China Yuan (CNY), 79.57 $\times$ 10^6 m^3, and 0.045 $\times$ 10^6 kg, individually. Conversely, the value of λ^- for model (8) is 0.981, and the corresponding values for economic, social, and environmental are 410.23 $\times$ 10^6 CNY, 70.21 $\times$ 10^6 m^3, and 0.039 $\times$ 10^6 kg, respectively.

Table 3. Results of objective function values.

λ^+ = 0.986			λ^- = 0.981		
Economic Benefit (10^6 CNY)	Social Benefit (10^6 m^3)	Environmental Benefit (10^6 kg)	Economic Benefit (10^6 CNY)	Social Benefit (10^6 m^3)	Environmental Benefit (10^6 kg)
434.01	79.57	0.045	410.23	70.21	0.039

In detail, Figure 2 shows the amount of water allocated to municipality in each region from different water resources. It can be seen that the total amount of domestic water demand is [129.25, 146.25] $\times$ 10^6 m^3, while the amount of water which is allocated to municipality is [129.25, 140.25] $\times$ 10^6 m^3. So the water shortage is 6 $\times$ 10^6 m^3 with the average deficiency rate being 4.1% under the upper

water demand, and the top two water shortage counties are Guangping County and Guantao County, whose deficit rate are 18% and 14.6% respectively. The amount of water allocated to municipality in Daming County, Linzhang County, and Wei County is very large, which accounts for about 65.3% of the total.
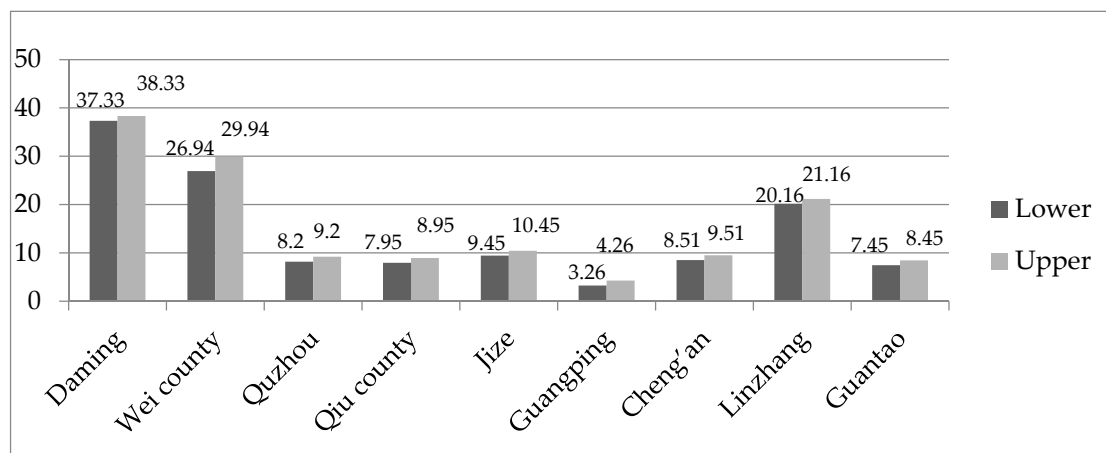

Figure 2. Result of water resources allocation to municipality (10^6 m^3).

Figure 3 is the result of total water quantity allocated to ecology in each region from different water resources. It is noted that the total amount of ecological water demand is $[9.60, 9.92] \times 10^6$ m^3, the amount of allocated water to ecology is 9.85×10^6 m^3. When the water demand equals the upper bound, the water deficiency is 0.07×10^6 m^3 with the average deficiency rate being 0.7%, and the same deficit rate happened in every administrative County.
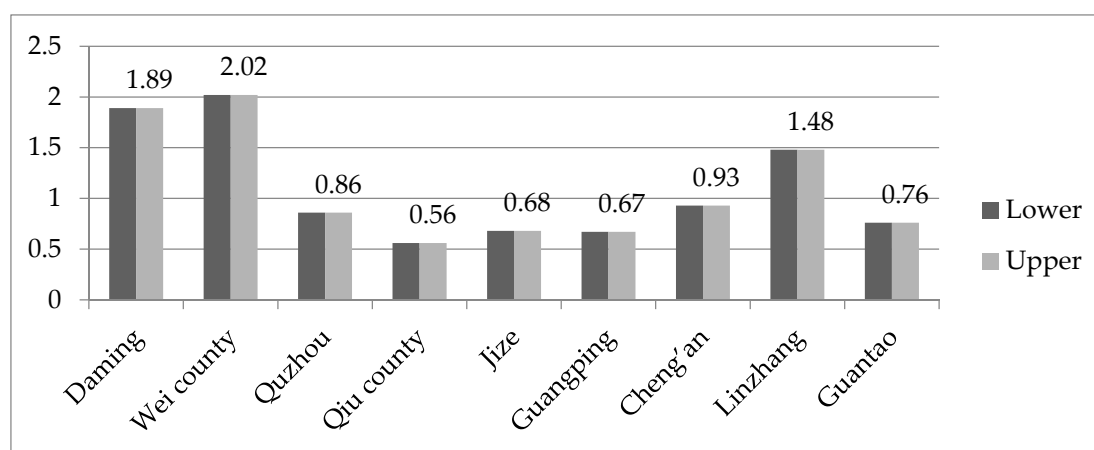

Figure 3. Result of water resources allocation to ecology (10^6 m^3).

Figure 4 represents the total water quantity of allocating to industry in every region from various water resources. It can be obtained that the total amount of industrial water demand is $[46.30, 67.85] \times 10^6$ m^3, the amount of water which is allocated to industry is $[47.10, 59.81] \times 10^6$ m^3. So the water deficit is 8.04×10^6 m^3 with the average water deficiency rate being 11.8% under the upper water demand, and the top three water shortage counties are Quzhou County (15%), Jize County (12%), and Wei County (13%), whose deficiency rate are larger than the average water deficiency rate.
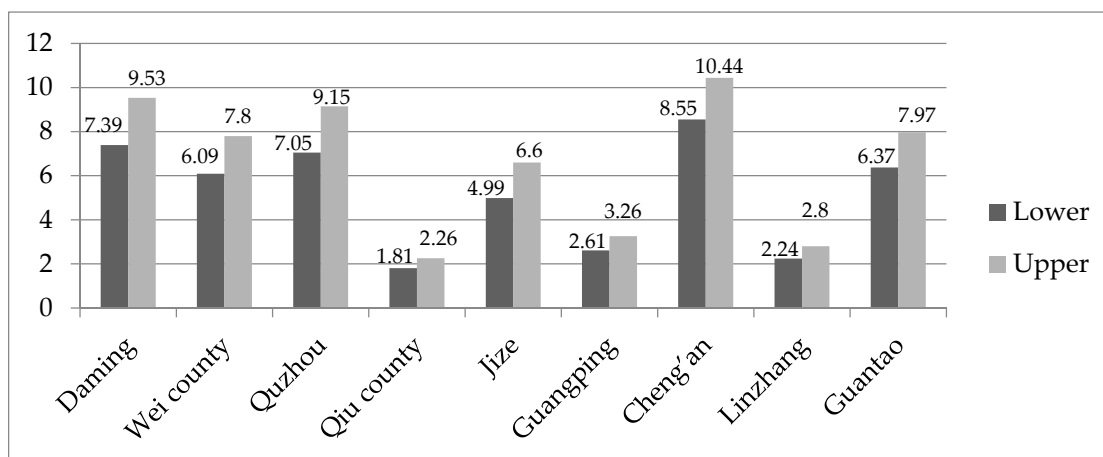
Figure 4. Result of water resources allocation to industry (10^6 m^3).

Figure 5 shows the total water quantity of allocating to agriculture in each region from different water resources. It is noted that the total amount of agricultural water demand is [859.63, 1375.17] $\times 10^6$ m^3, the amount of water allocated to agriculture is [917.19, 1022.28] $\times 10^6$ m^3. So there is a deficit of 352.89 $\times 10^6$ m^3 with the average deficiency rate being 25.6% under the upper water demand. Further, the top four water shortage counties of larger than the average water deficiency rate are Quzhou County, Guangping County, and Jize County with their deficient rate being 33%, 27%, and 28%, respectively. Based on the above results, it can be obtained that the water supply can fully meet requirement when the water demand equals to the lower bound. Conversely, when the water demand equals to the upper bound, the serious water shortage user is agriculture, while the serious water shortage counties are Quzhou County, Guangping County, and Jize County (whose average deficit rate are 33%, 27%, and 28%, individually).
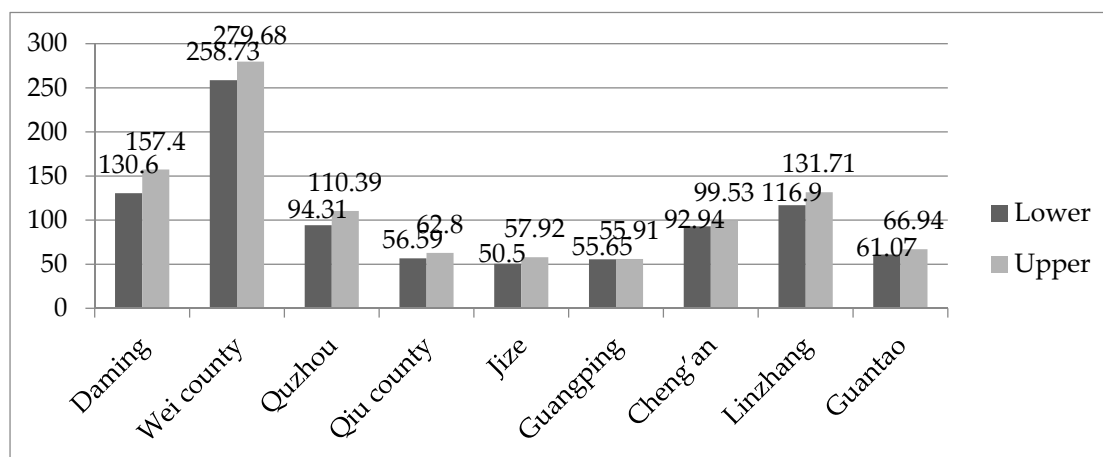

Figure 5. Result of water resources allocation to agriculture (10^6 m^3).

Table 4 shows the result of surface water allocated to every user in each administrative region. It can be seen that the amount water allocated to the domestic user, ecological user, industrial user, and agricultural user from surface water are [50.10, 55.49] $\times 10^6$ m^3, 3.69 $\times 10^6$ m^3, [34.66, 42.24] $\times 10^6$ m^3, [402.01, 438.61] $\times 10^6$ m^3, the total amount of surface water is [490.46, 540.03] $\times 10^6$ m^3, which is smaller than the surface water supply ([499.17, 550.19] $\times 10^6$ m^3). According to the results in Figures 2–5, it can be obtained that the surface water accounts for [39%, 40%], 37%, [71%, 74%], and [43%, 44%] of the total water allocated to the domestic user, ecological user, industrial user, and

agricultural user, respectively. Totally, all users would use surface water, and most of the surface water would supply to agriculture, the surface water supplied to ecology is the least. The reason for this situation is most of the surface water quality cannot satisfy municipality use, such as the Dongwushi reservoir water.

Table 4. Result of surface water allocated to every user (10^6 m^3).

Administrative Division	Domestic Water	Ecological Water	Industrial Water	Agricultural Water
Daming	[15.00, 15.50]	[1.34, 1.34]	[5.29, 6.78]	[40.00, 50.00]
Wei County	[8.49, 9.49]	[0.92, 0.92]	[4.60, 5.60]	[139.90,149.90]
Quzhou	[4.25, 5.25]	[0.33, 0.33]	[5.02, 5.51]	[33.65, 34.15]
Qiu County	[1.18, 1.56]	[0.08, 0.08]	[0.50, 0.52]	[14.00, 14.10]
Jize	[3.00, 3.01]	[0.13, 0.13]	[4.24, 5.64]	[17.27, 19.27]
Guangping	[1.75, 2.25]	[0.12, 0.12]	[1.84, 2.34]	[43.91, 45.91]
Cheng'an	[5.02, 5.52]	[0.23, 0.23]	[8.00, 9.49]	[39.94, 42.94]
Linzhang	[8.91, 9.91]	[0.40, 0.40]	[0.80, 1.00]	[37.34, 41.34]
Guantao	[2.50, 3.00]	[0.14, 0.14]	[4.37, 5.36]	[36.00, 41.00]

Table 5 represents the result of groundwater allocated to every user in each administrative region. It can be seen that the amount water allocated to the domestic water user, ecology water user, industry water user, and agriculture water user from groundwater are [36.54, 40.31] $\times$ 10^6 m^3, 2.22 $\times$ 10^6 m^3, [9.01, 13.30] $\times$ 10^6 m^3, and [389.64, 446.79] $\times$ 10^6 m^3, the total amount of groundwater is [437.41, 502.62] $\times$ 10^6 m^3. Combined with the results in Figures 2–5, it can be calculated that the groundwater accounts for [28%, 29%], 23%, [19%, 22%], and [42%, 44%] of the total water allocated to the domestic user, ecological user, industrial user, and agricultural user, individually. By contrast, more than 88% of all groundwater is supplied to agriculture, groundwater is the main source of agricultural water.

Table 5. Result of groundwater allocated to every user (10^6 m^3).

Administrative Division	Domestic Water	Ecological Water	Industrial Water	Agricultural Water
Daming	[4.00, 4.25]	[0.20, 0.20]	[1.02, 1.27]	[65.37, 75.57]
Wei County	[8.06, 8.66]	[0.34, 0.34]	[1.00, 1.50]	[75.80, 87.49]
Quzhou	[2.60, 2.61]	[0.24, 0.24]	[1.00, 1.50]	[41.34, 51.47]
Qiu County	[5.52, 6.02]	[0.31, 0.31]	[1.01, 1.30]	[36.82, 47.15]
Jize	[5.00, 6.00]	[0.15, 0.15]	[0.75, 1.24]	[31.23, 41.48]
Guangping	[0.95, 1.45]	[0.14, 0.14]	[0.45, 0.75]	[9.71, 12.66]
Cheng'an	[3.35, 3.74]	[0.19, 0.19]	[2.04, 2.96]	[49.93, 50.18]
Linzhang	[5.50, 5.71]	[0.38, 0.38]	[0.74, 1.20]	[64.79, 65.79]
Guantao	[1.56, 1.87]	[0.23, 0.23]	[1.00, 1.58]	[14.74, 15.00]

Table 6 gives the result of recycled water allocated to every user in each administrative region. The amount water allocated to the domestic water user, ecology water user, industry water user, and agriculture water user from recycled water are 0 $\times$ 10^6 m^3, 1.74 $\times$ 10^6 m^3, 0 $\times$ 10^6 m^3, and [85.85, 91.91] $\times$ 10^6 m^3, the total amount of recycled water is [87.59, 93.65] $\times$ 10^6 m^3. Based on the results in Figures 2–5, it can be known that the recycled water accounts for 0, 18%, 0, and 9% of the total water allocated to the domestic user, ecological user, industrial user, and agricultural user, individually. Therefore, only ecology water and agriculture water user use recycled water, and most of the recycled water is supplied to agriculture, it accounts for 98% of recycled water.

Table 6. Result of recycled water allocated to every user (10^6 m^3).

Administrative Division	Domestic Water	Ecological Water	Industrial Water	Agricultural Water
Daming	[0.00, 0.00]	[0.20, 0.20]	[0.00, 0.00]	[22.63, 22.67]
Wei County	[0.00, 0.00]	[0.18, 0.18]	[0.00, 0.00]	[16.03, 19.98]
Quzhou	[0.00, 0.00]	[0.15, 0.15]	[0.00, 0.00]	[6.29, 6.30]
Qiu County	[0.00, 0.00]	[0.12, 0.12]	[0.00, 0.00]	[6.15, 6.16]
Jize	[0.00, 0.00]	[0.15, 0.15]	[0.00, 0.00]	[7.00, 7.16]
Guangping	[0.00, 0.00]	[0.25, 0.25]	[0.00, 0.00]	[2.73, 2.74]
Cheng'an	[0.00, 0.00]	[0.25, 0.25]	[0.00, 0.00]	[5.83, 6.39]
Linzhang	[0.00, 0.00]	[0.23, 0.23]	[0.00, 0.00]	[13.27, 14.58]
Guantao	[0.00, 0.00]	[0.20, 0.20]	[0.00, 0.00]	[5.92, 5.93]

Table 7 is the result of transferred water allocated to every user in each administrative region. The amount water allocated to the domestic water user, ecology water user, industry water user, and agriculture water user from transferred water are [42.61, 44.45] $\times$ 10^6 m^3, 2.20 $\times$ 10^6 m^3, [3.43, 4.27] $\times$ 10^6 m^3, and [39.79, 44.97] $\times$ 10^6 m^3, the amount of transferred water is [88.03, 95.89] $\times$ 10^6 m^3. Totally, the transferred water would account for [32%, 33%], 22%, 7%, and 4% of the total water allocated to the domestic user, ecological user, industrial user, and agricultural user, respectively. According to the different water quality of transferred water, they would be allocated to various users. There are six counties in which all users would use transferred water: Daming County, Wei County, Quzhou County, Qiu County, Guantao County, and Jize County. Meanwhile, there are three counties in which domestic water and ecology water use transferred water: Guangping County, Cheng'an County, and Linzhang County. Therefore, the transferred water plays a great role in this water resources system, and should be organically combined with local water conservancy.

Table 7. Result of transferred water allocated to every user (10^6 m^3).

Administrative Division	Domestic Water	Ecological Water	Industrial Water	Agricultural Water
Daming	[18.32, 18.57]	[0.15, 0.15]	[1.08, 1.47]	[4.20, 5.00]
Wei County	[9.45, 10.45]	[0.36, 0.36]	[0.49, 0.63]	[8.00, 10.00]
Quzhou	[1.35, 1.36]	[0.14, 0.14]	[0.46, 0.54]	[10.98, 12.98]
Qiu County	[1.25, 1.26]	[0.23, 0.23]	[0.30, 0.43]	[4.59, 4.79]
Jize	[1.45, 1.49]	[0.25, 0.25]	[0.20, 0.23]	[7.00, 7.16]
Guangping	[0.56, 0.57]	[0.16, 0.16]	[0.00, 0.00]	[0.00, 0.00]
Cheng'an	[0.59, 0.60]	[0.26, 0.26]	[0.00, 0.00]	[0.00, 0.00]
Linzhang	[6.25, 6.26]	[0.46, 0.46]	[0.00, 0.00]	[0.00, 0.00]
Guantao	[3.39, 3.89]	[0.20, 0.20]	[0.90, 0.97]	[5.02, 5.04]

4.2. Comparison with Weighted Sum Method

In this study, the classical weighted sum method (WSM) is adopted to solve model (8) for comparison with the proposed method. According to Zhang et al. [53], three different weights are set to be 0.7, 0.2, and 0.1 for objectives (8a–c), respectively, and the obtained solution is shown in Table 8. For better comparison, the results based on other two weights ((0.2, 0.7, and 0.1) and (0.2, 0.1, and 0.7)) are also provided in Tables 9 and 10. In addition, the results of objective function values under three different weight sets are given in Table 11.

Table 8. Result of water resources allocation to every user (w_i = (0.7, 0.2, 0.1)) (10^6 m^3).

Administrative Division	Domestic Water	Ecological Water	Industrial Water	Agricultural Water
Daming	[36.12, 37.12]	[1.82, 1.82]	[7.32, 9.43]	[126.50, 153.10]
Wei County	[25.83, 28.84]	[1.93, 1.93]	[6.13, 7.90]	[256.73, 276.68]
Quzhou	[8.00, 9.10]	[0.83, 0.83]	[7.03, 9.05]	[92.31, 106.39]
Qiu County	[8.65, 9.95]	[0.53, 0.53]	[1.74, 2.16]	[54.59, 60.80]
Jize	[9.35, 9.95]	[0.64, 0.64]	[4.89, 6.50]	[48.50, 53.92]
Guangping	[3.16, 4.06]	[0.65, 0.65]	[2.51, 3.06]	[52.65, 53.91]
Cheng'an	[8.31, 9.21]	[0.88, 0.88]	[8.15, 10.04]	[87.94, 94.53]
Linzhang	[19.26, 20.16]	[1.44, 1.44]	[2.14, 2.50]	[112.90, 126.71]
Guantao	[7.15, 8.05]	[0.74, 0.74]	[6.17, 7.37]	[59.07, 60.94]

Table 9. Result of surface water allocated to every user (w_i = (0.2, 0.7, 0.1)) (10^6 m^3).

Administrative Division	Domestic Water	Ecological Water	Industrial Water	Agricultural Water
Daming	[35.63, 36.62]	[1.86, 1.86]	[7.42, 9.03]	[124.50, 150.10]
Wei County	[25.63, 28.54]	[2.02, 2.02]	[6.23, 7.60]	[253.73, 272.68]
Quzhou	[7.83, 9.00]	[0.87, 0.87]	[7.18, 9.01]	[90.31, 104.39]
Qiu County	[8.05, 9.35]	[0.57, 0.57]	[1.79, 2.01]	[53.59, 59.80]
Jize	[9.05, 9.15]	[0.68, 0.68]	[4.95, 6.55]	[47.50, 52.92]
Guangping	[3.12, 4.00]	[0.67, 0.67]	[2.57, 3.16]	[50.15, 51.01]
Cheng'an	[8.12, 9.01]	[0.94, 0.94]	[8.35, 10.34]	[84.74, 90.59]
Linzhang	[18.56, 29.06]	[1.47, 1.47]	[2.39, 2.70]	[106.98, 120.11]
Guantao	[7.10, 8.01]	[0.79, 0.79]	[6.32, 7.77]	[58.27, 58.74]

Table 10. Result of groundwater allocated to every user (w_i = (0.2, 0.1, 0.7)) (10^6 m^3).

Administrative Division	Domestic Water	Ecological Water	Industrial Water	Agricultural Water
Daming	[34.82, 35.92]	[1.88, 1.88]	[7.44, 9.33]	[121.10, 148.14]
Wei County	[25.59, 28.04]	[2.10, 2.10]	[6.07, 7.40]	[248.73, 271.18]
Quzhou	[7.79, 8.80]	[0.89, 0.89]	[7.02, 8.71]	[87.37, 100.69]
Qiu County	[7.75, 8.95]	[0.61, 0.61]	[1.73, 1.91]	[51.59, 57.89]
Jize	[8.99, 9.01]	[0.72, 0.72]	[4.88, 6.05]	[45.70, 50.98]
Guangping	[3.10, 3.92]	[0.71, 0.71]	[2.48, 3.06]	[49.95, 50.01]
Cheng'an	[8.09, 8.81]	[0.97, 0.97]	[8.05, 10.24]	[81.04, 88.19]
Linzhang	[18.26, 28.76]	[1.51, 1.51]	[2.17, 2.50]	[102.18, 116.71]
Guantao	[7.09, 7.89]	[0.80, 0.80]	[6.10, 7.29]	[56.17, 57.24]

Table 11. Results of objective function values by the weighted sum method (WSM) .

Weight	Objective Function Value	Economic Benefit (10^6 CNY)	Social Benefit (10^6 m^3)	Environmental Benefit (10^6 kg)
w_i = (0.7, 0.2, 0.1)	f^+ = 309.32 × 10^6	421.87	70.06	0.037
	f^- = 297.64 × 10^6	406.34	64.17	0.032
w_i = (0.2, 0.7, 0.1)	f^+ = 131.37 × 10^6	390.86	76.01	0.036
	f^- = 123.70 × 10^6	370.17	71.02	0.031
w_i = (0.2, 0.1, 0.7)	f^+ = 84.99 × 10^6	389.96	70.03	0.043
	f^- = 80.28 × 10^6	369.17	64.08	0.037

By comparing, it can be known that the results obtained by WSM are very similar to the solutions of the proposed approach totally. However, both of the amounts of water resources allocated to every

user in Tables 8–10 and objective function values in Table 11 fluctuate with the change of weight. When the weight of economic benefit target becomes smaller, the amount of water resources allocated to industry reduces, while the amount of water resources allocated to other users increases. As everyone knows, weights are generally determined by people, and thus have great subjectivity. Therefore, the results obtained by WSM would be subjective, which is less reasonable than the proposed approach in this study.

5. Conclusions

In this paper, an integrated method was presented to solve interval multi-objective planning by coupling fuzzy programming and ITSM. The proposed model can not only explicitly address system uncertainty with interval parameters but it can also effectively reflect different objectives with multiple water resources. Moreover, the presented model can provide a reliable multi-water resources joint scheduling measure under different fuzzy membership degrees to balance various contradictions among water users. The interval multi-objective planning model can be transferred into two deterministic single objective sub-models that correspond to the upper and lower bounds of the fuzzy membership degree. Therefore, interval solutions can be obtained by solving the two sub-models sequentially.

The multi-water resources problem in the eastern part of Handan, China has been studied to demonstrate applicability of the proposed model. The obtained solutions indicated that it could not only provide optimized benefits and water allocation schemes for every water user, but also relieve the water resources shortage situation by organically combining the transferred water and local water conservancy. Meanwhile, it also indicated that the water supply could fully meet requirements when the water demand equaled the lower bound. Conversely, when the water demand equaled the upper bound, industry and agriculture sectors would face serious water shortage, while Quzhou County, Guangping County, and Jize County would also confront serious water shortages. Compared with the results generated by the weighted sum approach, the final solutions of the proposed method are more reasonable. Therefore, the proposed approach can help generate desired policies for water resources management with maximized multiple benefits and reasonable water allocation to each user, and thus effectively promote the sustainable utilization of water resources and social development in the study area.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "M.S. conceived and designed the experiments; P.W. performed the experiments; M.S. and P.W. analyzed the data; B.Z. contributed reagents/materials/analysis tools; M.S. wrote the paper." Authorship must be limited to those who have contributed substantially to the work reported.

Conflicts of Interest: The authors declare no conflict of interest.

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