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Multi-objective optimal allocation of water resources based on ‘three red lines’ in Qinzhou, China

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Abstract

Water shortages and pollution emerge because of anthropogenic demands. Since 2011, ‘China’s Most Stringent Water Resources Management’ (CMSWRM) has been comprehensively enacted in the country. This paper presents the characteristics of the ‘three red lines’ (TRL) and a multi-objective optimal allocation model based on the TRL constraint, considering the benefits for society, the economy, and the environment. This model had been applied to the reasonable allocation of water supply and demand in Qinzhou for the planning years of 2020 and 2030. Two water resource allocation scenarios for these years were configured by setting different chemical oxygen demand (COD) concentrations for wastewater discharge in the municipal, secondary, tertiary, and agricultural sectors. The gamultiobj function based on the NSGA-II algorithm was used to solve the model in MATLAB. The results indicate that if COD concentrations in each sector are not reduced, then restrictions on domestic water sources will be necessary, both in 2020 and 2030. The two water resource allocation scenarios in 2020 and 2030 can provide a reference for decision-makers in Qinzhou to implement CMSWRM.

Keywords: NSGA-II algorithm; Optimal allocation; Three red lines; Water quality; Water quantity

Introduction

With improvements in living standards, people’s requirements for water quantity and water quality have increased. Water shortages and deterioration of water quality have caused conflicts in the

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supply and demand of regional water resources. There are also problems such as low water use efficiency and the fact that water ecology continues to be negatively impacted by human activities (Mei, 2010; Liu *et al.*, 2013). Under the combined effects of these factors, the economic, social, and environmental benefits of water resources are difficult to optimize, which restricts regional economic development and social stability.

The optimal allocation of water resources is an important means to alleviate supply–demand conflicts in different regions. By distributing limited water resources to different sectors scientifically and reasonably, the maximum benefits of water use can be obtained (Habibi Davijani *et al.*, 2016a, 2016b). Thus, particular development theories have been put forward which approach water resources allocation based on balance development (Liu *et al.*, 2015), sustainable development (Niu *et al.*, 2016), and evaporation transpiration (ET) development (Zhou *et al.*, 2009).

The methods above pay more attention to water quantity allocation, with less emphasis on water quality. Other theories such as ecology development (Naiman & Bilby, 1998; Myers & Bazely, 2003), green development (Adam, 1995), and low carbon use (Kanakoudis *et al.*, 2012; Kanakoudis & Papadopoulou, 2014; Kanakoudis, 2015) comprehensively consider regional water quantity and water quality factors but neglect water use efficiency when considering the allocation of water resources. This can lead to problematic policy recommendations to resolve the contradiction between supply and demand, such as building new water supply facilities rather than optimizing the use of existing options.

In 2011, the No. 1 Document of the Central Committee of the Communist Party of China clearly articulated 'China's Most Stringent Water Resources Management' (CMSWRM) (CPC Central Committee and State Council, 2010). The three red lines (TRL) constraint is the core of CMSWRM. They consist of the total water use red line (TWURL), the water use efficiency red line (WUERL), and the controlling pollution red line (CPRL) (Global Water Partnership, 2013).

The purpose of establishing the TWURL is to strictly limit the rapid growth of total water use and to control the development of water resources within the scope of carrying capacity. The purpose of re-establishing the WUERL is to enhance the efficiency of water use, thus saving water. Controlling agricultural and industrial water use efficiency is crucial in this respect. 'Irrigation efficiency' (IE) is an important indicator to measure the efficiency of the agriculture sector in regions which are less influenced by climate conditions (Jensen, 2007) and plant structure (Liu & Song, 2019). 'Water used per CNY10,000 industrial added value' (WUPCIAV) can reflect the technology of industrial water use, the level of water-saving reforms, and enterprise management (Zang *et al.*, 2016) and can thus be a suitable indicator for evaluating industrial water use efficiency. The purpose of establishing the CPRL is to strengthen water pollution prevention and water resources protection, so that the total amount of allowed pollutant discharge (TAOAPD) into rivers can be controlled considering the carrying capacity in water environments (Yi *et al.*, 2017).

At present, the essence of Chinese water resources management (WRM) involves combining the TRL with regional water resources allocation (WRA). Optimal models connecting the TRL constraint are necessary to solve WRA problems (Wang *et al.*, 2012). Wang & Zhang (2014) presents a multi-source joint regulation model based on the TRL by considering the objective of socio-economic benefits. Related studies have also been conducted by Liang & Zuo (2013), Tursunmo (2015), and Zhao (2015). However, they only considered quota constraints. Ignoring the WUPCIVA index will lead to increasing water demand in the secondary sector, which further aggravates the imbalance between supply and demand.

Different researchers have constructed WRM models to support local implementations of the national CMSWRM initiative: in Yangquan city (Ren, 2015); Weihe basin (Wang *et al.*, 2015); Taiyuan city

(Jiang *et al.*, 2016); and Yuhuan city (Zhong *et al.*, 2018), However, they all use sectoral pollutant discharge concentrations in status years instead of planning years, which would likely cause excessive total sewage discharge into rivers in planning years.

Further, reviewing the literature it appears that extant studies have focused on areas experiencing water shortages due to a lack of water resources. However, Qinzhou is located on the southwest coast of Guangxi and has a subtropical marine monsoon climate with an average annual rainfall of 2,026.3 m^3. Due to the lack of large-scale water storage projects in the upper reaches, Qinzhou can be characterized as a water shortage area from an engineering perspective which is obviously different from those water shortage areas which experience a lack of water resources (Chen *et al.*, 2018a).

This paper seeks to address the issue of regional water resources allocation given the CMSWRM context. The objective of the paper is to present a systematic framework of water resources allocation considering TRL constraints to support CMSWRM, and establish a multi-objective non-linear programming model to allocate domestic and cross-basin water to different sectors in Qinzhou.

Methodology

The principles of water resources allocation based on the TRL

Allocating water given the TRL means adhering to the constraints of water supply, water demand, and total sewage discharge in the model. The system framework of water resources allocation based on the TRL is shown in Figure 1 and the principles of water resource allocation are as follows:

1. The TWURL controls total water withdrawal by calculating the rate of water resource development and utilization. Either domestic water sources (surface water, groundwater, and reuse water) or water from cross-basin diversion projects (CBDP) can be used to allocate water to each sector. The sum of the water supplied by the two types of water sources must not exceed the regional TWURL constraint.
2. Water used per CNY 10,000 industrial added value (WUPCIAV) and irrigation efficiency (IE) are important indicators for quantifying the WUERL; these indicators are respectively applied to industrial and agricultural water demand forecasts in each planning year, which can then limit the increasing water demand in these sectors and allow the total volume of water allocated to be restrained. The results of water demand forecasts are used as water demand constraints in the allocation model.
3. It would be prudent to convert the CPRL into an index of the total amount of allowed pollutant discharge (TAOAPD) including many pollutant indicators as a constraint in the model. However, current monitoring capabilities do not cover all these pollutants, so, chemical oxygen demand (COD) which is monitored by a governmental entity in China can be used as a representative indicator to proxy for a broader array of pollutants. The TAOAPD for COD is thus the water quality constraint in the model, and the total amount of COD discharged by each sector using domestic and CBDP water sources must not exceed the regional TAOAPD for COD.
4. Domestic water sources should be prioritized for supplying water in view of the higher cost of CBDP. When domestic water sources are fully utilized, sectors still lacking water could consider using CBDP water sources.

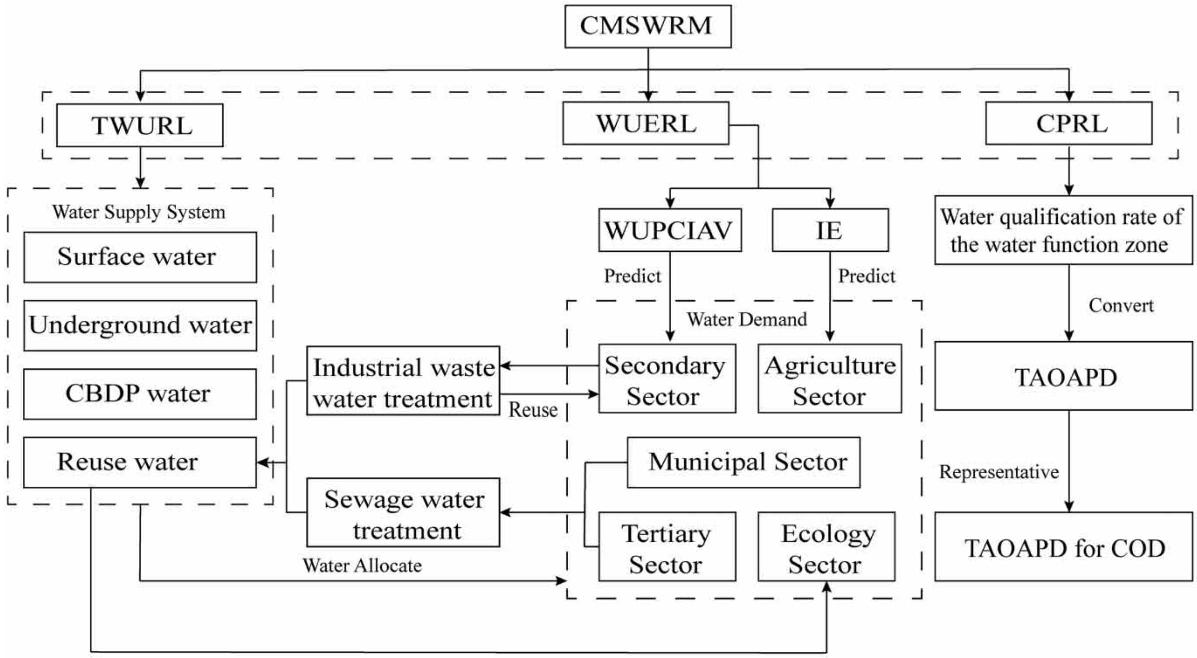

Fig. 1. Conceptual framework of water allocation based on the three red lines (TRL).

Optimal water resources allocation model: objective functions

(1) Social benefits target

Minimum water shortage over the entire region is used as the social benefits target:

$$\min f_1(x, y) = \sum_{k=1}^{K}\sum_{j=1}^{J}\beta_j^k\left[D_J^k - \left(\sum_{i=1}^{I}x_{ij}^k + \sum_{l=1}^{L}y_{lj}^k\right)\right] \tag{1}$$

where k is the number of sub-areas; i and l denote types of domestic and CBDP water sources, respectively; j is type of water use sector; β_j^k is the weight coefficient of sector j in sub-area k; D_j^k is the water demand of sector j under the WUERL constraint in sub-area k; x_{ij}^k is types of domestic water sources i allocating water to sector j in sub-area k; and y_{lj}^k is types of CBDP water sources l allocating water to sector j in sub-area k.

(2) Economic benefits target

Gross domestic product (GDP) is the key headline economic indicator used by governments and international organizations around the world. Using the GDP generated by water use in each sector as the economic benefits target can be expressed as follows:

$$\max f_2(x, y) = \sum_{k=1}^{K} \sum_{j=1}^{J} b_j^k \left(\sum_{i=1}^{I} x_{ij}^k + \sum_{l=1}^{L} y_{lj}^k \right) \tag{2}$$

where b_{ij}^k is the coefficient of water use production value of sector j in sub-area k.

(3) Environment benefits target

Under the condition of the TAOAPD for COD, the minimum amount of COD discharged by each water use sector is used as the environment benefits target:

$$\min f_3(x, y) = \sum_{k=1}^{K} \sum_{j=1}^{J} c_j \alpha_j \left(\sum_{i=1}^{I} x_{ij}^k + \sum_{\mathrm{l}=1}^{L} y_{\mathrm{l}j}^k \right) \tag{3}$$

where c_j is the COD emissions concentration of sector j and α_j is the coefficient of sewage emissions of sector j.

Optimal water resources allocation model: constraints

(1) Water supply capacity constraints

Water allocated to the k sub-areas should not exceed the water supply capacity of domestic and CBDP water sources:

$$\sum_{k=1}^{K} \sum_{i=1}^{I} \sum_{j=1}^{J} x_{ij}^k \leq W_{i,Dome}^k \tag{4}$$

$$\sum_{k=1}^{K} \sum_{l=1}^{L} \sum_{j=1}^{J} y_{lj}^k \leq W_{l,Cross}^k \tag{5}$$

where $W_{i,Dome}^k$ and $W_{l,Cross}^k$ are the available water supplied by domestic water source i and *CBDP* l in sub-area k, respectively.

(2) Users' water demand constraint under the WUERL

Water allocated to each sector from domestic and CBDP water sources should not exceed the water demands in each sector. The industrial and agricultural sectors must follow the *WUPCIAV* and *IE* indicators, respectively, under the *WUERL* in particular.

$$\sum_{k=1}^{K}\sum_{i=1}^{I}\sum_{j=1}^{J}x_{ij}^{k}+\sum_{k=1}^{K}\sum_{l=1}^{L}\sum_{j=1}^{J}y_{lj}^{k}\leq D_{j}^{k} \tag{6}$$

(3) Guaranteed municipal water supply rate

Water allocated to the municipal sector in each sub-area should meet more than 95% of the water demand of this sector:

$$\sum_{k=1}^{K}\sum_{i=1}^{I}\sum_{l=1}^{L}\frac{\left(x_{i,Muni}^{k}+y_{l,Muni}^{k}\right)}{D_{Muni}^{k}}*100\%\geq 95\% \tag{7}$$

where $x_{i,Muni}^{k}$ and $y_{l,Muni}^{k}$ are the water allocated to the municipal sector by domestic water source i and *CBDP* water source l in sub-area k, respectively; D_{Muni}^{k} is the water demand of the municipal sector in sub-area k.

(4) TWURL constraint

$$\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{i=1}^{I}x_{ij}^{k}+\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{l=1}^{L}y_{lj}^{k}\leq Z_{Total}^{k} \tag{8}$$

where Z_{Total}^{k} is the upper limit of the *TWURL* constraint in sub-area k.

(5) CPRL constraint

$$\sum_{k=1}^{K}\sum_{j=1}^{J}c_{j}\alpha_{j}\left(\sum_{i=1}^{I}x_{ij}^{k}+\sum_{L=1}^{L}y_{lj}^{k}\right)\leq Z_{COD} \tag{9}$$

where Z_{COD} is the *TAOAPD* for *COD*.

(6) Non-negative constraints

$$x_{ij}^{k}\geq 0 \tag{10}$$

$$y_{lj}^{k}\geq 0 \tag{11}$$

Optimal water resources allocation model: NSGA-II algorithm

NSGA-II (Deb *et al.*, 2002) is an evolutionary algorithm for solving multi-objective optimization problems. The algorithm assigns fitness values to chromosomes based on a non-dominated sorting approach. Non-dominated solutions are equally valued solutions to a Pareto front. The non-dominated sorting approach aims to preserve diversity among the non-dominated solutions, making use of crowding distance. The crowding distance is a measure of solution density that is used in the selection operator: the less close a solution is to another solution, the higher the chance of selection. In the process of optimization, all objectives are considered to be equally important. When the algorithm finishes searching for a set of optimal solutions, relevant decision-makers analyze and select their preferred solution from this set. If a decision-maker does not have enough target information in advance, or needs to change the expectation value based on developments in their understanding or experience of the problem, interactive use can improve the search efficiency of the algorithm. Importantly, this has proven to be an appropriate algorithm for solving water resource management problems (Bazargan-Lari *et al.*, 2009; Shokri *et al.*, 2014; Ahmadi *et al.* 2015).

Case study

Background

Qinzhou is divided into five administrative divisions (Figure 2): Qinnan, Qinbei, Qingang, Lingshan, and Pubei. There are 388 water storage projects with a total storage capacity of $80{,}002 \times 10^4$ m^3, in which the total annual designed water supply capacity is $80{,}829 \times 10^4$ m^3 (Chen *et al.*, 2018a). In 2014, Qinzhou consumed 15.16×10^8 m^3 water in total, WUPCIAV was 65 m^3, IE was 0.456, and the water qualification rate of the water function zone was 66% (Qinzhou Water Conservancy Bureau, 2014). It is anticipated that Qinzhou will operate the Yujiang CBDP in 2030, which will increase the water supply to 3.229×10^8 m^3 to address water shortages (Qinzhou Water Resources and Hydropower Survey and Design Institute, 2008).

Planning years and TRL indicators

Planning years are set as 2020 and 2030. To implement stringent water resources management in Qinzhou, the target for total water use will be set at 16.53×10^9 m^3 in 2020 and 16.95×10^9 m^3 in 2030 (Guangxi Water Resources Department, 2011). The WUPCIAV indicator will decrease to 50 m^3 in 2020 and 40 m^3 in 2030; and the IE will reach 0.53 in 2020 and 0.6 in 2030. According to the quantified capacity of the water function area of small and medium-sized rivers in Qinzhou and the control plan for total pollutant discharge (Guangxi Water Resources and Hydropower Survey and Design Institute, 2015), TAOAPD for COD will be limited to 44,275.8 ton in 2020 and 44,211.4 ton in 2030.

Water demand prediction

Results are presented in Table 1 using the quota method to forecast the five sectors' water demand in the region under a guaranteed rate of $p = 75\%$ 2020 and 2030. The quotas are determined with reference to Guangxi urban water consumption quota DB45/T 679-2017 (Guangxi Water Resources Department, 2017a), Guangxi main industrial products water consumption quota DB45/T 678-2017 (Guangxi Water Resources Department, 2017b), and Guangxi agriculture, forestry, fishery, and rural water consumption quota DB45/T 804-2012 (Guangxi Water Resources Department, 2012). The relevant social and

Fig. 2. Location and geography of Qinzhou.

economic data were obtained from the Qinzhou City Master Plan (2012–2030) (People's Government Office of Qinzhou, 2013).

Water supply prediction

The method proposed by Chen *et al*. (2018b) is used to forecast the available water supply in Qinzhou in the planning years. As noted, the Yujiang CBDP will be operational in 2030, augmenting the water

Table 1. Sectoral water demand in Qinzhou in planning years (p = 75%) (10^4 m^3).

Planning Year	Sub-Area	Municipal Sector	Secondary Sector	Tertiary Sector	Ecology	Agriculture Sector	Total
2020	Qinnan	3,234.95	3,339.75	1,122.81	383.76	19,202.55	27,283.82
	Qinbei	4,075.37	5,332.55	505.55	474.55	22,828.26	33,216.27
	Qingang	1,799.6	12,387.56	1,306.94	350.05	11.04	15,855.18
	Lingshan	6,871.91	3,819.77	675.72	905.75	49,169.98	61,443.13
	Pubei	4,301.17	5,370.84	504.09	520.51	15,737.24	26,433.85
	Total	20,283	30,250.47	4,115.11	2,634.61	106,949.07	164,232.26
2030	Qinnan	4,124.52	8,323.23	2,257.82	416.29	16,863.08	31,984.94
	Qinbei	5,266.24	14,164.38	1,016.59	757.83	20,125.09	41,330.13
	Qingang	4,228.71	26,033.94	2,628.08	570.73	14.63	33,476.08
	Lingshan	8,736.48	10,146.64	1,358.78	1,532.91	41,117.74	62,892.54
	Pubei	5,461.71	14,276.62	1,013.66	891.49	14,059.69	35,703.18
	Total	27,817.65	72,944.81	8,274.93	4,169.26	92,180.23	205,386.87

supply to Qinzhou. Relevant data concerning this additional supply are taken from the Yujiang Cross-basin Diversion Project Water Resources Argument Report (Qinzhou Water Resources and Hydropower Survey and Design Institute, 2008). In addition, according to the report requirements, the CBDP water will only supply the municipal, secondary, tertiary, and agricultural sectors in Qinbei, Qingang, and Lingshan. Water supply predictions under a guaranteed rate of $p = 75\%$ in Qinzhou in 2020 and 2030 are shown in Table 2.

Model parameters

(1) Sector weight coefficient β_j^k

The sector weight coefficient β_j^k reflects the priority of sector j in terms of being supplied with water relative to other sectors in sub-area k (Yan *et al.*, 2018). The sectoral weight coefficients should sum to

Table 2. Available water supply of Qinzhou in 2020 and 2030 (p = 75%) (10^4 m^3).

		Domestic Water Sources				
Planning Year	Sub-Area	Surface Water	Ground Water	Reuse Water	Yujiang CBDP Water	Total
2020	Qinnan	36,999.1	955.6	1,825	0	39,779.7
	Qinbei	22,760.4	1,079.8	0		23,840.2
	Qingang	5,917.4	33.8	1,825		7,776.2
	Lingshan	40,077.1	1,899	0		41,976.1
	Pubei	20,525.4	1,269.8	0		21,795.2
	Total	126,279.4	5,238	3,650		135,167.4
2030	Qinnan	38,243.6	964.7	1,825	32,290	41,033.3
	Qinbei	27,598	1,090.1	0		28,688.1
	Qingang	6,983	34.1	4,015		11,032.1
	Lingshan	42,332.6	1,917.2	0		44,249.8
	Pubei	26,924.3	1,282	0		28,206.3
	Total	142,081.5	5,288	5,840		185,499.5

1, in which the determination for each sector is expressed by the following equation:

$$\beta_j^k = \frac{1 + n_{\max}^k - n_j^k}{\sum_{j=1}^{j} (1 + n_{\max}^k - n_j^k)} \tag{12}$$

where n_j^k is the water supply order of water use sectors in sub-area k and $n_{\max}^k$ is the maximum order in sub-area k.

According to the characteristics of water use sectors in Qinzhou, and with reference to the principle of 'First live, then production' (Zeng, 2008), the sectoral supply sequence is municipal, tertiary, secondary, ecology, and agriculture with sector weights (Equation 12) of 0.33, 0.27, 0.20, 0.13, and 0.07, respectively.

(2) Water use output coefficient b_j^k

The water use output coefficient b_j^k is used to measure how much GDP is generated using 1 m^3 water in each sector, which is determined by Equation (13). The output coefficients for different sectors are shown in Table 3:

$$b_j = \frac{GDP_j}{D_j}, \tag{13}$$

where GDP_j is the GDP value of sector j in the study area.

(3) Sewage discharge coefficient α_j

The sewage discharge coefficient α_j measures the ratio of wastewater generation in the process of water use.

According to the code for urban wastewater and storm water engineering planning GB 50318-2017 (Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2017), the coefficients of sewage discharge in the municipal, tertiary, and secondary sectors are 0.8, 0.8, and 0.6, respectively. Sewage discharge in agriculture is mostly related to the loss of fertilizer, so the rate of fertilizer use can be used to determine the sewage discharge coefficient in that sector. Thus, based on Ma *et al.* (2012), the coefficient of sewage discharge in agriculture is 0.6.

Table 3. Water use output coefficients in Qinzhou (CNY/m^3).

Planning Year	Municipal Sector	Secondary Sector	Tertiary Sector	Ecology	Agriculture Sector
2020	0	251	1,377	0	23
2030	0	320	1,957	0	36

(4) COD concentrations c_j

The COD concentration c_j represents the amount of COD produced using 1 m^3 water in different sectors, as per Equation (14):

$$c_j = \frac{M_j^{COD}}{W_j * \alpha_j} \tag{14}$$

where M_j^{COD} denotes measured COD emissions in sector j. W_j is water consumption in sector j. Due to the form of sewage discharged from the tertiary sector being similar to that of the municipal sector, $c_{Tertiary}$ should be equal to $c_{Municipal}$.

According to the *Qinzhou Environmental Bulletin* (Qinzhou Ecology and Environment Bureau, 2014) and *Qinzhou Water Resources Bulletin* (Qinzhou Water Conservancy Bureau, 2014), in 2014, total COD emissions from the municipal, secondary, and agricultural sectors in Qinzhou were 23,730.64 ton, 6,636.61 ton, and 12,970.24 ton, respectively, and the total water consumption in these three sectors was $22{,}775 \times 10^4$ m^3, $18{,}289 \times 10^4$ m^3, and $110{,}123 \times 10^4$ m^3, respectively.

Using Equation (14), the status-quo concentrations of COD for each sector were $c_{Tertiary} = c_{Municipal} = 130.25$ g/m^3, $c_{Secondary} = 57.96$ g/m^3, and $c_{Agric} = 19.63$ g/m^3.

Because it is complex to forecast COD concentrations in the planning years, two scenarios were developed by setting different COD concentrations for each sector to give ample scope for local decision-makers to appreciate the consequences of plausible alternative futures.

In scenario 1, for 2020 we used the status-quo concentrations of COD in each sector. Sewage treatment facilities will be constructed to reduce the amount of pollutants discharged from the municipal, secondary, and tertiary sectors in Qinzhou. Therefore, the primary sewage discharge standard (GB 18918-200; Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2002) was used to determine the COD concentrations for the municipal and tertiary sectors in 2030 i.e., 50 g/m^3.

In scenario 2, for 2020 we used the secondary sewage discharge standard (GB 18918-200; Ministry of Housing and Urban-Rural Development of the People's Republic of China, 2002) to determine COD concentrations i.e., 100 g/m^3. By 2030, with the gradual improvement of sewage treatment facilities in Qinzhou, the COD concentrations of the municipal, secondary, and tertiary sectors align with the primary discharge standard. As the total amount of COD discharge from the agricultural sector tends to be stable, the COD concentrations of the agricultural sector in the two scenarios are taken as 19.63 g/m^3 in 2020 and 2030.

Model optimization

Since groundwater only supplies the municipal sector in Qinzhou and all of the reuse water is generated from industrial water treatment, reuse water can only be allocated to the secondary sector. Because the water supply volume from these two water sources is small, different domestic water sources will not be distinguished to simplify the model solution. In other words, the study only considered the water supply sequence coefficient between domestic and CBDP water sources. Water allocated to each sector from the two water sources in each sub-area was used as the model decision variables i.e., X_1, X_2, …, X_{25}, …, X_{37}.

The function gamultiobj based on the NSGA-II algorithm was employed to solve the optimization model. Genetic parameters were set as follows: the Pareto Fraction is 0.3, the population size is 200, there are 10,000 generations, StallGenLimit is 10,000, the crossover fraction is 0.8, and TolFun is 1×10^{-100}. The result of the model operation is the Pareto solution to water allocation for the two scenarios under a guaranteed rate of $p = 75\%$ in 2020 and 2030. Then, a set of solutions is selected that best meet the relevant socio-economic and environmental objectives.

Results and discussion

The target results concerning the optimal allocation of water resources in the two scenarios for the planning years 2020 and 2030 in Qinzhou are shown in Table 4. If COD concentrations are not reduced, the water shortage in Qinzhou in 2020 and 2030 will amount to $29{,}278.6 \times 10^4$ m^3 and $58{,}612.8 \times 10^4$ m^3, respectively, and total GDP will be $1{,}434.1 \times 10^8$ CHY and $2{,}326 \times 10^8$ CHY, respectively. The total amount of COD pollutants discharged will be 44,275.8 tons and 44,211.4 tons in 2020 and 2030, respectively, which reaches the upper limit of the TAOAPD for COD in both planning years. After reducing the COD concentration of pollutants, the water shortage in Qinzhou decreases to $29{,}064.9 \times 10^4$ m^3 and $35{,}886.4 \times 10^4$ m^3, in 2020 and 2030, respectively; the total GDP increases to $1{,}509.9 \times 10^8$ CHY and $4{,}194.1 \times 10^8$ CHY, respectively; and the total amount of COD pollutants discharged reduces to 37,892.2 tons and 40,947.3 tons, respectively.

The water volume allocation results for 2020 are shown in Figure 3. In scenario 1, the overall total allocated volume in the region is $134{,}953.61 \times 10^4$ m^3, and the disaggregated water volume allocations in Qinnan, Qinbei, Qingang, Lingshan, and Pubei are $27{,}283.82 \times 10^4$ m^3, $25{,}989.7 \times 10^4$ m^3, $15{,}436.84 \times 10^4$ m^3, $44{,}091.08 \times 10^4$ m^3, and $22{,}152.17 \times 10^4$ m^3, respectively. As the total amount of COD generated by water consumption in each sector is 44,275.8 tons, and it just reaches the upper limit of the TAOAPD for COD in 2020, to ensure the total amount of COD does not exceed the upper limit, Qinzhou has 231.8×10^4 m^3 volume of water which cannot be used. In Qinnan, the allocated volume not only meets the water demand itself, but surplus water can even be distributed to the other four water scarce sub-areas at volumes of $2{,}149.51 \times 10^4$ m^3, $7{,}660.72 \times 10^4$ m^3, $2{,}114.98 \times 10^4$ m^3, and 356.93×10^4 m^3, respectively.

In scenario 2, the total allocated water volume is $135{,}167.4 \times 10^4$ m^3, all of which is utilized. The water volume allocation in the five sub-areas is $27{,}283.82 \times 10^4$ m^3, $24{,}249.54 \times 10^4$ m^3, $15{,}569.51 \times 10^4$ m^3, $44{,}553.96 \times 10^4$ m^3, and $23{,}510.57 \times 10^4$ m^3, respectively. In Qinnan, the allocated volume still meets the water demand, and surplus water is distributed to the other four water scarce sub-areas at volumes of 409.34×10^4 m^3, $7{,}793.41 \times 10^4$ m^3, $2{,}577.86 \times 10^4$ m^3, and $1{,}715.37 \times 10^4$ m^3, respectively.

Table 4 Target results associated with optimal allocations in two scenarios in 2020 and 2030.

Planning Year	Scenario	Social Benefits (10^4 m^3)	Economic Benefits (10^8 m^3)	Environment Benefits (ton)
2020	1	29,278.6	1,434.1	44,275.8
	2	29,064.9	1,509.9	37,607.6
2030	1	58,612.8	2,326	44,211.4
	2	35,886.4	4,194.1	40,947.3

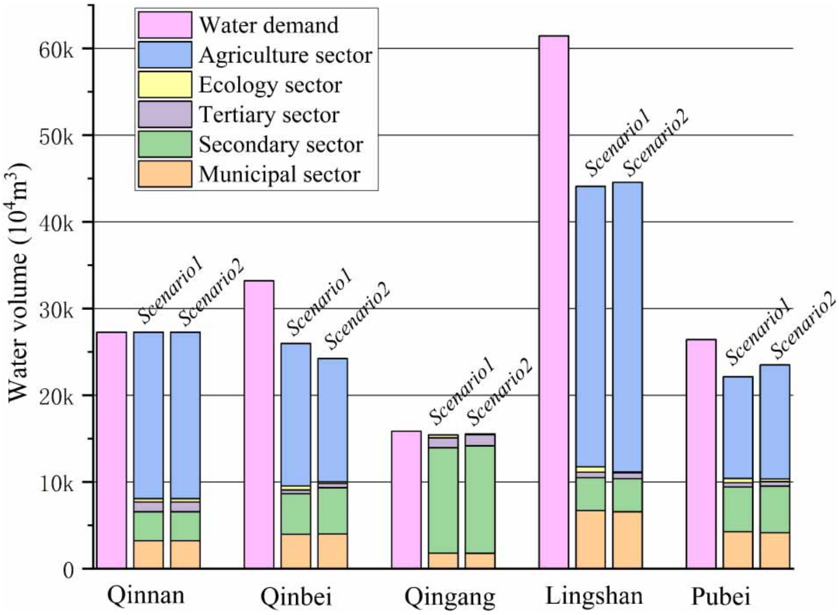

Fig. 3. Water volume allocation results for 2020.

The water volume allocation results for 2030 are shown in Figure 4. In scenario 1, the total allocated volume is 146,774.08 × 10^4 m^3, and the volumes allocated in Qinnan, Qinbei, Qingang, Lingshan, and Pubei are 31,984.94 × 10^4, 30,079.29 × 10^4, 12,880.48 × 10^4, 44,464.76 × 10^4, and 28,454.67 × 10^4 m^3, respectively. Due to the COD concentration of pollutants not being reduced, the total amount of COD generated by all sectors just using domestic water sources will have reached the upper limit of the TAOAPD for COD in 2030, so that water cannot be sourced from the Yujiang CBDP. At the same time, 6,435.43 × 10^4 m^3 of domestically sourced water cannot be used. Qinnan can distribute its surplus water to the other four water scarce sub-areas at volumes of 301.12 × 10^4, 1,848.43 × 10^4, 215.03 × 10^4, and 248.41 × 10^4 m^3, respectively.

In scenario 2, the allocated volume by domestic water and Yujiang CBDP is 153,209.51 × 10^4 and 16,290.49 × 10^4, respectively. The domestic water volume allocation in the five sub-areas is 31,984 × 10^4, 29,111.22 × 10^4, 15,505.07 × 10^4, 44,310.8 × 10^4, and 32,387.6 × 10^4 m^3, respectively, and the Yujiang CBDP supplies water in the three of these sub-areas – Qinbei, Qingang, and Lingshan, at volumes of 8,917.59 × 10^4, 6,179.18 × 10^4, and 1,207.08 × 10^4 m^3, respectively(shown in Figure 5). Due to the total allocated volume in Qinzhou being 169,500 × 10^4 m^3, which will have met the upper limit of TWURL in 2030, there is 15,999.51 × 10^4 m^3 of Yujiang CBDP water that cannot be used. Qinnan can distribute its surplus water to the other four water scarce sub-areas at volumes of 423.12 × 10^4, 4,473.02 × 10^4, 61.07 × 10^4, and 4,181.34 × 10^4 m^3, respectively.

Assuming the COD concentration of pollutants is not reduced, the water shortage rates in each water use sector in 2020 and 2030 are shown in Figures 6 and 7, respectively. The excessive COD concentrations in the municipal sector, and no benefit from water use, will directly cause water scarcity; therefore, the water shortage rates in this sector in Qinbei, Qingang, Lingshan, and Pubei will be 2.38%, 0.24%, 2.3%, and 0.95%, respectively, in 2020, and 3.49%, 3.71%, 3.72%, and 0.58%, respectively, in 2030. The water

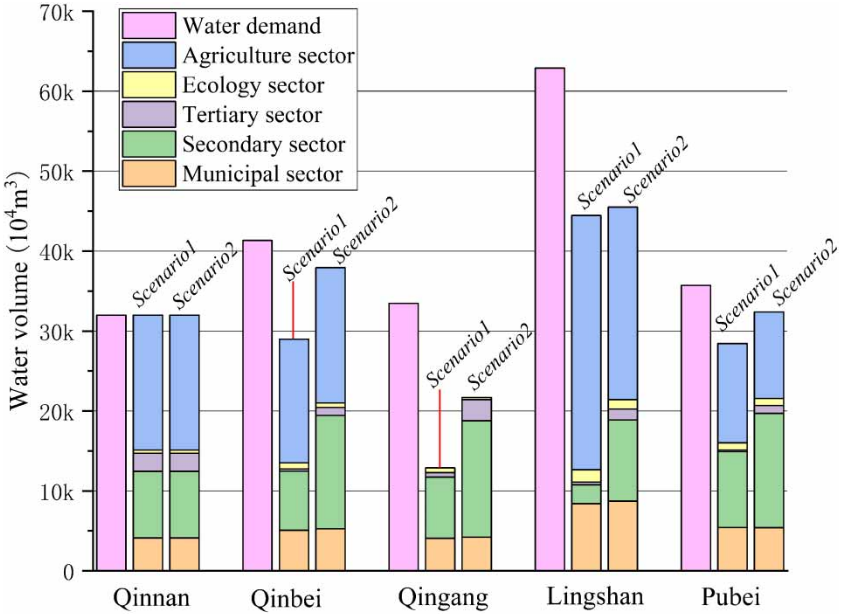

Fig. 4. Water volume allocation results for 2030.

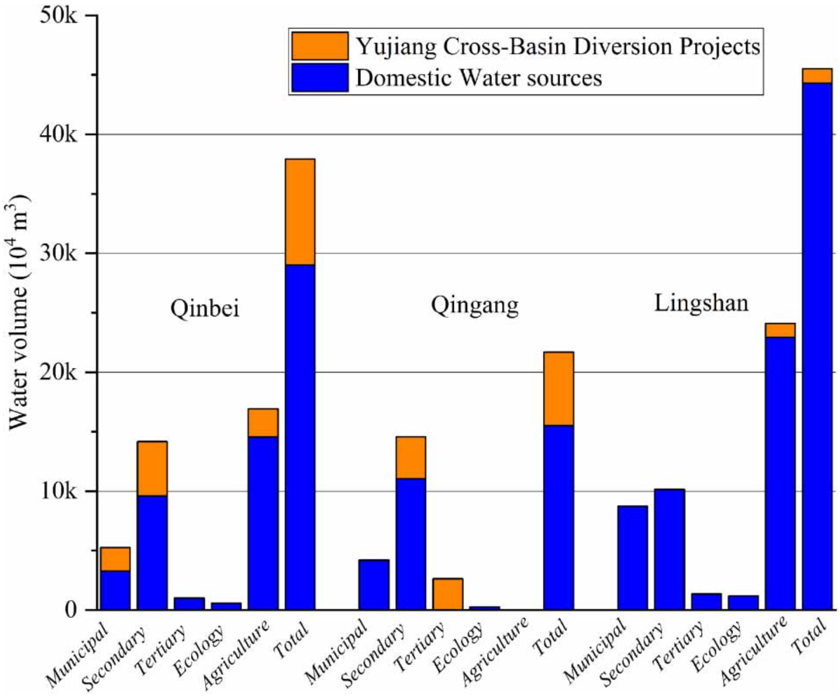

Fig. 5. Water volume allocation from Yujiang CBDP.

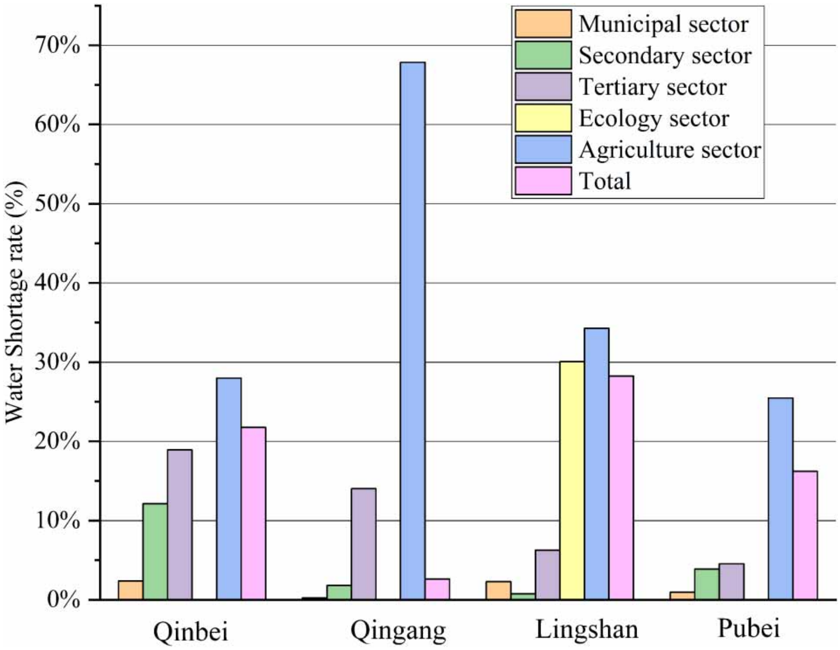

Fig. 6. Water shortages in scenario 1 in 2020.

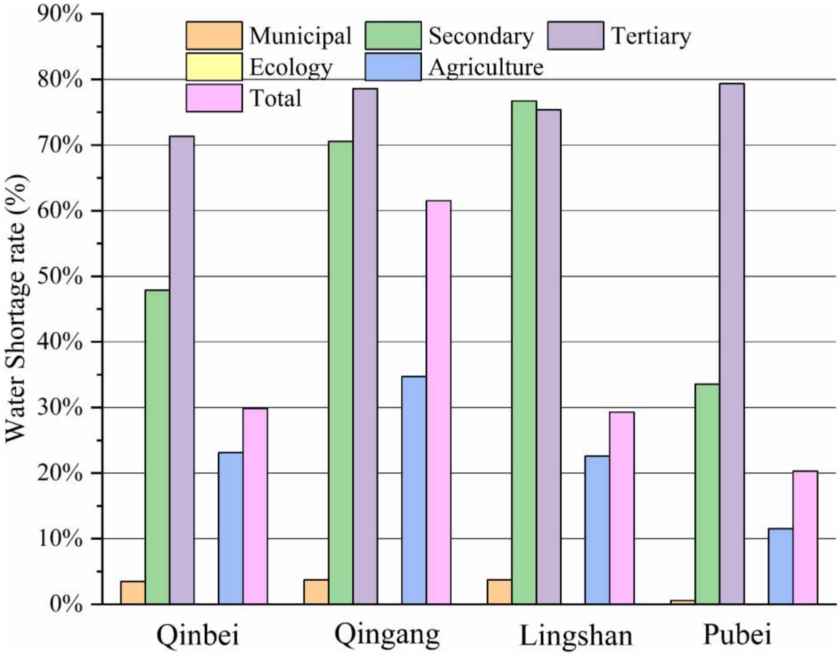

Fig. 7. Water shortages in scenario 1 in 2030.

shortage rates in the tertiary sector in the four water scarce sub-areas will be 18.92%, 14.02%, 6.25%, and 4.55%, respectively, in 2020, and 71.36%, 78.59%, 75.4%, and 79.36%, respectively, in 2030. Although the COD concentrations produced by the tertiary sector are the same as those from the municipal sector, there is no water supply guarantee rate, resulting in a high water shortage rate in that sector.

Due to the rapid growth of water consumption in the secondary sector in the two planning years, and the lower weight set by the model, the water shortage rate of the sector is also large: 12.13%, 14.02%, 6.25%, and 4.55%, respectively, in 2020, and 47.87%, 70.56%, 76.72%, and 33.56%, respectively, in 2030. Moreover, because of the lower COD concentrations discharged by the secondary sector, the water shortage rate of the sector is significantly smaller than that of the tertiary industry.

In both 2020 and 2030, the water shortage rate of the ecology sector will be 0. This is because water consumption in this sector does not lead to COD pollutant discharges. Therefore, to meet the overall objectives of model, and the TAOAPD for COD, the volume allocated to other sectors, especially the tertiary sector, will be largely transferred to the ecology sector.

The huge amount of water used in the agricultural sector (which is greater than any other sector in the region) coupled with the lower economic benefits of water use, and the minimum weight given by the model result in a large water volume shortage in this sector. The water shortage rates in the agricultural sector in the four water scarce sub-areas will be 27.98%, 67.89%, 34.27%, and 25.48%, respectively, in 2020, and 23.11%, 34.7%, 22.6%, and 11.53%, respectively, in 2030.

When the COD concentration of pollutants is reduced, the water shortage rates in each water use sector in Qinzhou in 2020 and 2030 are shown in Figures 8 and 9, respectively. Domestic water sources in Qinzhou in 2020 and 2030 can be fully utilized. Although part of the volume from the Yujiang CBDP source cannot be used in 2030, the water shortage in Qinzhou in the two planning years will be significantly decreased. The water shortage rates in the municipal sector in the four water scarce sub-areas will

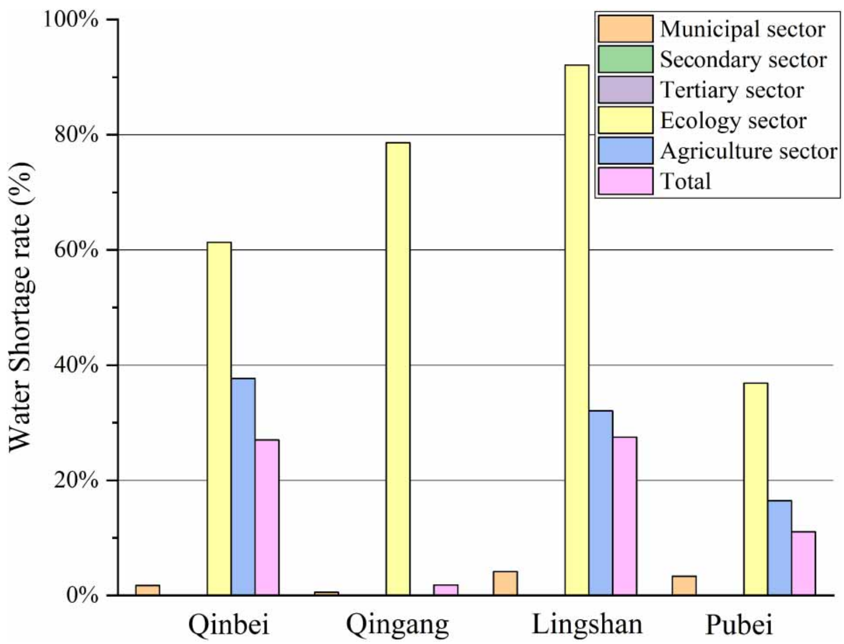

Fig. 8. Water shortage rates in scenario 2 in 2020.

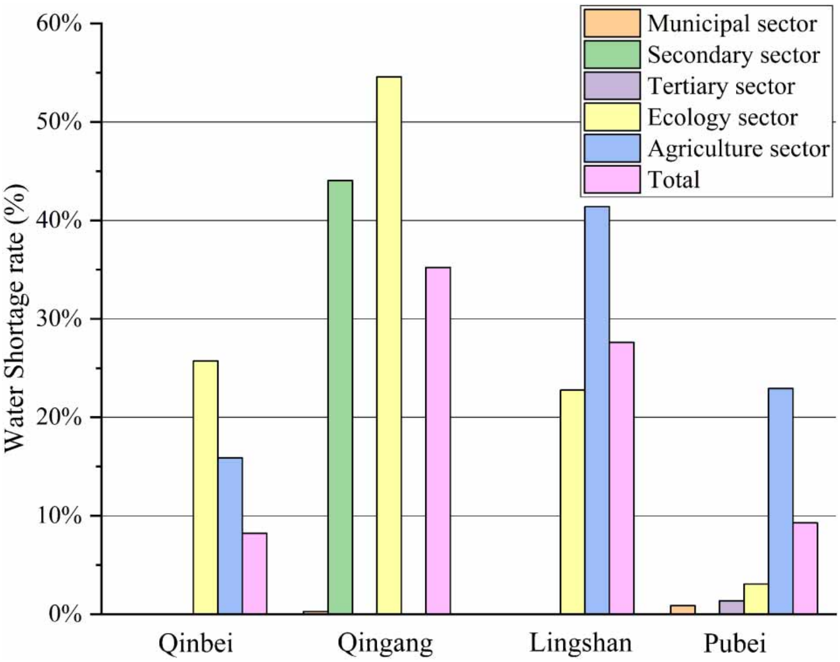

Fig. 9. Water shortage rates in scenario 2 in 2030.

be 1.77%, 0.58%, 4.15%, and 3.33%, respectively, in 2020, which has a slight upward trend compared with scenario 1; because the Yujiang CBDP will operate in 2030, only two sub-areas – Qingang and Pubei – will be short of water, at rates of 0.26% and 0.88%, respectively.

Since using water in the secondary and tertiary sectors can produce large economic benefits and small COD concentrations, water volumes tend to be allocated to these two sectors. Therefore, they can meet their water demands in 2020. Although the secondary sector will still meet demand in 2030, a 1.36% water shortage rate occurs in the tertiary sector in Pubei in that year because this sub-area cannot use the CBDP water sources.

As water use in the ecology sector does not produce marked economic benefits and the sector weight is too low, the volume allocated to it originally will be largely transferred to other sectors, resulting in a large water shortage rate in the sector. The water shortage rates in the ecology sector in the four water scarce sub-areas will be 61.31%, 78.63%, 92.11%, and 36.87%, respectively, in 2020, and 25.73%, 54.58%, 22.77%, and 3.06%, respectively, in 2030.

The agricultural sector benefits from increased water volume allocation compared to scenario 1, so the water shortage rates will be significantly reduced, being 37.69%, 0.03%, 32.07%, and 16.45%, respectively, in 2020, and 15.88%, 44.22%, and 22.95%, respectively, in Qinbei, Lingshan, and Pubei in 2030.

Conclusions

To address the issue of regional water resource allocation under CMSWRM, the paper presents a systematic allocation framework considering TRL constraints to support CMSWRM. A multi-objective linear programming model is configured in MATLAB to allocate domestic and CBDP water across sectors in Qinzhou. The gamultiobj function based on the NSGA-II algorithm was used to solve the model. It can be discerned from the solution that when the COD concentrations in each sector are not reduced, a proportion of the domestic water sources cannot be utilized, both in 2020 and 2030. Moreover, Yujiang CBDP projects were also unable to operate, which further aggravates the contradiction between supply and demand in Qinzhou owing to the TAOAPD for COD. However, if the COD concentrations in each sector are reduced, Qinzhou can obtain comprehensive benefits, in which water shortages in the region will amount to $29{,}064.9 \times 10^4$ and $35{,}886.4 \times 10^4$ m^3 in 2020 and 2030, respectively; total GDP will be $1{,}509.9 \times 10^8$ CHY and $4{,}194.1 \times 10^8$ CHY, respectively; and the total amount of COD pollutants discharged will be 37,892.2 and 40,947.3 tons, respectively.

It is necessary to speed up the improvement of sewage treatment facilities in Qinzhou to reduce the concentration of pollutants discharged from various sectors for the sake of solving the contradiction between supply and demand in Qinzhou under CMSWRM in the two planning years. While the secondary and agricultural sectors have already met the WUERL, they still experience water shortages. Therefore, water use efficiency in Qinzhou should be improved by increasing water conservation intensity in each sector, as well as interventions to better optimize industrial structure.

As agriculture consumes more water than any other sector, it is a particularly critical focus from management and sustainability perspectives. Thus the optimization of crop planting structures in irrigation areas represents fruitful terrain for future research, pursuant of increasing water use efficiency and decreasing total water consumption in Qinzhou. Finally, it is problematic and erroneous to overly rely on GDP as a comprehensive benefit indicator. Future research should seek to design and operationalize a composite economic benefit index which accounts for a broader array of pertinent metrics covering health, wellbeing, water security, and economic stability as well as accounting for the non-market economic values of ecosystems as estimated by different expressed and revealed preference techniques.

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