



Collaborative optimal allocation of water resources and sewage discharge rights in watershed cities: considering equity among water sectors

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Abstract

Water supply systems in watershed cities face challenges due to increasing water demand and arbitrary sewage discharge allocations. Previous studies have primarily focused on water resource allocation and sewage discharge rights, neglecting the intricate interactions between the two. This study introduces a novel approach by integrating sewage discharge rights into the watershed's water resource allocation mechanism. A multi-objective optimization model was developed, employing the Gini coefficient to balance the equitable and economic aspects across various water sectors. This model takes into account the distinct water demands and sewage discharge requirements of different sectors. The findings of this study are as follows: (a) the Gini coefficients for water demand allocation and sewage discharge rights allocation exhibit simultaneous optimization and display consistent trends; (b) when the importance of sewage discharge relative to other water users increases, the return on investment for domestic and industrial water use decreases, but the fairness of water distribution improves; (c) proper allocation of sewage discharge rights can effectively enhance the economic value of agricultural water use. Overall, this strategy has the potential to enhance both the equality and economic benefits of the water supply system while ensuring the sustainable utilization of water and sewage rights in the basin cities.

Keywords Water · Sewage discharge right · Collaborative allocation · Equity · Multi-objective optimization

Introduction

Cities worldwide are currently grappling with serious water security issues (Chandra et al., 2021; Delorit et al., 2019). Research on urban water security is defined and analyzed in various ways. While some studies evaluating urban water

resources focus on industrial economics, municipal water use, and agricultural production, others concentrate on urban water stress and water supply systems (Arya et al., 2015; Dadmand et al., 2020). Previous research has proposed two strategies: optimal water resource allocation and sewage management (Canter et al., 2014; Daughton et al., 2017; Xie et al., 2022). In this study, we aim to optimize urban water supply systems based on sustainable development principles, specifically focusing on sewage discharge rights allocation, to ensure safe and robust urban water supply, water equity, and environmental protection.

The watershed urban water supply system functions as a closed-loop hydrological cycle, with watershed managers allocating water resources to individual cities to meet domestic, agricultural, and industrial needs (Yao et al., 2020; Pourmand et al., 2020). Meanwhile, individual water-using sectors discharge domestic, agricultural, and industrial effluents into the watershed, impacting the ecological environment (Shen et al., 2021; Dai et al., 2020). Additionally, decision-makers have varying preferences for future changes in supply and demand (Siciliano et al., 2017; Kroll et al.,

Highlights

- Innovative integration of sewage discharge rights into watershed water management.
- A multi-objective model was developed to optimize the urban water supply system.
- A model that considers equity, economics, and the environment can improve sustainable water use.

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2019). Consequently, we assign different weights to assess the changes in water supply under different scenarios.

However, to meet urban water supply demands, we require a specific allocation framework. When constructing a multi-objective optimization method, four factors should be taken into full consideration: water equity (Yuan et al., 2022), economic development (Zhang et al., 2017), agricultural production (Zhu et al., 2019; Zhang et al., 2018), and environmental protection (Xu et al., 2020; Zhang et al., 2018). Hence, this study aims to achieve the following four objectives: (1) ensure industrial water equity for regional economic development; (2) ensure agricultural production equity for food security; (3) ensure municipal water equity for water supply security; and (4) allocate sewage discharge rights equitably to minimize the negative impact of water activities on the environment.

To meet urban water supply demands, this study proposes a multi-objective planning model that maximizes the equitable allocation of sewage discharge rights while considering equitable allocation of industrial, agricultural, and domestic water use in the basin. The practicality and feasibility of the model are verified using the Minjiang River Basin (MRB) in western China. With uneven water resource allocation and significant regional development disparities in the MRB, some cities are facing severe water shortages (Xu et al., 2017; Yao et al., 2020). Despite the local government implementing various measures to restrict sewage discharge (Gong et al., 2022), improve water use efficiency, and promote water recycling, numerous challenges persist (Cao et al., 2020; Zhang et al., 2021). Consequently, based on existing urban water supply system optimization models, this study aims to optimize the urban water supply system in the MRB. The innovations of this study are as follows: (1) the development of a multi-objective model to optimize the urban water supply system and ensure sustainable and equitable water supply; (2) the incorporation of sewage discharge rights into the models to mitigate the impact of water pollution on urban water systems; and (3) the achievement of a collaborative allocation of water resources and sewage discharge rights by balancing equity and efficiency.

The remainder of this study is as follows: “[Literature review](#)” section summarizes the literature, and “[Materials and method](#)” section presents the multi-objective optimization model. In the “[Results and discussion](#)” section, the results and analysis of the model are given in the context of a case study. Conclusions and management insights are presented in the “[Conclusion and policy implications](#)” section.

Literature review

More and more researchers are paying attention to the subject of urban water security. Some experts have primarily analyzed the urban water delivery system and have made

significant progress (Yazdi and Moridi, 2017; Murray et al., 2010; Nabi et al., 2019). However, the urban water system primarily concerns water equity, economic growth, and environmental preservation. As a result, prior research has integrated urban water safety, water supply, and sewage treatment methods (Yzac et al., 2019; Xu et al., 2015). Xie et al. (2013) considered all demands, costs, and water flows in urban water systems. In most places, research on water supply safety significantly differs from policymakers’ management strategies (Wang et al., 2019; Sun et al., 2010). A study on enhancing urban water resources is necessary to ensure shared growth within social, economic, and ecological contexts (Tu et al., 2015).

The use of mathematical programming models for water resource management has recently gained popularity (Friesen et al., 2017; Guo et al., 2010). Relevant scholars have developed an optimal allocation model for cross-border and cross-basin water resources (Liu et al., 2020a). There are also studies on maximizing economic benefits, equity, and ecological sustainability (Lekakis et al., 1997; Li et al., 2021). Furthermore, many scholars have created optimization models to address the paradox of regional water resource scarcity resulting from the balance of supply and demand for regional water resources (Mo et al., 2014; Nasiri-Gheidari et al., 2018). To ensure a long-term water supply, when evaluating or comparing the current plan for allocating water resources, Canter and Chawla (2014) use the Gini coefficient as a qualitative measure. However, there are few quantitative studies on the equitable allocation of urban water resources that take sewage discharge rights into account. Therefore, we developed a multi-objective programming model to optimize urban water resource allocation; consider allowable sewage discharge from cities; promote the equity of industrial, agricultural, and domestic water use in the basin; and assess the impact of sewage discharge on the water environment.

The equitable allocation of urban water resources is crucial for alleviating conflicts between water sectors (Konishi et al., 2015; Song et al., 2016; Soller et al., 2018). Scholars have investigated the equity of water resource allocation from various perspectives (Hu et al., 2016; Mooselu et al., 2020; Hou et al., 2018). In terms of equity, Cullis et al. (2009) pioneered the use of the Gini coefficient to assess the equality of water resource allocation. Subsequently, Elbakidze et al. (2018) used the Gini coefficient as an evaluation or comparison index for the existing water resource allocation strategy to qualitatively measure the equality of water resources.

The literature is summarized in the following table (Liu et al., 2023). However, in the existing research, only the different characteristics of life, agriculture, industry, and value chain are considered, and there is no effective restriction on the environmental pollution caused by sewage discharge (Peng et al., 2022; Chang et al., 2022).

Study field	Method	Multi-objective	Reference
Urban water delivery system	Simulation-based optimization approach	No	Yazdi and Moridi (2017), Murray et al. (2010), Nabi et al. (2019)
Watershed water resources management	Urban water safety, water supply, and sewage treatment methods	Yes	Yzac et al. (2019), Xu et al. (2015), Xie et al. (2013)
Water supply safety research	Policymakers' management strategy	No	Wang et al. (2019), Sun et al. (2010)
Urban water resources allocation	Multi-objective bi-level programming model	Yes	Tu et al. (2015)
Water resource management	Mathematical programming models	No	Friesen et al. (2017), Guo et al. (2010)
Cross-border and cross-basin water resources	Optimal allocation model	No	Liu et al. (2020b)
Water resource allocation	Multi-objective optimal	Yes	Lekakis et al. (1997), Li et al. (2021)
Balance of supply and demand for regional water resources	Optimization models	No	Mo et al. (2014), Nasiri-Gheidari et al. (2018)
Water resource allocation	Qualitative measurement	No	Canter and Chawla (2014)
Water resource and sewage discharge rights allocation	Multi-objective optimal allocation model	Yes	This study

Materials and method

Study area

The Minjiang River Basin (MRB), as an important Yangtze River tributary, Fig. 1(a) shows a map of China, Fig. 1(b) shows a map of Sichuan Province, and Fig. 1(c) shows the entire Minjiang River Basin jurisdiction, is rich in water resources (Fig. 1), with an average annual accessible water amount of 114,927 million m³. According to the geographical characteristics of the mainstream, the MRB includes eight cities and states in Sichuan Province, including Aba, Chengdu, Meishan, Ya'an, Leshan, Neijiang, Zigong, and Yibin City. By the end of 2019, the total population of the basin's eight cities will be 36.529 million, the cultivated land area will be 2198.05

thousand hectares, and the entire value of the industrial sector will be 926.857 billion yuan. The total amount of water consumed is 11.274 billion cubic meters. The MRB supplies water to the domestic, agricultural, industrial, and ecological sectors of eight cities under the supervision of the basin management authority.

Data sources and pre-processing

The population, cultivated land area, industrial GDP, and sewage discharge of eight cities in the MRB were statistically examined based on the Sichuan statistical yearbook 2006–2020 (Table 1). Simultaneously, the yearly average water amount and household, agricultural, industrial, and ecological water consumption of eight cities along the Minjiang River were statistically analyzed, according to the Sichuan Water Resources Communiqué (Table 2). The maximum and minimum water needs for the eight cities were calculated from 2015 to 2019. The average yearly water resources and water needs were computed using data from 2015 to 2019. The local subareas provided detailed socioeconomic statistics. According to the water resources bulletin, the MRB can provide 114.927 billion cubic meters of available water to 18.751 million residents each year, of which 0.25% is from other water sources (Table 3). From Tables 1, 2, and 3, it is evident that Chengdu is the area with the highest water consumption and also the largest wastewater discharge.

Model

The optimal allocation strategy of water resources considering basin sewage discharge rights distribution is a complex multi-system integration problem. The following assumptions need to be made about the problem:

- (1) The Watershed Management Bureau makes rational decisions to avoid emergencies.
- (2) The Watershed Management Bureau fully understands the objective function and internal constraints. Furthermore, the behavior of watershed managers is reasonable.
- (3) The total available water quantity of the basin is considered a random variable with seasonal and natural variation, which is transformed into a deterministic variable through the annual average water flow of the basin.

This study starts from the initial available water quantity of the water supply system in the basin; focuses on the equity of the urban water use sector; incorporates sewage discharge into the limitation of the water supply system; uses the Gini coefficient to measure the equity of domestic, agricultural, and industrial water use and the satisfaction rate of sewage

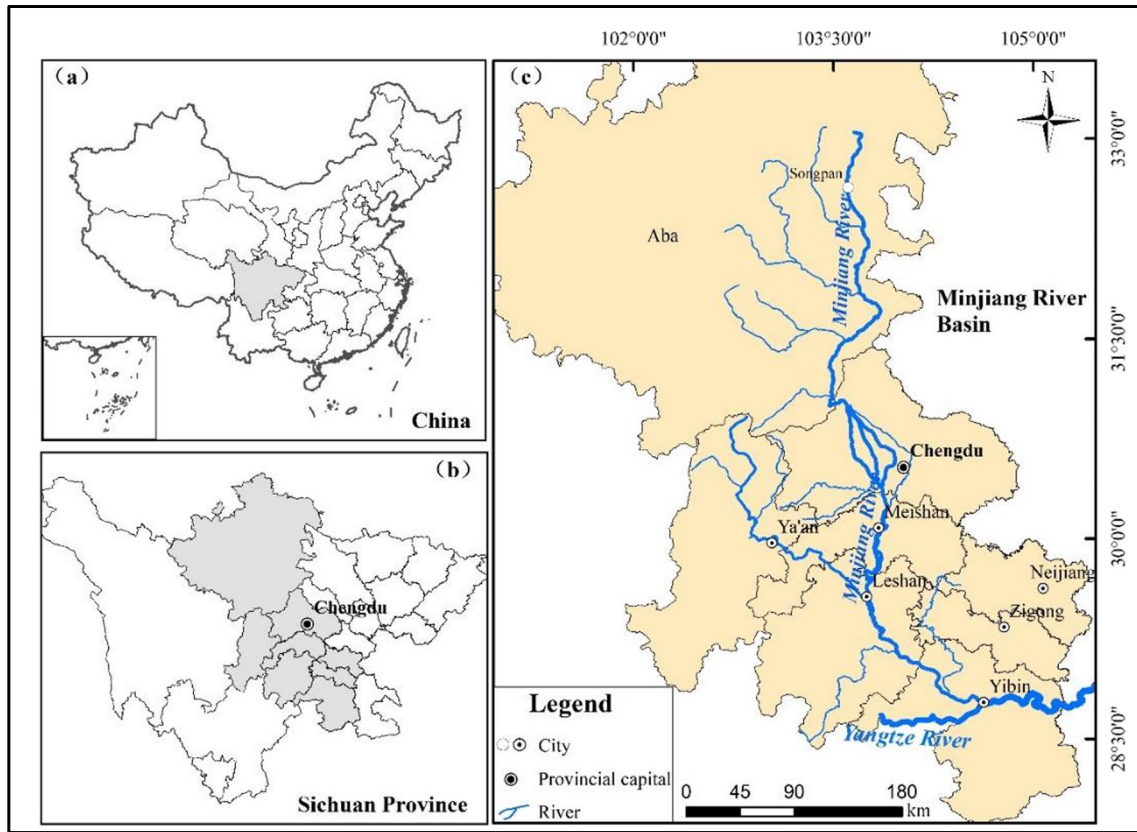


Fig. 1 Map of MRB

rights; and establishes a water and sewage rights allocation scheme for the urban water supply system, so that the water use sector in Xiantao City can ensure water security in a sustainable and stable manner. The goal of stable economic development and environmental pollution control is achieved. The decision framework is shown in Fig. 2.

To facilitate a clearer model, we refer to the study of Zhang et al. (2022), where the nomenclature in the model

is illustrated and the relevant parameters and variables are expressed as follows:

Nomenclature

MRB Minjiang River Basin

Dom Domestic water user sector

Table 1 Basic data of the MRB (2019, 10⁸ m³)

City	P_j	N_j	E_j	R_j^{wes}	evp_j^{agr}	evp_j^{ind}
Chengdu	1658.1	523.15	5244.62	107,300.75	3.00	2675.83
Zigong	292.2	216.31	572.70	5460	6.81	1022.68
Neijiang	370.0	273.79	489.88	5483.05	7.08	1045.77
Leshan	327.1	271.61	801.88	3627	9.18	556.86
Meishan	299.5	241.05	527.13	6371.67	1.28	627.54
Yibin	457.3	487.61	1308.92	2050	5.27	581.74
Ya'an	154.1	101.26	227.20	2197	5.26	463.67
Aba	94.6	83.27	96.24	320	3.67	1924.8

source (Sichuan statistical yearbook 2019), <http://tjj.sc.gov.cn/scstjj/c105855/nj.shtml>; <http://slt.sc.gov.cn/scssl/sjfw/sjfw.shtml>

Table 2 The water consumption of different parts of the subarea in MRB (2019, 10⁹ m³)

City	Dom	Agr	Ind	Eco	T_0
Chengdu	14.1	31.9	13.2	1.39	1149.27
Zigong	1.5	4.2	1.5	0.11	
Neijiang	2.5	7.1	2.5	0.16	
Leshan	1.9	8.6	2.4	0.16	
Meishan	2.6	6	3.2	0.81	
Yibin	1.2	3.3	1.4	0.33	
Ya'an	1.1	5.6	1.7	0.15	
Aba	0.6	1.3	0.7	0.03	

source (Sichuan statistical yearbook 2019), <http://tjj.sc.gov.cn/scstjj/c105855/nj.shtml>; <http://slt.sc.gov.cn/scssl/sjfw/sjfw.shtml>

Agr Agricultural water user sector

Ind Industrial water user sector

Index

j Index of subarea i in the MRB, $j = 1$: Chengdu, $j = 2$: Zigong, $j = 3$: Neijiang, $j = 4$: Leshan, $j = 5$: Meishan, $j = 6$: Yibin, $j = 7$: Ya'an, $j = 8$: Aba

Parameters

Table 3 Minimum, maximum water demand and sewage discharge rights in all cities (2019, 10⁹ m³)

City	$(x_j^i)^{min}$			$(x_j^i)^{max}$			$(R_j^{wes})^{min}$	$(R_j^{wes})^{max}$
	x_j^{dom}	x_j^{agr}	x_j^{ind}	x_j^{dom}	x_j^{agr}	x_j^{ind}		
Chengdu	13.35	30.91	8.44	15.14	32.91	15.14	0.823	1.073
Zigong	1.48	3.75	1.39	1.7	4.42	1.96	0.047	0.054
Neijiang	1.76	3.89	1.47	1.67	4.09	2.02	0.037	0.043
Leshan	2.28	6.69	2.44	3.2	7.64	3.72	0.039	0.054
Meishan	1.77	8.09	1.87	1.96	8.75	2.61	0.033	0.036
Yibin	1.86	4.89	2.61	2.67	6.36	5.11	0.044	0.080
Ya'an	1.05	3.14	1.31	1.31	3.57	1.75	0.016	0.020
Aba	0.61	1.15	0.2	0.74	1.37	0.74	0.001	0.003

source (Sichuan statistical yearbook 2019), <http://tjj.sc.gov.cn/scstjj/c105855/nj.shtml>; <http://slt.sc.gov.cn/scssl/sjfw/sjfw.shtml>

Fig. 2 Decision-making framework

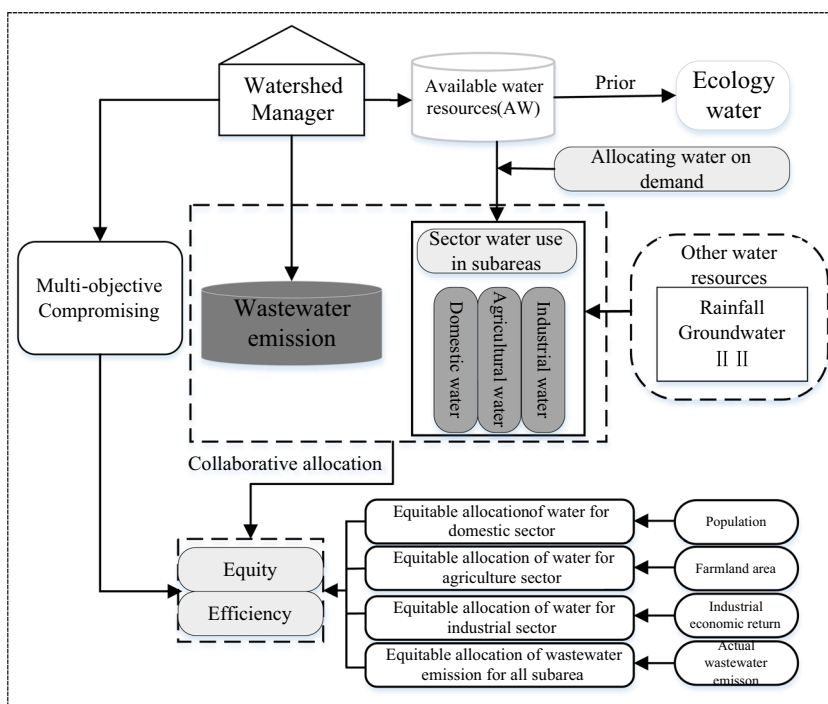


Table 4 Basic plan for allocation of water resources and sewage discharge rights (10^9 m^3)

City	x_j^{dom}	x_j^{agr}	x_j^{ind}	R_j^{wes}
Chengdu	13.35	30.91	8.44	1.073
Zigong	1.7	4.42	1.39	0.055
Neijiang	1.76	4.09	1.47	0.037
Leshan	2.28	7.64	3.72	0.039
Meishan	1.96	8.09	1.87	0.033
Yibin	2.67	6.36	2.61	0.045
Ya'an	1.05	3.14	1.75	0.016
Aba	0.62	1.37	0.74	0.002

source (Sichuan statistical yearbook 2019), <http://tjj.sc.gov.cn/scstjj/c105855/nj.shtml>

$x_j^{dom}, x_j^{agr}, x_j^{ind}$: Domestic/agricultural/industrial water allocated to area j (10^9 m^3)

R_j^{wes} : Sewage emission permits allocated to area j (10^9 m^3)

P_j : The resident population of subarea j (10^4 p)

N_j : The cultivated land of subarea j (10^3 hm^2)

E_j : The total value of industrial economy of subarea j (yuan/ m^3)

T_0 : The annual average amount of water available in the MRB (10^9 m^3)

S_j : The ecological water demand in sub-area j

OW^i : Other water resources such as groundwater and rainfall in subarea j (10^9 m^3)

R_0 : The total amount of sewage allocated to be discharged in the MRB (10^4 m^3)

$(x_j^{dom})^{min}, (x_j^{dom})^{max}$: The minimum/maximum of domestic water sector demand in subarea j (10^9 m^3)

$(x_j^{agr})^{min}, (x_j^{agr})^{max}$: The minimum/maximum of agricultural water sector demand in subarea j (10^9 m^3)

$(x_j^{ind})^{min}, (x_j^{ind})^{max}$: The minimum/maximum of industrial water sector demand in subarea j (10^9 m^3)

$(R_j^{wes})^{min}, (R_j^{wes})^{max}$: The minimum/maximum of sewage discharge rights in subarea j (10^4 m^3)

evp_j^{agr}, evp_j^{ind} : The economic value of agricultural/industrial produced by unilateral water in subarea j (yuan/ m^3)

Objective functions

- (1) Maximize equity in domestic water use

Fig. 3 Comparison between model water allocation plan and actual scheme

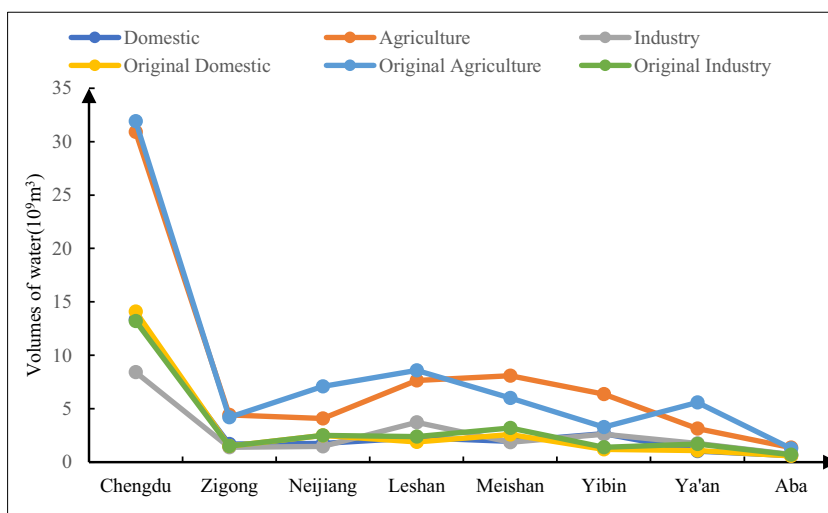
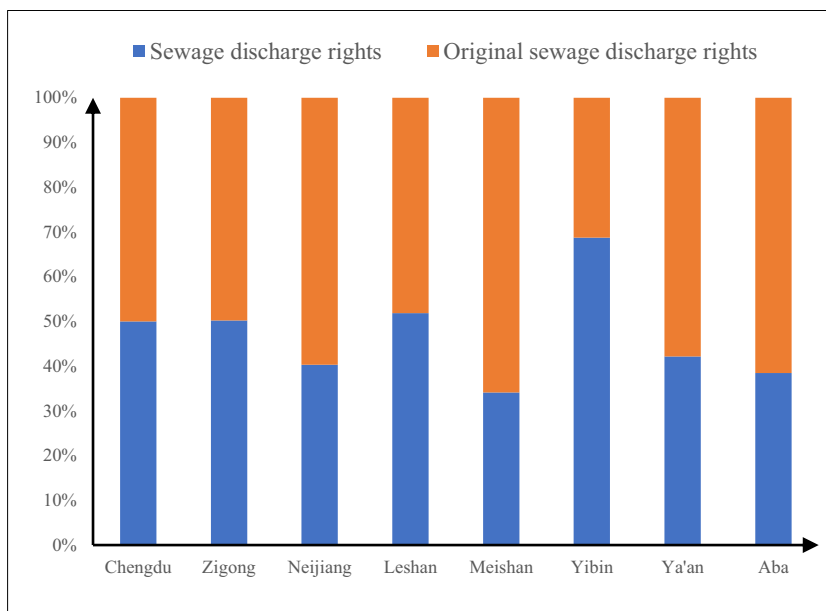


Fig. 4 Model sewage right allocation scheme and actual discharge right allocation scheme



In this study, per capita water quantity is used to measure the equity of domestic water allocation. Watershed managers should try their best to meet the basic demand of domestic water use, that is, to minimize the Gini coefficient of domestic water use. It can be expressed as follows:

$$\text{ming}_1(x_j^{dom}) = \frac{1}{2 \cdot J \cdot \sum_{j=1}^J \frac{x_j^{dom} + OW^{dom}}{p_j}} \sum_{a=1}^J \sum_{b=1}^J \left| \frac{x_a^{dom} + OW^{dom}}{p_a} - \frac{x_b^{dom} + OW^{dom}}{p_b} \right| \tag{1}$$

a and b represent any two cities in the basin; $(x_j^{dom} + OW^{dom})/p_j$ represents the per capita water consumption of city j in river basin. p_a and p_b represent the resident population of a city and b city, respectively.

(B) Maximize equity in agricultural water use

The subarea of cultivated land is used to measure the equity of agricultural water allocation. Watershed managers should try to meet the basic demand of agricultural water, that is, to minimize the Gini coefficient of agricultural water; it can be expressed as follows:

$$\text{ming}_2(x_j^{agr}) = \frac{1}{2 \cdot J \cdot \sum_{j=1}^J \frac{x_j^{agr} + OW^{agr}}{N_j}} \sum_{a=1}^J \sum_{b=1}^J \left| \frac{x_a^{agr} + OW^{agr}}{N_a} - \frac{x_b^{agr} + OW^{agr}}{N_b} \right| \tag{2}$$

$(x_j^{agr} + OW^{agr})/N_j$ represents the water consumption per unit cultivated land area in j city of the river basin. N_a and N_b represent the cultivated land area of a city and b city, respectively.

(III) Maximize equity in agricultural water use

Fig. 5 Gini coefficient of water sector and sewage allocation scheme under different weights

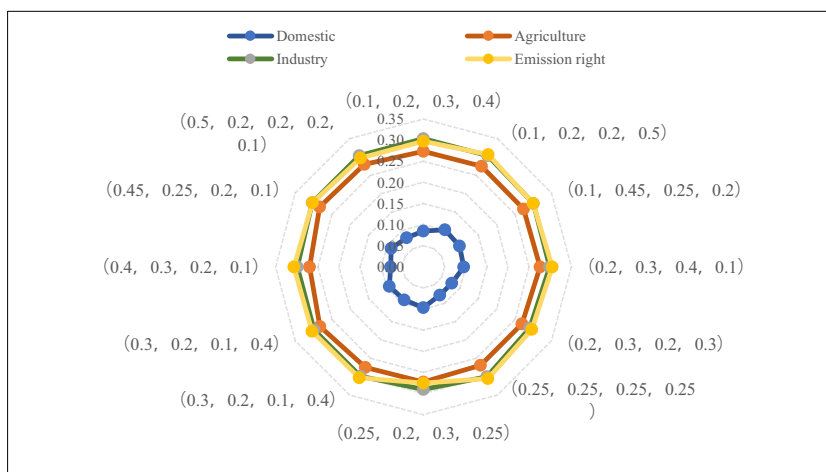
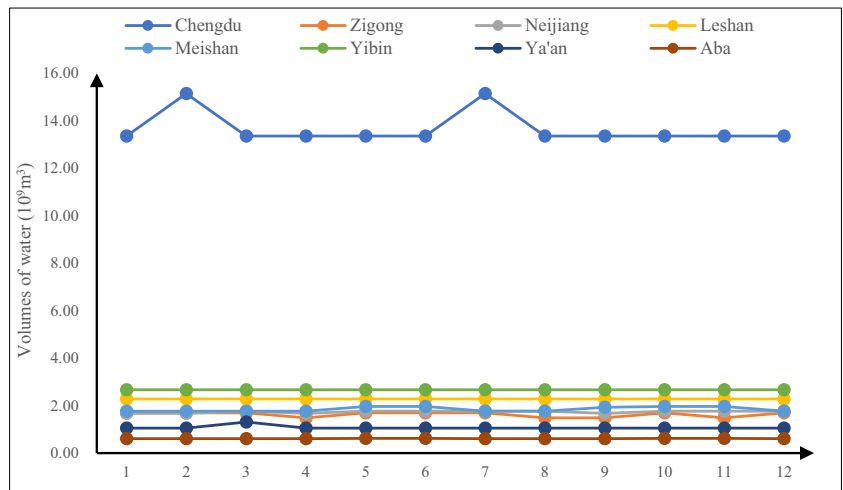


Table 5 Water allocation schemes of domestic sector under different weights

Serial number	1	2	3	4	5	6	7	8	9	10	11	12
City	Weight											
	(0.1,0.2,0.3,0.4)	(0.1,0.2,0.2,0.5)	(0.1,0.45,0.25,0.2)	(0.2,0.3,0.4,0.1)	(0.2,0.3,0.2,0.3)	(0.25,0.25,0.25,0.25)	(0.25,0.2,0.3,0.25)	(0.3,0.2,0.1,0.4)	(0.3,0.2,0.1,0.4)	(0.4,0.3,0.2,0.1)	(0.45,0.25,0.2,0.1)	(0.5,0.2,0.2,0.1)
Chengdu	13.35	15.14	13.35	13.35	13.35	13.35	15.14	13.35	13.35	13.35	13.35	13.35
Zigong	1.70	1.70	1.70	1.48	1.70	1.70	1.70	1.48	1.48	1.70	1.48	1.70
Neijiang	1.67	1.67	1.76	1.67	1.76	1.76	1.76	1.48	1.67	1.76	1.76	1.76
Leshan	2.28	2.28	2.28	2.28	2.28	2.28	2.28	2.28	2.28	2.28	2.28	2.28
Meishan	1.77	1.77	1.77	1.77	1.96	1.96	1.77	1.77	1.93	1.96	1.96	1.77
Yibin	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67	2.67
Ya'an	1.05	1.05	1.31	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
Aba	0.61	0.61	0.61	0.61	0.62	0.62	0.61	0.61	0.61	0.62	0.62	0.61

Fig. 6 Water allocation scheme for domestic water sector



Economic returns are a critical factor in measuring equality for industrial water allocation. The allocation of industrial water should be maximized to meet the demand for industrial water, that is, to maximize the Gini coefficient of industrial water use; it can be expressed as follows:

$$\max g_2(x_j^{ind}) = \frac{1}{2 \cdot J \cdot \sum_{j=1}^J \frac{x_j^{ind} + OW^{ind}}{E_j}} \sum_{a=1}^J \sum_{b=1}^J \left| \frac{x_a^{ind} + OW^{ind}}{E_a} - \frac{x_b^{ind} + OW^{ind}}{E_b} \right| \quad (3)$$

$(x_j^{ind} + OW^{ind})/E_j$ represents the unilateral water industry GDP of j city in the basin; E_a and E_b represents the industrial GDP of a city and b city, respectively.

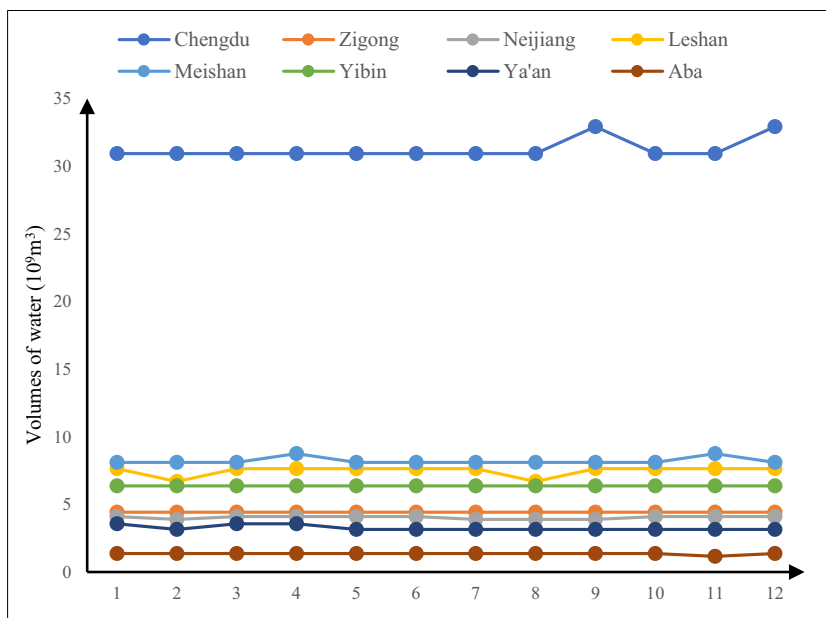
(IV) Maximize the allocation of sewage discharge rights

The satisfaction rate of sewage discharge rights is the key factor to measure equality for the allocation of

Table 6 Water allocation schemes of agricultural sector under different weights

Serial number	1	2	3	4	5	6	7	8	9	10	11	12
City	Weight											
	(0.1,0.2,0.3,0.4)	(0.1,0.2,0.2,0.5)	(0.1,0.45,0.25,0.2)	(0.2,0.3,0.4,0.1)	(0.2,0.3,0.2,0.3)	(0.25,0.25,0.25,0.25)	(0.25,0.2,0.3,0.25)	(0.3,0.2,0.1,0.4)	(0.3,0.2,0.1,0.4)	(0.4,0.3,0.2,0.1)	(0.45,0.25,0.2,0.1)	(0.5,0.2,0.2,0.1)
Chengdu	30.91	30.91	30.91	30.91	30.91	30.91	30.91	30.91	32.91	30.91	30.91	32.91
Zigong	4.42	4.42	4.42	4.42	4.42	4.42	4.42	4.42	4.42	4.42	4.42	4.42
Neijiang	4.09	3.89	4.09	4.09	4.09	4.09	3.89	3.89	3.89	4.09	4.09	4.09
Leshan	7.64	6.69	7.64	7.64	7.64	7.64	7.64	6.69	7.64	7.64	7.64	7.64
Meishan	8.09	8.09	8.09	8.75	8.09	8.09	8.09	8.09	8.09	8.09	8.75	8.09
Yibin	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36	6.36
Ya'an	3.57	3.14	3.57	3.57	3.14	3.14	3.14	3.14	3.14	3.14	3.14	3.14
Aba	1.37	1.37	1.37	1.37	1.37	1.37	1.37	1.37	1.37	1.37	1.15	1.37

Fig. 7 Water allocation scheme for agricultural water sector



discharge rights. Therefore, the allocation of sewage discharge rights should maximize the Gini coefficient to meet the needs of discharge rights; it can be expressed as follows:

$$\text{ming}_3(R_j^{wes}) = \frac{1}{2 \cdot J \cdot \sum_{j=1}^J \frac{R_j^{wes}}{E_j}} \sum_{a=1}^J \sum_{b=1}^J \left| \frac{R_a^{wes}}{E_a} - \frac{R_b^{wes}}{E_b} \right| \quad (4)$$

R_j^{wes} / E_j represents the sewage discharge rights needed by j city to produce unit economic value in the MRB.

Constraints

(1) Limited water resources available

According to China’s “three red lines system” (<http://www.mwr.gov.cn/szs/slcs/201612/t20161222776422.html>), the MRB’s available water resources vary with time every year, so the total water resources allocated to the MRB management authority’s eight cities should be less than the MRB’s annual average water quantity; it can be expressed as:

$$0 \leq \sum_{j=1}^8 (x_j^{dom} + x_j^{agr} + x_j^{ind}) < T_0 \quad (5)$$

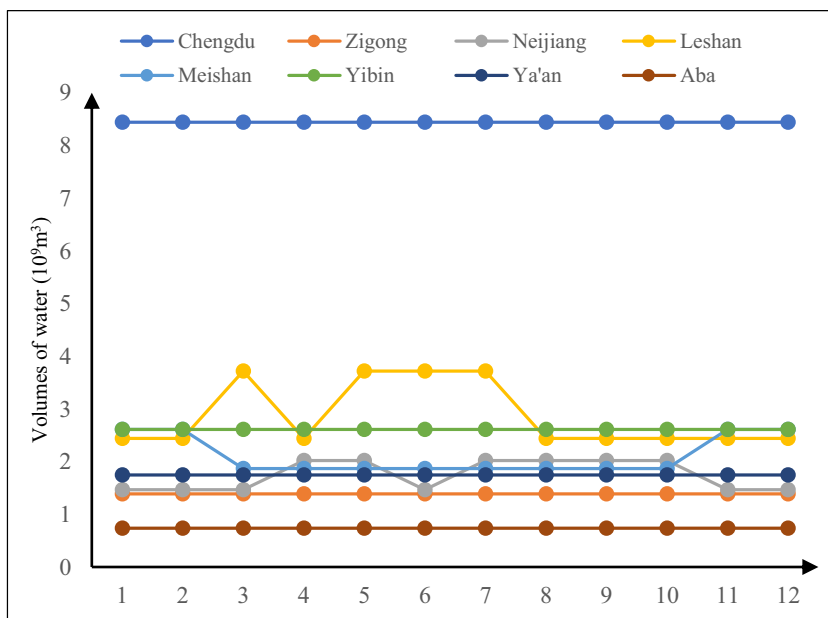
(B) Ecological water restrictions

To protect the ecological environment and ensure water security, it is necessary to maintain ecological water use, so the

Table 7 Water allocation schemes of industrial sector under different weights

Serial number	1	2	3	4	5	6	7	8	9	10	11	12
City	Weight											
	(0.1,0.2,0.3,0.4)	(0.1,0.2,0.2,0.5)	(0.1,0.45,0.25,0.2)	(0.2,0.3,0.4,0.1)	(0.2,0.3,0.2,0.3)	(0.25,0.25,0.25,0.25)	(0.25,0.2,0.3,0.25)	(0.3,0.2,0.1,0.4)	(0.3,0.2,0.1,0.4)	(0.4,0.3,0.2,0.1)	(0.45,0.25,0.2,0.1)	(0.5,0.2,0.2,0.1)
Chengdu	8.44	8.44	8.44	8.44	8.44	8.44	8.44	8.44	8.44	8.44	8.44	8.44
Zigong	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39	1.39
Neijiang	1.47	1.47	1.47	2.02	2.02	1.47	2.02	2.02	2.02	2.02	1.47	1.47
Leshan	2.44	2.44	3.72	2.44	3.72	3.72	3.72	2.44	2.44	2.44	2.44	2.44
Meishan	2.61	2.61	1.87	1.87	1.87	1.87	1.87	1.87	1.87	1.87	2.61	2.61
Yibin	2.61	2.61	2.61	2.61	2.61	2.61	2.61	2.61	2.61	2.61	2.61	2.61
Ya'an	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75	1.75
Aba	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74	0.74

Fig. 8 Water allocation scheme for industrial water sector



MRB management authority should prioritize ecological water use when allocating water resources; it can be expressed as:

$$T_0 - \sum_{j=1}^8 S_j \geq \sum_{j=1}^8 (x_j^{dom} + x_j^{agr} + x_j^{ind}) \tag{6}$$

(III) Water demand restriction

To assure fundamental usage and development and prevent resource waste in the water sector, the minimum water demand for each sector must be satisfied. Each area will only receive the water necessary to meet its highest aspirations. It can be expressed as:

$$(x_j^{dom})^{min} \leq x_j^i \leq (x_j^{dom})^{max}, (x_j^{agr})^{min} \leq x_j^j \leq (x_j^{agr})^{max}, (x_j^{ind})^{min} \leq x_j^i \leq (x_j^{ind})^{max} \tag{7}$$

(IV) Restrictions on the allocation of discharge rights

To ensure primary usage and development, prevent waste of discharge rights, and safeguard the ecological environment, the minimum discharge rights demand for each sub-area of the basin must be satisfied, and the discharge rights allotted to each subarea must not exceed its maximum expectations. It can be expressed as:

$$(R_j^{wes})^{min} \leq R_j^{wes} \leq (R_j^{wes})^{max} \tag{8}$$

(E) Total discharge limit

The river basin management authority allows a limited amount of sewage to be discharged and will set a total amount to limit the discharge of sewage in river basin.

Table 8 Allocation schemes of sewage discharge rights under different weights

Serial number	1	2	3	4	5	6	7	8	9	10	11	12
City	Weight											
	(0.1,0.2,0.3,0.4)	(0.1,0.2,0.2,0.5)	(0.1,0.45,0.25,0.2)	(0.2,0.3,0.4,0.1)	(0.2,0.3,0.2,0.3)	(0.25,0.25,0.25,0.25)	(0.25,0.2,0.3,0.25)	(0.3,0.2,0.1,0.4)	(0.3,0.2,0.1,0.4)	(0.4,0.3,0.2,0.1)	(0.45,0.25,0.2,0.1)	(0.5,0.2,0.2,0.1)
Chengdu	10.73	10.73	10.73	10.73	10.73	10.73	10.73	10.73	10.73	10.73	10.73	10.73
Zigong	0.55	0.55	0.48	0.55	0.48	0.55	0.48	0.55	0.55	0.55	0.55	0.55
Neijiang	0.37	0.44	0.44	0.37	0.37	0.37	0.37	0.37	0.44	0.44	0.37	0.37
Leshan	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.55
Meishan	0.36	0.33	0.33	0.33	0.36	0.33	0.33	0.36	0.36	0.33	0.36	0.33
Yibin	0.45	0.45	0.45	0.45	0.45	0.45	0.80	0.45	0.45	0.45	0.45	0.45
Ya'an	0.21	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Aba	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

$$0 < R_j^{wes}, \sum_{j=1}^J R_j^{wes} \leq R^0 \tag{9}$$

Global model

The Gini coefficient represents the equity of water resource allocation and sewage discharge right allocation by fusing the objective function with constraint criteria. The following is the global model formula:

$$\begin{aligned} \min g_1(x_j^{dom}) &= \frac{1}{2 \cdot J \cdot \sum_{j=1}^J \frac{x_j^{dom} + OW^{dom}}{p_j}} \sum_{a=1}^J \sum_{b=1}^J \left| \frac{x_a^{dom} + OW^{dom}}{p_a} - \frac{x_b^{dom} + OW^{dom}}{p_b} \right| \\ \min g_2(x_j^{agr}) &= \frac{1}{2 \cdot J \cdot \sum_{j=1}^J \frac{x_j^{agr} + OW^{agr}}{N_j}} \sum_{a=1}^J \sum_{b=1}^J \left| \frac{x_a^{agr} + OW^{agr}}{N_a} - \frac{x_b^{agr} + OW^{agr}}{N_b} \right| \\ \max g_3(x_j^{ind}) &= \frac{1}{2 \cdot J \cdot \sum_{j=1}^J \frac{x_j^{ind} + OW^{ind}}{E_j}} \sum_{a=1}^J \sum_{b=1}^J \left| \frac{x_a^{ind} + OW^{ind}}{E_a} - \frac{x_b^{ind} + OW^{ind}}{E_b} \right| \\ \max g_4(R_j^{wes}) &= \frac{1}{2 \cdot J \cdot \sum_{j=1}^J \frac{R_j^{wes}}{E_j}} \sum_{a=1}^J \sum_{b=1}^J \left| \frac{R_a^{wes}}{E_a} - \frac{R_b^{wes}}{E_b} \right| \end{aligned}$$

$$\left. \begin{aligned} &0 \leq \sum_{j=1}^8 (x_j^{dom} + x_j^{agr} + x_j^{ind}) < T_0 \\ &T_0 - \sum_{j=1}^8 S_j + OW \geq \sum_{j=1}^8 (x_j^{dom} + x_j^{agr} + x_j^{ind}) \\ &(x_j^{dom})^{\min} \leq x_j^i \leq (x_j^{dom})^{\max} \\ &(x_j^{agr})^{\min} \leq x_j^i \leq (x_j^{agr})^{\max} \\ &(x_j^{ind})^{\min} \leq x_j^i \leq (x_j^{ind})^{\max} \\ &(R_j^{wes})^{\min} \leq R_j^i \leq (R_j^{wes})^{\max} \\ &\sum_{j=1}^J R_j^{wes} \leq R_0 \\ &x_j^i \geq 0, R_j^{wes} \geq 0 \end{aligned} \right\} s.t. \tag{10}$$

Specific solution steps for these objectives

According to the above global multi-objective optimization model, the weight preferences of decision-makers are

$$Q(\vartheta_i) = \min \left(\vartheta_1 \left(\frac{g_1 - g_1^{\circ}}{g_1^{\circ\circ} - g_1^{\circ}} \right) + \vartheta_2 \left(\frac{g_2 - g_2^{\circ}}{g_2^{\circ\circ} - g_2^{\circ}} \right) - \vartheta_3 \left(\frac{g_3 - g_3^{\circ}}{g_3^{\circ\circ} - g_3^{\circ}} \right) + \vartheta_4 \left(\frac{g_4 - g_4^{\circ}}{g_4^{\circ\circ} - g_4^{\circ}} \right) \right), i = 1, 2, 3, 4 \tag{12}$$

$Q(\vartheta_i)$ is the equal objective function of the watershed administration. The proportions of $\vartheta_1, \vartheta_2, \vartheta_3$ and ϑ_4 are the proportions of corresponding decision variables g_1, g_2, g_3 and g_4 . $g_1^{\circ}, g_2^{\circ}, g_3^{\circ}$ and g_4° and $g_1^{\circ\circ}, g_2^{\circ\circ}, g_3^{\circ\circ}$ and $g_4^{\circ\circ}$ represent the optimal/worst value of g_1, g_2, g_3 and g_4 when optimized separately.

set, and the multi-objective optimization model is converted into a single-objective optimization model as follows:

$$\max \vartheta_1 g(x_j^{dom}) + \vartheta_2 g(x_j^{agr}) + \vartheta_3 g(x_j^{ind}) + \vartheta_4 g(R_j^{wes}) \tag{11}$$

where $\vartheta_1 + \vartheta_2 + \vartheta_3 + \vartheta_4 = 1$. According to the established single-objective optimization model, the optimization solver in Matlab is invoked to solve it as follows:

- (1) Convert the established multi-objective optimization model into a single-objective optimization model, and convert that single-objective model into a specific code
- (2) Invoke the GA algorithm in Matlab given a specific range of values for the decision variables in the model
- (3) Bring the constraints into the model to determine the available range of water resources and wastewater discharge rights
- (4) Derive satisfactory solutions for different combinations of weight scenarios based on the values of ω , and select decision options according to the decision-maker’s preferences

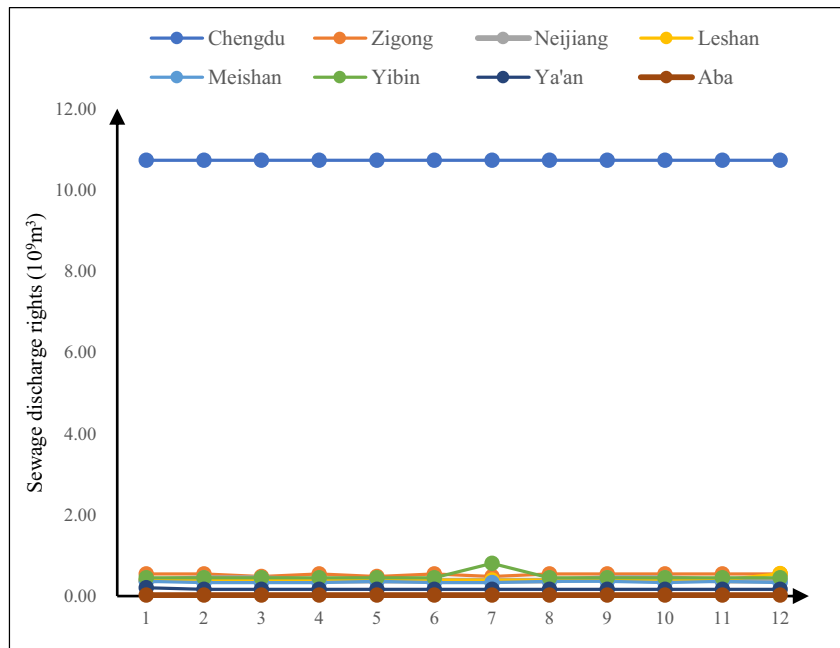
Results and discussion

The weighted technique is employed to incorporate the agricultural, household, and industrial sectors, along with the Gini coefficient of discharge rights allocation, when applying the model to the MRB. It is important to note that the correlation between the allocation of sewage discharge rights and the conventional distribution of water resources is not taken into account; hence, the water use sector and sewage discharge rights are weighted simultaneously. Prior to utilizing the weighting approach, $g_1, g_2, g_3,$ and g_4 are standardized to eliminate the impact of the target value range. Therefore, the equality objective function is formulated as a result:

Analysis of the rationality of the allocation plan

The model is applied to the MRB and the following allocation results are obtained by solving the equality function, which includes the allocation scheme of domestic, agriculture, industrial, and discharge rights. When $\vartheta_1=0.25, \vartheta_2=0.25, \vartheta_3=0.25,$

Fig. 9 Allocation scheme of sewage discharge rights



$\vartheta_4=0.25$, it serves as the basic scheme for the allocation of water resources and discharge rights (Table 4).

Comparison of water allocation schemes with and without sewage discharge rights

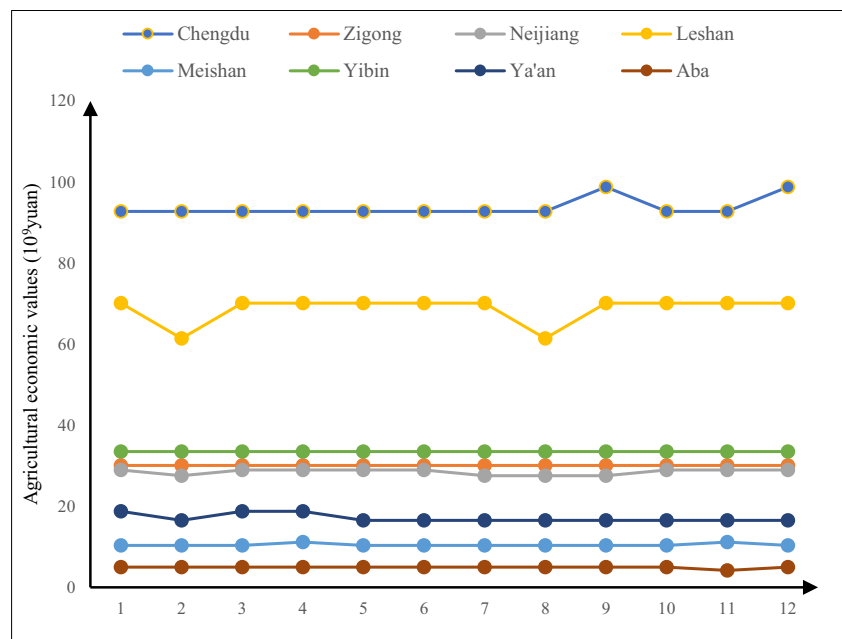
The discharge rights are not taken into account when developing the model. The model’s output is shown in Table 4. The longitudinal axis of Fig. 3 indicates the amount of water allotted by the water use sector, while the horizontal axis represents the eight cities flowing through the MRB. The change in agricultural water use is the most evident, and the change in industrial water use is more clear, according to a comparison between the present water allocation plan of the water sector (without

taking the discharge right into account) and the model water allocation scheme. Domestic water consumption has changed the least. Agricultural water consumption is more steady than real water allocation in the water diversion plan taking discharge rights into account, which benefits the equitable growth of 8 cities in the MRB. Among them, Chengdu’s industrial water consumption has been lowered by 476 million cubic meters, in keeping with the city’s scientific and technical transformation and development policy of lowering industrial water use and enhancing water use efficiency. In terms of industrial water consumption, Zigong, Neijiang, Leshan, Meishan, Yibin, Ya’an, and Aba prefectures have all increased, while Chengdu has decreased and the other seven cities have climbed.

Table 9 Agricultural economic values under different weight sets in each subarea

Serial number	1	2	3	4	5	6	7	8	9	10	11	12
City	Weight											
	(0.1,0.2,0.3,0.4)	(0.1,0.2,0.2,0.5)	(0.1,0.45,0.25,0.2)	(0.2,0.3,0.4,0.1)	(0.2,0.3,0.2,0.3)	(0.25,0.25,0.25,0.25)	(0.25,0.2,0.3,0.25)	(0.3,0.2,0.1,0.4)	(0.3,0.2,0.1,0.4)	(0.4,0.3,0.2,0.1)	(0.45,0.25,0.2,0.1)	(0.5,0.2,0.2,0.1)
Chengdu	92.73	92.73	92.73	92.73	92.73	92.73	92.73	92.73	98.73	92.73	92.73	98.73
Zigong	30.10	30.10	30.10	30.10	30.10	30.10	30.10	30.10	30.10	30.10	30.10	30.10
Neijiang	28.96	27.54	28.96	28.96	28.96	28.96	27.54	27.54	27.54	28.96	28.96	28.96
Leshan	70.14	61.41	70.14	70.14	70.14	70.14	70.14	61.41	70.14	70.14	70.14	70.14
Meishan	10.36	10.36	10.36	11.20	10.36	10.36	10.36	10.36	10.36	10.36	11.20	10.36
Yibin	33.52	33.52	33.52	33.52	33.52	33.52	33.52	33.52	33.52	33.52	33.52	33.52
Ya'an	18.78	16.52	18.78	18.78	16.52	16.52	16.52	16.52	16.52	16.52	16.52	16.52
Aba	5.03	5.03	5.03	5.03	5.03	5.03	5.03	5.03	5.03	5.03	4.22	5.03
Sum	289.60	277.20	289.60	290.45	287.34	287.34	285.92	277.20	291.92	287.34	287.38	293.34

Fig. 10 Agricultural economic values of MRB subarea under different weight sets



Comparison of sewage discharge rights allocation schemes

By comparing the emission rights allocation schemes in percentage form on the bar chart, Fig. 4 shows the comparison results and indicates the sewage discharge rights allocated to 8 cities on the Minjiang River when considered comprehensively. The changes in Chengdu, Zigong, and Leshan are the most stable. Yibin, Meishan, Ya’an, and Aba vary greatly, in which Yibin, Meishan, and Aba vary by 20.1%, 15.3%, and 10%, respectively. Because of the close relationship between sewage discharge and the location of the Chengdu Basin, the upstream sewage discharge is the least in the MRB, and the water quality of the basin is the best in the middle reaches of the river. Chengdu produces the most sewage, which has a great impact on water quality. However, the downstream water quality is the worst, so in the allocation of sewage rights, we should increase the

sewage discharge rights of upstream Aba and downstream Zigong to promote economic development so that the ecological environment of the basin can be protected.

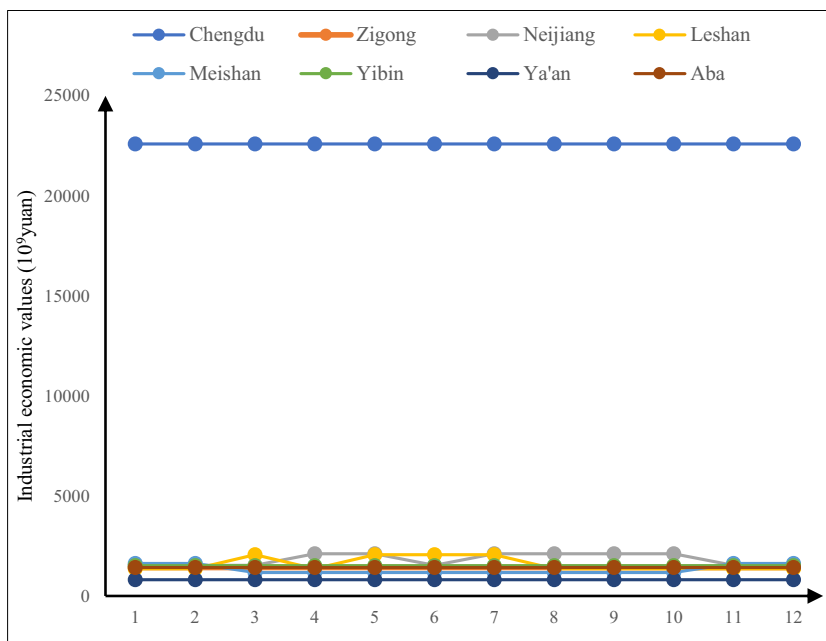
Robustness analysis of allocation schemes under different weights

Water sector and sewage discharge rights play a crucial role in measuring equity, and different weights can also reflect the preference of watershed management authorities in the water sector and discharge rights to a certain extent. Figure 3 shows the Gini coefficient of the allocation scheme under different weights. Figure 5 shows that when the weight is changed, the Gini coefficient of the allocation scheme remains stable and effective. Meanwhile, in Fig. 5, the Gini coefficient of the domestic water sector is the smallest; the Gini coefficient range is [0.08, 0.1]. The Gini coefficient of the agricultural

Table 10 Industrial economic values under different weight sets in each subarea

Serial number	1	2	3	4	5	6	7	8	9	10	11	12
City	Weight											
	(0.1,0.2,0.3,0.4)	(0.1,0.2,0.2,0.5)	(0.1,0.45,0.25,0.2)	(0.2,0.3,0.4,0.1)	(0.2,0.3,0.2,0.3)	(0.25,0.25,0.25,0.25)	(0.25,0.2,0.3,0.25)	(0.3,0.2,0.1,0.4)	(0.3,0.2,0.1,0.4)	(0.4,0.3,0.2,0.1)	(0.45,0.25,0.2,0.1)	(0.5,0.2,0.2,0.1)
Chengdu	22,584.01	22,584.01	22,584.01	22,584.01	22,584.01	22,584.01	22,584.01	22,584.01	22,584.01	22,584.01	22,584.01	22,584.01
Zigong	1421.53	1421.53	1421.53	1421.53	1421.53	1421.53	1421.53	1421.53	1421.53	1421.53	1421.53	1421.53
Neijiang	1537.28	1537.28	1537.28	2112.46	2112.46	1537.28	2112.46	2112.46	2112.46	2112.46	1537.28	1537.28
Leshan	1358.74	1358.74	2071.52	1358.74	2071.52	2071.52	2071.52	1358.74	1358.74	1358.74	1358.74	1358.74
Meishan	1637.88	1637.88	1173.50	1173.50	1173.50	1173.50	1173.50	1173.50	1173.50	1173.50	1637.88	1637.88
Yibin	1518.34	1518.34	1518.34	1518.34	1518.34	1518.34	1518.34	1518.34	1518.34	1518.34	1518.34	1518.34
Ya'an	811.42	811.42	811.42	811.42	811.42	811.42	811.42	811.42	811.42	811.42	811.42	811.42
Aba	1424.35	1424.35	1424.35	1424.35	1424.35	1424.35	1424.35	1424.35	1424.35	1424.35	1424.35	1424.35
Sum	32,293.55	32,293.55	32,541.95	32,404.34	33,117.12	32,541.95	33,117.12	32,404.34	32,404.34	32,404.34	32,293.55	32,293.55

Fig. 11 Industrial economic values of MRB subarea under different weight sets



water sector is smaller, and the Gini coefficient range is [0.2, 0.25]. There is no significant difference between the Gini coefficient of the sewage right and the industrial water use sector, but compared with the agricultural and domestic water sectors, the Gini coefficient is [0.25, 0.34]. Because most of the units of domestic water use are individuals, the water consumption is more average, and it is mainly used for the daily use of family life. Therefore, the Gini coefficient is the smallest, the agricultural water use is mainly used for cultivated land to produce grain, and the water consumption is also more average, but there is an impact on the scale of agriculture. As a result, the Gini coefficient of agriculture is larger than that of the life Gini coefficient. In the allocation of industrial water and discharge rights, priority is given to large-scale enterprises, which can maximize economic utility and lead to the largest Gini coefficient of industry and discharge rights.

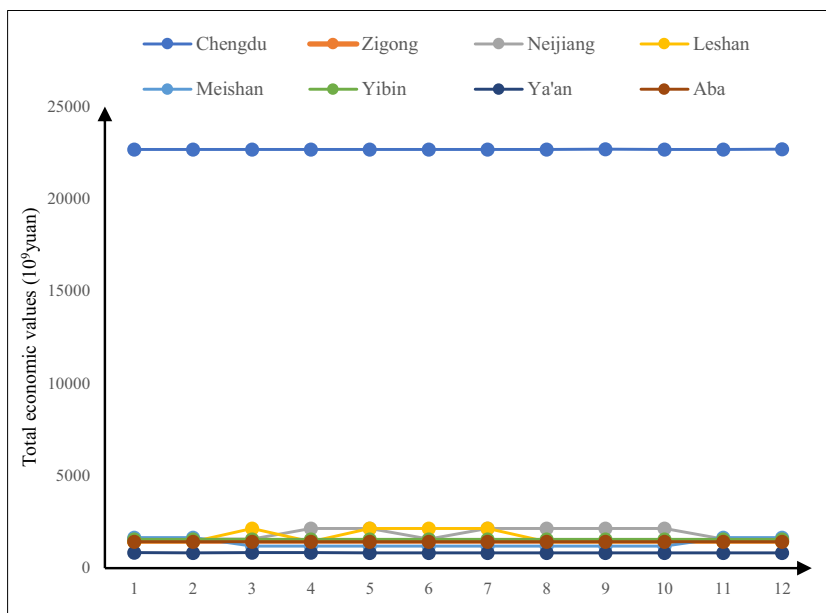
Robustness analysis of equity in domestic water

The water allocation scheme for the domestic water sector under different weights is shown in Table 5. When $\vartheta_1 = 0.25, \vartheta_2 = 0.25, \vartheta_3 = 0.25, \vartheta_4 = 0.25$, as per the basic scheme of the allocation of water resources and sewage discharge rights, the amount of domestic water allocated to Chengdu at this time is the largest, and the sum of the water allocations of the other seven cities is not larger than that of the domestic water sector of Chengdu, which is consistent with the actual water allocation. It is worth noting that in this study, 12 sets of weight sets are compiled into numbers 1 to 12 in order to facilitate graphic interpretation and explanation. Figure 6 depicts the domestic water sector’s water allocation in the MRB’s eight cities using different weights. According

Table 11 Total economic value under different weight sets in all each subarea

Serial number	1	2	3	4	5	6	7	8	9	10	11	12
City	Weight											
	(0.1,0.2,0.3,0.4)	(0.1,0.2,0.2,0.5)	(0.1,0.45,0.25,0.2)	(0.2,0.3,0.4,0.1)	(0.2,0.3,0.2,0.3)	(0.25,0.25,0.25,0.25)	(0.25,0.2,0.3,0.25)	(0.3,0.2,0.1,0.4)	(0.3,0.2,0.1,0.4)	(0.4,0.3,0.2,0.1)	(0.45,0.25,0.2,0.1)	(0.5,0.2,0.2,0.1)
Chengdu	22,676.74	22,676.74	22,676.74	22,676.74	22,676.74	22,676.74	22,676.74	22,676.74	22,682.74	22,676.74	22,676.74	22,682.74
Zigong	1451.62	1451.62	1451.62	1451.62	1451.62	1451.62	1451.62	1451.62	1451.62	1451.62	1451.62	1451.62
Neijiang	1566.23	1564.82	1566.23	2141.41	2141.41	1566.23	2139.99	2139.99	2139.99	2141.41	1566.23	1566.23
Leshan	1428.87	1420.15	2141.65	1428.87	2141.65	2141.65	2141.65	1420.15	1428.87	1428.87	1428.87	1428.87
Meishan	1648.23	1648.23	1183.85	1184.70	1183.85	1183.85	1183.85	1183.85	1183.85	1183.85	1649.07	1648.23
Yibin	1551.85	1551.85	1551.85	1551.85	1551.85	1551.85	1551.85	1551.85	1551.85	1551.85	1551.85	1551.85
Ya'an	830.20	827.93	830.20	830.20	827.93	827.93	827.93	827.93	827.938	827.93	827.93	827.93
Aba	1429.38	1429.38	1429.38	1429.38	1429.38	1429.38	1429.38	1429.38	1429.38	1429.38	1428.57	1429.38
Sum	32,583.15	32,570.75	32,831.55	32,694.79	33,404.46	32,829.29	33,403.04	32,681.54	32,696.26	32,691.68	32,580.92	32,586.89

Fig. 12 Total economic values of each subarea under different weight sets

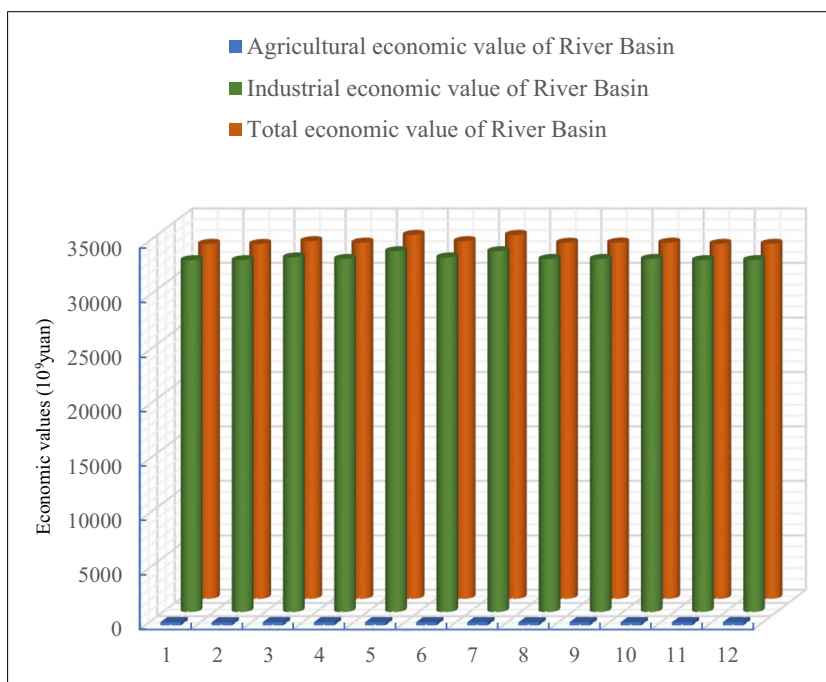


to the change of weight value, the water allocation of the domestic water sector changes with the change of weight, among which the change of Chengdu is the most obvious. When the weight is (0.1, 0.2, 0.5) and (0.25, 0.2, 0.3, 0.25), there will be a wave peak in the water allocation of the domestic water sector in Chengdu. The water allocation of domestic water departments in eight cities in the MRB changed little, and the model results were stable.

Robustness analysis of equity in agricultural water

Table 6 shows the water allocation schemes for the agricultural water sector under different weights. When $\vartheta_1 = 0.25, \vartheta_2 = 0.25, \vartheta_3 = 0.25, \vartheta_4 = 0.25$, as per the basic scheme of the allocation of water resources and sewage discharge rights, the amount of agricultural water allocated to Chengdu is the largest, with a water allocation of

Fig. 13 Variation of economic value in the MRB under coordinative allocation scheme



3.091 billion cubic meters. Figure 7 shows the water allocation of the agricultural water use department in 8 cities of the MRB under different weights. When the weight is (0.3, 0.2, 0.1, 0.4), the water allocation of the agricultural water sector in Chengdu will peak, and the water allocation of the agricultural water sector will increase in the end. Under the change of weight, the result of water allocation in the agricultural water use department in 8 cities of the MRB is small, and the result of the model is stable.

Robustness analysis of equity in industrial water

Table 7 and Fig. 8 show the water allocation scheme for the industrial water use sector under different weights in the MRB. The water allocation of the industrial water sector varies with the change of weight, among which Chengdu has the most stable change, among which Leshan and Meishan vary greatly. When the weights of Leshan are (0.1, 0.45, 0.25, 0.2), (0.2, 0.3, 0.2, 0.3), (0.25, 0.25, 0.25, 0.25), and (0.25, 0.2, 0.3, 0.25), the industrial water allocation reaches its peak; the industrial water content varies from about 120 million cubic meters to about 120 million cubic meters. Despite some adjustments in the MRB's industrial water allocation for eight cities, the changes are minor, and the model's predictions remain consistent.

Robustness analysis of equity of sewage discharge right

Table 8 shows the allocation of discharge rights under different weights. When $\vartheta_1 = 0.25$, $\vartheta_2 = 0.25$, $\vartheta_3 = 0.25$, $\vartheta_4 = 0.25$, as per the basic scheme of sewage discharge right allocation, Chengdu has the most prominent discharge right at this time. The discharge right is 1.073 billion cubic meters, and the sum of the other seven city discharge rights is not larger than the Chengdu sewage discharge right, which is consistent with the actual water allocation. Figure 9 shows the allocation scheme of discharge rights in 8 cities of the MRB under different weights. According to the change of weight value, the value of discharge right varies with the change of weight, among which the change of discharge right in Yibin City is the most obvious. When the weight is (0.25, 0.2, 0.3, 0.25), where will there be a peak of sewage discharge in Yibin City? The range of discharge rights allocation in the MRB has shifted slightly due to a weight change. The results of the model are stable and can show the allocation preference of watershed management authorities.

The influence of preference degree on economy in allocation scheme

The allocation scheme generated by the multi-objective optimal configuration model can affect the economic development of each subarea. To a certain extent, the preference of watershed managers for agricultural water use is mainly reflected in the agricultural water use. The agricultural economy will give priority to the development of the agricultural economy, and the amount of water allocated in the subarea will be less. When considering economic growth, since domestic water use is mainly to solve the living problems of residents, it should not be included in the scope of economic calculation. Therefore, only agricultural and industrial water should be considered when measuring the economic benefits.

Table 9 shows that the Chengdu still ranks first with 9.273 billion yuan in agricultural economic value, while the rest are Leshan, Yibin, Zigong, Neijiang, Ya'an, Meishan, and Aba. However, the agricultural economic value of Chengdu does not exceed the sum of the other seven cities, which is due to the tremendous development of high-tech and precision manufacturing industries in Chengdu, resulting in a certain degree of agricultural economic value. When the weight is 9, the weight is (0.3, 0.2, 0.1, 0.4), when the proportion of agricultural water consumption reaches 30% and the proportion of multi-objective optimal allocation system is relatively large, which leads to the increase of the agricultural economy of Chengdu, Leshan, and Neijiang. When the weights of Leshan are (0.1, 0.2, 0.2, 0.5) and (0.025, 0.25, 0.1, 0.4), the proportion of agricultural water use is relatively small, accounting for less than 25%, but the sewage discharge weight is relatively large, accounting for about 40%. Watershed managers will pay more attention to sewage discharge and treatment and will use more water to treat sewage discharge and discharge, and then the agricultural economic value of Leshan City will decline. Chengdu and Leshan have changed violently. Yibin, Zigong, Neijiang, Ya'an, Meishan, and Aba have changed more smoothly (Fig. 10).

For the preference degree of watershed managers, it is vital to consider the multi-objective optimal allocation model to obtain the greatest industrial economic value. Table 10 shows the industrial economic values of each subarea, the change of Leshan and Neijiang is more apparent, and the change degree of other cities is relatively small, which is because the water use of Leshan and Neijiang is mainly agricultural water. Industrial water use is mainly in the production of building materials and auto parts. When watershed managers pay attention to sewage treatment and discharge, the industrial economies

of Leshan and Neijiang are greatly impacted. As a result, the industrial economic values of Leshan and Neijiang fluctuated wildly (Fig. 11). While watershed managers choose the allocation scheme, different preferences will affect the economic development of the basin subarea, so it is necessary to make reasonable adjustments and choices according to the actual water use situation of the regional industry.

Through the analysis of the agricultural and industrial economies, it is discovered that the basin's economic value and industrial economic value are closely associated. This is because the industrial economic value is significantly more than the agricultural economic value. Table 11 shows the total economic value of each subarea under various weight sets, and the total economic value of each subarea coincides with the degree of change of the regional industrial economic value. Figures 12 and 13 show the change in economic value of the MRB under the allocation scheme. From the point of view of the economic value of the whole basin, the degree of change in the economic value of the MRB under different weight sets is similar to that of the industrial economy of the whole basin. Therefore, the preference degree of watershed managers can reflect the synergistic relationship between sewage discharge and water resource allocation and determine the essential elements of economic development. This study also only provides the model presentation with the mentioned 12 special weights, indicating management decisions based on the preferences of watershed leaders.

Conclusion and policy implications

In the process of global SDG advancement, this study uses multi-objective planning to achieve equity in SDG 6 by combining the allocation of water resources with the allocation of sewage rights. Different weights are established to weigh the water demand of each sector under different preferences. According to the results of the study, the Gini coefficients of agricultural, household, industrial, and discharge rights allocations show simultaneous optimization and stable modification, and the following conclusions are drawn: (1) the allocation of discharge rights is an important part of the water allocation plan, and the synergistic allocation of sewage discharge rights and water resources facilitates the achievement of equity; (2) the allocation of discharge rights has a greater impact on the equity and economic value of domestic and industrial water allocations; and (3) the greater the proportional importance of wastewater discharge, the lower the economic return and the more equitable the allocation of water resources between domestic and industrial sectors.

Based on the basin allocation plans and the model results, the following insights were obtained: (1) basin managers must consider wastewater discharge within the basin as an inherent constraint to measure equity when allocating water resources; (2) more preference can be given to the allocation of wastewater discharge rights when considering environmental risks; and (3) sectors with higher water demand can increase the economics of water allocation.

In summary, the developed model has specific applicability to individual watersheds. The model conclusions given in this study are also achieved by applying alternative weights to the objective function and do not include every potential outcome under the model. In addition, multi-basin case studies and effluent measurements are frequent in water management practice, which is a major direction for further research in the future.

Author contribution Mingkang Yuan: conceptualization, methodology, validation, writing—original draft. Xudong Chen: software, validation, data curation, review original draft. Yue Li: data curation, supervision, writing—review and editing. Zixuan Zhang: software, validation, data curation. Lin Wang: data collection and processing, editing and typesetting.

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Data availability The data that has been used is open.

Declarations

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