



A Multi-Objective and Equilibrium Scheduling Model Based on Water Resources Macro Allocation Scheme

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Abstract

A multi-objective and equilibrium scheduling model is established based on water resources macro allocation (WRMAA) scheme to describe the scheduling process accurately in the specific scheduling period. The proposed coupling method sets the WRMAA schemes as the boundary data of the water resources micro scheduling (WRMIS) model and some indicators are used to couple WRMAA and WRMIS models in terms of objective functions, constraints and time series. The runoff deviation factor of ecological node (RDFEN) is brought into the coupling process in order to reflect the ecological scheduling effects. At last, the proposed model is successfully applied to the regional water resources scheduling in Jinan of Shandong Province, China, on a ten-day basis. The results reveal that the ecological base flow should be taken into account in normal and moderately dry years for the short-term planning period, and it should be recommended for the long-term planning period whatever the water condition is. The water deficit ratio of the long-term planning period is much lower than that of the short-term planning period, which verifies its superiority. Hence, the proposed model provides an effective approach to achieving the coordination of macro planning and micro scheduling management of future water resources, especially for the specific scheduling period.

Keywords Multi-objective and equilibrium scheduling · Water resources macro allocation · Water resources micro scheduling · Coupling methods · Ecological scheduling

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1 Introduction

The allocation and scheduling of water resources are intended to achieve optimal distribution of water resources at the macro and micro level, respectively. The goal of the latter is to practice the schemes of the former into practical distribution. Specifically, the water resources macro allocation (WRMAA) is concerned with the overall planning of water resources at the macro level according to the historical inflow series and water use of demand information. The focus of recent research interest in WRMAA has shifted from maximizing water quantity (Willis et al. 1989; Salewicz and Loucks 1989) and water quality (Pingry et al. 1990; Willey et al. 1996) to considering water right (Zaman et al. 2009; Lumbroso et al. 2014). Also, artificial intelligence and space technology (Hou 2012) are increasingly used in the water resources allocation instead of mathematical programming techniques, such as linear or nonlinear programming, dynamic programming and multi-objective optimization. The artificial intelligence and space technology are the modern and new technology which utilized for simulating and extending human intelligence by the space theory.

The water resources micro scheduling (WRMIS) is simulated by means of regulation function of the water conservancy projects, the main purpose of which is to optimize the distribution of water resources at a specific time. A number of methods have been developed for WRMIS, which can be broadly classified into two categories: the conventional methods (Llich et al. 2000) that base on the basic principles of water resources scheduling and rely on the runoff regulation or the reservoir operation chart, and the optimal methods such as mathematical programming (Ahmed 2001; Peng 2013), simulation models and algorithm (Guo et al. 2011; Fang et al. 2018). Notably, the ecological scheduling of water resources takes into account not only the economic and social benefits, but also the ecological benefits (Wang et al. 2018).

In existing studies of reservoir ecological operation, besides the social and economic factors, the ecological factor was paid more and more attention in recent years. The river ecological system should be protected as a prerequisite for the water resources allocation (Yu et al. 2018). In some ecological scheduling models, the ecological runoff is taken as a constraint in order to satisfy the water demand of river ecological environment (Hu et al. 2008; Alminagorta et al. 2016). In contrast, the water demand of river ecological environment can also be taken as an objective (Jing et al. 2015; Mao et al. 2016; Li et al. 2018), or both the costs and profits of ecological runoff are taken into account in the operation models (Bryan et al. 2010).

In most instances, the allocation model can be used to make annual scheduling of water resources, which usually can maximize the benefit of water resources. However, significant deviation is very likely to occur when applying the allocation model to a specific scheduling period (such as ten-day and daily). There are also some difficulties in accurately describing the scheduling states and processes in the specific scheduling period. This suggests the need to combine WRMAA with WRMIS. In this study, the WRMAA schemes are taken as the boundary data of water usage, and then WRMAA is coupled with WRMIS in terms of objective functions, constraints and time series. The runoff deviation factor of the ecological node (RDFEN) is introduced into the coupling process to reflect the ecological scheduling effects. The WRMIS models considering or not considering the ecological base flow are compared. Finally, a case study is performed in Jinan, the capital of Shandong Province in Eastern China that emphasizes the harmonious relationship between human and water ecological health, in order to verify the feasibility and applicability of the proposed WRMIS model.

2 Methodology

2.1 Coupling Methods of WRMAA and WRMIS

The proposed framework for coupling WRMAA and WRMIS is schematically shown in Fig. 1 which comprises two layers: (a) WRMAA and its consequences; and (b) WRMIS and its implementation and solving process.

There is a clear need to consider the effects of some important factors on regional water quantity, such as increase in regional water demand, changes in the availability of water supply and construction of hydraulic engineering projects. The actual inflow of regional water conservancy projects in natural and artificial hydrological cycles can be determined. Meanwhile, the appropriate amount of water supplied from water source to each water user can be clearly defined with multiple simulations of WRMAA system. It is worth noting that the consequences of WRMAA can provide the initial boundary conditions for the WRMIS model from three aspects: objective functions, constraints and time series. Here, detailed description of WRMAA is omitted.

2.1.1 Coupling of Objective Functions

One important objective is concerned with the social benefit of water resources. In order to minimize regional shortage, the actual water supply for each water user in the WRMAA model can be defined as the water demand of each water user in the WRMIS model. However, the

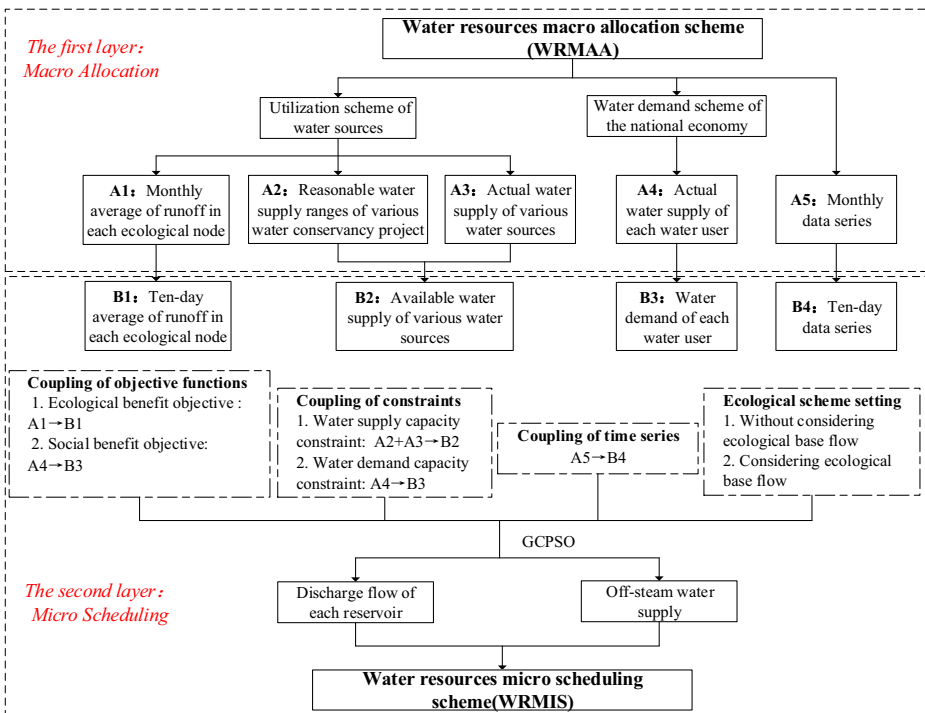


Fig. 1 Study framework for coupling methods of WRMAA and WRMIS

ecological benefit of water resources should also be considered. The RDFEN described in formula (3) in the following section is used to reflect the changes in the ten-day average of runoff after ecological scheduling. The smaller the RDFEN value is, the lower the degree of hydrological variation will be. Additionally, the ten-day average of runoff under natural condition can be coupled with that under the WRMAA scheme.

2.1.2 Coupling of Constraints

The available water supply of each water source and the water demand of each water user are considered to be the constraints. The former can be determined based on the specific constraints of water supply capacity, water conveyance capacity and reservoir storage for simulation of WRMIS model, while the actual water demand of each water user in the WRMIS model can be determined by adjusting the proportion of water supply for each water user according to the guarantee rates of water usage.

2.1.3 Coupling of Time Series

According to the temporal characteristics of domestic, industrial and ecological water demands, the monthly time series data can be processed into ten-day time series data as the inputs of the WRMIS model. The domestic water demands include regional population and domestic water consumption quota, which can be relatively uniform and thus the ten-day time series data can be obtained from monthly time series data in the WRMAA model. The ecological and industrial water demands can be determined in a similar way. Nevertheless, the agricultural water demand is closely related to regional irrigation regime, and thus crop type, cropping pattern and irrigation quota should be considered in dealing with the ten-day data from the monthly data in the WRMAA model.

2.2 Model Generalization

In addition to the above constraints, there are a variety of factors such as regional water resources endowment and economic and industrial policies that may affect the spatial and temporal allocation of water resources. Hence, we propose to take into account the changing trends of surface and groundwater resources in order to provide optimal solutions for regional water resources allocation on the planning level. The WRMIS model is simulated and an equilibrium solution is obtained considering the influences of different factors. Thus, the equilibrium solution space of the WRMIS model is the subset of the optimal solution space of the WRMAA model, as shown in Fig. 2.

2.3 Construction of the WRMIS Model

The WRMIS model would operate on a ten-day time step according to the scheduling needs. In the following formulas, the letter t , i and j represent the time step ($t = 1, 2, \dots, 36$), the water user (urban life, industry, ecology outer river, agriculture and rural life, $i = 1, 2, \dots, 5$) and the unit (described in Section 3.1, $j = 1, 2, \dots, 6$) which involved in the WRMIS model, respectively. The water supply from various water sources to the i^{th} water user at time step t in the j^{th} unit is taken as the decision variable.

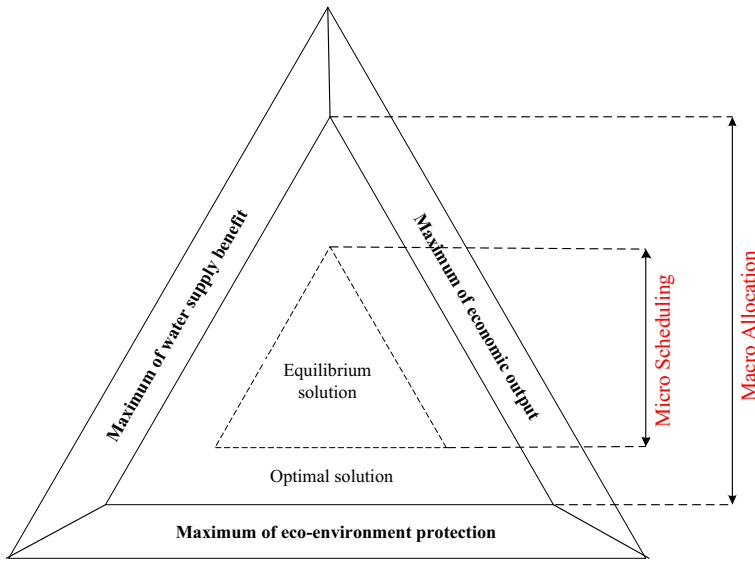


Fig. 2 Conceptual model of WRMIS

2.3.1 Objective Function

There are three types of main objective functions, as follows.

1) Social benefit objective

The social benefit objective here is to minimize the total water deficit, which can be expressed as:

$$MinE_1 = Min \sum_{t=1}^T \sum_{j=1}^m \sum_{i=1}^n \left[Min|0, (W_{tij} - Gs_{tij} - Gg_{tij} - Gd_{tij} - Gr_{tij})| \right] \tag{1}$$

where W_{tij} is the water demand of the i^{th} water user at time step t in the j^{th} unit, 10^4 m^3 ; and Gs_{tij} , Gg_{tij} , Gd_{tij} and Gr_{tij} are the water supply from surface water, groundwater, diverted water and reclaimed water to the i^{th} water user at time step t in the j^{th} unit, 10^4 m^3 , respectively.

2) Economic benefit objective

The economic benefit objective here is to maximize the net profit, which can be expressed as:

$$MaxE_2 = Max \sum_{t=1}^T \sum_{j=1}^m \sum_{i=1}^n \left[(Bs_{tij} - Cs_{tij})Gs_{tij} + (Bg_{tij} - Cg_{tij})Gg_{tij} + (Bd_{tij} - Cd_{tij})Gd_{tij} + (Br_{tij} - Cr_{tij})Gr_{tij} \right] \tag{2}$$

where Bs_{tij} , Bg_{tij} , Bd_{tij} and Br_{tij} are the benefit of per unit amount of surface water, groundwater, diverted water and reclaimed water used by the i^{th} water user at time step t in the j^{th} unit, yuan per 10^4 m^3 , respectively; and Cs_{tij} , Cg_{tij} , Cd_{tij} and Cr_{tij} are the cost of per unit amount of surface water, groundwater, diverted water and reclaimed water used by the i^{th} water user at time step t in the j^{th} unit, yuan per 10^4 m^3 , respectively.

3) Ecological benefit objective

The ecological benefit objective here is to minimize the value of RDFEN, which can be expressed as:

$$\text{Min}E_3 = \text{Min} \left(\sqrt{\frac{1}{36} \times \sum_{t=1}^{36} M_m^2} \right) \quad (3)$$

$$M_m = \left| \frac{Nm_{0,m} - Nm_{e,m}}{Nm_{e,m}} \right| \times 100\% \quad (4)$$

where $Nm_{0,m}$ and $Nm_{e,m}$ are the ten-day average of runoff after and before the ecological scheduling, m^3/s . It is worth noting that $Nm_{e,m}$ can be coupled with the ten-day average of runoff from the WRMAA model. M_m is the percentage deviation between the ten-day average of runoff after and before the ecological scheduling, %.

2.3.2 Constraints

Unlike traditional scheduling models, there are two main types of constraints coupled with the WRMAA model, as follows.

1) Available water supply of various water sources

a. Available water supply of local surface water:

$$\sum_{i=1}^5 Gs_{ij} \leq Ws_{ij} \quad (5)$$

b. Allowable withdrawal of groundwater:

$$\sum_{i=1}^5 Gg_{ij} \leq Wg_{ij} \quad (6)$$

c. Available water supply of diverted water:

$$\sum_{i=1}^5 Gd_{ij} \leq Wd_{ij} \quad (7)$$

d. Available water supply of reclaimed water:

$$\sum_{i=1}^5 Gr_{ij} \leq Wr_{ij} \quad (8)$$

where Ws_{tj} , Wg_{tj} , Wd_{tj} and Wr_{tj} are the actual water supply of local surface water, groundwater, diverted water and reclaimed water at time step t in the j^{th} unit, 10^4 m³, respectively, all of which can be calculated by the WRMAA model.

2) Water demand of each water user

a. Domestic water demand (given priority):

a1. Urban water demand:

$$W_{t1j} \leq GS_{t1j} + Gg_{t1j} + Gd_{t1j} \leq U_{t1j} \tag{9}$$

a2. Rural water demand:

$$W_{t5j} \leq GS_{t5j} + Gg_{t5j} + Gd_{t5j} \leq U_{t5j} \tag{10}$$

b. River ecological water demand:

$$\beta_s W_{t3j} \leq GS_{t3j} + Gg_{t3j} + Gd_{t3j} + Gr_{t3j} \leq U_{t3j} \tag{11}$$

c. Industrial and agricultural water demand:

$$G_{t2j} + G_{t4j} \leq \text{Max}\{(W_{t2j} + W_{t4j}), (W_{tj} - G_{t1j} - G_{t3j} - G_{t5j})\} \tag{12}$$

$$G_{t1j} = GS_{t1j} + Gg_{t1j} + Gd_{t1j} \tag{13}$$

$$G_{t2j} = GS_{t2j} + Gg_{t2j} + Gd_{t2j} + Gd_{t2j} + Gr_{t2j} \tag{14}$$

$$G_{t3j} = GS_{t3j} + Gg_{t3j} + Gd_{t3j} + Gr_{t3j} \tag{15}$$

$$G_{t4j} = GS_{t4j} + Gg_{t4j} + Gd_{t4j} + Gr_{t4j} \tag{16}$$

$$G_{t5j} = GS_{t5j} + Gg_{t5j} + Gd_{t5j} \tag{17}$$

$$W_{tj} = \sum_{i=1}^5 W_{tij} \tag{18}$$

where W_{t1j} , W_{t2j} , W_{t3j} , W_{t4j} and W_{t5j} are the urban, industrial, ecological, agricultural and rural water demands at time step t in the j^{th} unit, 10^4 m³, respectively, all of which can be calculated

by the WRMAA model; U_{t1j} , U_{t3j} and U_{t5j} are the predicted urban, ecological and rural water demands at time step t in the j^{th} unit, 10^4 m^3 , respectively; β_s is the satisfaction coefficient of river ecological water demand, which must be less than 1; G_{t1j} , G_{t2j} , G_{t3j} , G_{t4j} and G_{t5j} are the total water supply from various water sources to each water user at time step t in the j^{th} unit, 10^4 m^3 ; and W_{tj} is the total water demand of each water user at time step t in the j^{th} unit, which can be coupled with the WRMAA model, 10^4 m^3 .

3 Case Study

3.1 Study Area and Data

Jinan is the capital of Shandong province in Eastern China ($36^\circ 40' \text{ N}$, $117^\circ 00' \text{ E}$) (Wang et al. 2017), and it occupies a transition zone between the northern foothills of Mount Tai to the south of the city and the valley of the Yellow River to the north (see Fig. 3). It has a population of 7.04 million and a Gross Domestic Product of 577.06 billion yuan in 2014. Jinan has six districts (Lixia, Shizhong, Tianqiao, Huaiyin, Licheng and Changqing (CQ)), one city (Zhangqiu (ZQ)) and three counties (Pingyin (PY), Shanghe (SH) and Jiyang (JY)). The first five districts are collectively known as the Chengwu (CW) District. There are three basins, including Haihe Basin, Huaihe Basin and Yellow River Basin. In Jinan, the multi-year average amount of water resources is 1.72 billion m^3 , approximately 58% of which is available for use. There are a total of 12 reservoirs for water supply, including Xingling (XL) Reservoir, Dazhan (DAZ) Reservoir, Duzhang (DZ) Reservoir, Wohushan (WHS) Reservoir, Shidian (SD) Reservoir, Gutou (GT) Reservoir, Donghu (DH) Reservoir, Duozhuang (DZU) Reservoir, Langmaoshan (LMS) Reservoir, Yuqinghu (YQH) Reservoir, Jinxiuchuan (JXC) Reservoir and Queshan (QS) Reservoir. The basic parameters (shown in Table 1) and historical inflows of these 12 reservoirs are obtained from authoritative water resources departments. In Table 1, the dead, normal and flood limit water levels of the 12 reservoirs are taken as the constraints for reservoir scheduling in the following model.

The years of 2025 and 2030 is taken as the short and long-term planning period, respectively. The statistical data of social and economic developments are collected from the Jinan Statistical Yearbook 2014 (Hydrological information port of Jinan, 2018) and the National Economic and Social Development Statistical Bulletin 2014 released by the Jinan Statistical Information Network (Jinan Bureau of Statistics, 2018; Jinan Statistical Information Network, 2018). Based on the water resources scheduling in Jinan (shown in Fig. 4) and the historical reservoir inflows for the period of 1956–2014, three typical hydrological years with a probability of 50%, 75% and 95% are selected to represent normal, moderately dry and extremely dry conditions, respectively.

3.2 Scheduling Purposes and Plan Setting

The scheduling purposes in this study are to ensure safe water supply and sound ecological environment by appropriately scheduling water conservancy projects in Jinan. Specifically, the 12 reservoirs are taken as the scheduling objects, and the safe water supply in Jinan and surrounding counties and the ecological base flow of main urban rivers should be guaranteed. A water supply project is being built for the eastern cities of

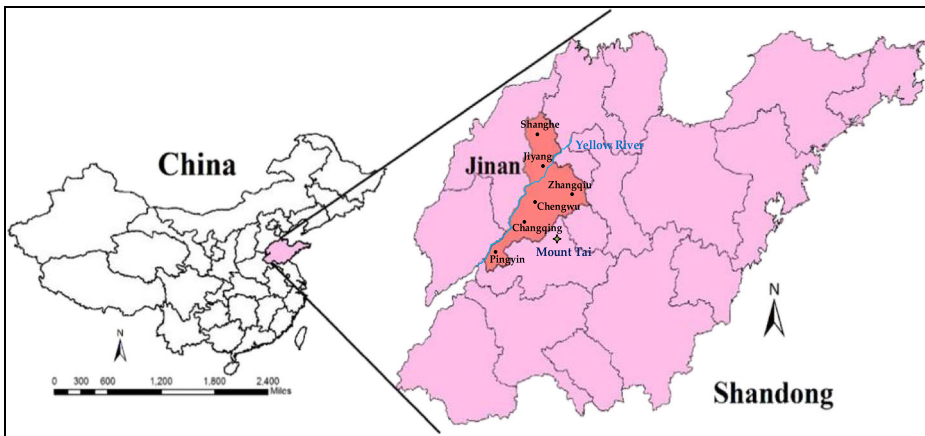


Fig. 3 Location of Jinan in Shandong Province, China

Jinan. Thus, the WRMIS model is simulated and calculated in two scenarios with two plans in each scenario.

ScenarioI: Before the completion of the water supply project

Plan A: Ecological base flow is not considered

Plan B: Ecological base flow is considered

ScenarioII: After the completion of the water supply project

Plan A: Ecological base flow is not considered

Plan B: Ecological base flow is considered

The initial boundary conditions in scenariolare selected from the data of the base year (2014) in the WRMAA model; while these in scenarioII are selected from the data of years 2025 and 2030.

Table 1 The basic parameters of involved 12 reservoirs in Jinan (m)

Reservoir	Dead water level	Normal water level	Flood limit water level
DH Reservoir	19.0	30.0	31.5
WHS Reservoir	112.7	129.0	131.8
DZU Reservoir	279.0	304.3	306.7
DAZ Reservoir	69.0	78.0	80.4
XL Reservoir	95.0	103.3	107.1
DZ Reservoir	40.0	46.6	48.0
LMS Reservoir	172.7	187.0	187.0
YQH Reservoir	31.1	38.9	40.4
JXC Reservoir	225.0	251.0	251.5
QS Reservoir	23.7	29.1	30.4
SD Reservoir	122.0	138.7	139.3
GT Reservoir	77.6	88.0	89.6

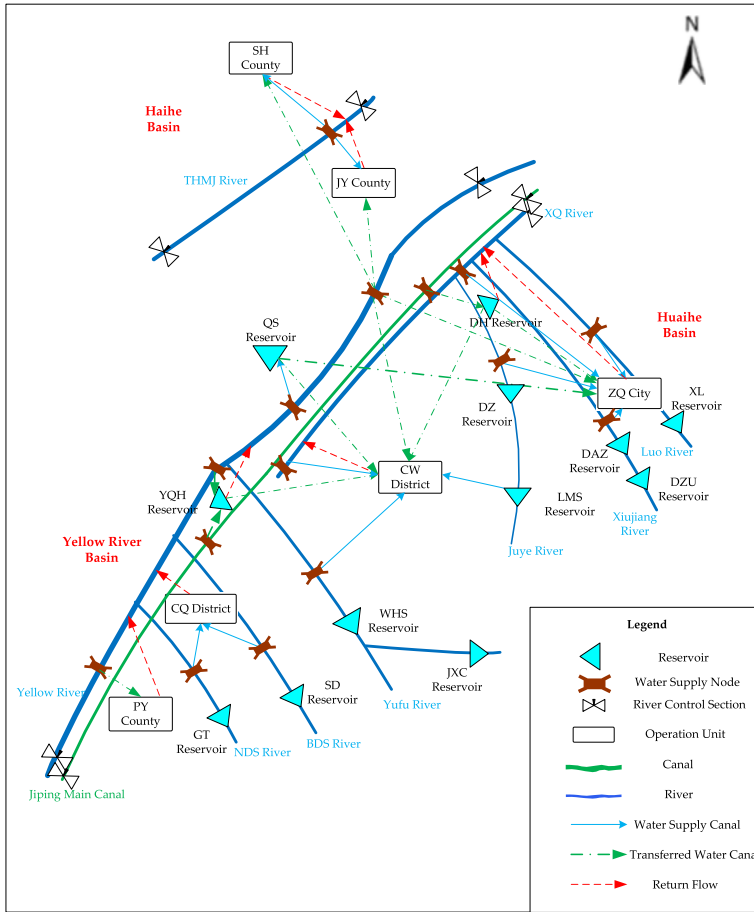


Fig. 4 Schematic Diagram of Water Resources Scheduling in Jinan

4 Results and Discussion

4.1 WRMIS for Short-Term Planning Period

Under the runtime environment of MATLAB R2014a, the WRMIS model proposed in Section 2.3 was applied in this section with the Gaussian chaos particle swarm optimization (GCPSO) algorithm. The long-term hydrological series for the period 1956–2014 were simulated on ten-day basis, and the ecological base flow of some main control sections was taken as the ecological water demand of downstream rivers. The off-stream water balance between water supply and demand under normal, moderately dry and extremely dry conditions is shown in Table 2, and the discharge runoff of key reservoirs in the two scenarios are shown in Figs. 5, 6, 7, 8, 9, 10. In order to obtain the guarantee rates of ecological base flow under different conditions, the ecological base flow curves were also drawn for comparison.

Table 2 Off-stream water balance between water supply and demand based on the WRMIS model (Scenario I) (million m³)

Plan A

Plan B

Condition	Admini.	WD	WS	GW	RW	TW	Total WS	Water Deficit	Water Ratio	Condition	Admini.	WD	WS	GW	RW	TW	Total WS	Water Deficit	Water Ratio
Normal year	Reg.	668	225	166	76	201	668	0	0.00%	Normal year	Reg.	668	225	166	76	201	668	0	0.00%
	CW District	125	49	75	1	0	125	0	0.00%		CW District	125	49	75	1	0	125	0	0.00%
	CO District	321	80	194	1	46	321	0	0.00%		CO District	321	80	194	1	46	321	0	0.00%
	ZQ City	106	38	68	0	0	106	0	0.00%		PY County	106	38	68	0	0	106	0	0.00%
	PY County	283	87	78	2	116	283	0	0.00%		JY County	283	87	78	2	116	283	0	0.00%
	JY County	187	40	107	1	39	187	0	0.00%		SH County	187	40	107	1	39	187	0	0.00%
Moderately dry year	Total	1690	519	688	810	402	1690	0	0.00%	Moderately dry year	Total	1690	519	688	810	402	1690	0	0.00%
	CW District	693	219	162	76	239	693	0	0.00%		CW District	693	189	162	76	239	663	30	4.33%
	CO District	132	60	71	1	0	132	0	0.00%		CO District	132	55	71	1	0	658	5	3.79%
	ZQ City	333	55	194	1	77	327	6	1.86%		ZQ City	333	40	194	1	77	312	21	6.31%
	PY County	117	38	64	0	15	117	0	0.00%		PY County	117	34	64	0	15	113	4	3.42%
	JY County	305	77	72	2	153	304	2	0.55%		JY County	305	62	72	2	153	289	17	5.57%
Extremely dry year	SH County	193	35	84	1	71	191	2	1.23%	Extremely dry year	SH County	193	25	84	1	71	181	12	6.22%
	Total	1774	484	647	81	555	1762	10	0.54%		Total	1774	405	647	81	555	1683	89	5.02%
	CW District	691	139	158	76	317	690	1	1.00%		CW District	691	95	158	76	317	646	45	6.51%
	CO District	135	57	69	1	3	132	3	2.48%		CO District	135	52	69	1	3	127	8	5.93%
	ZQ City	334	67	186	1	67	321	13	3.97%		ZQ City	334	45	186	1	67	299	35	10.3%
	PY County	122	35	62	0	25	121	1	1.10%		PY County	122	28	62	0	25	114	8	6.56%
Total	JY County	317	73	86	2	149	310	7	2.23%	Total	JY County	317	47	86	2	149	285	32	10.1%
	SH County	200	37	89	1	68	195	5	2.64%		SH County	200	21	89	1	68	179	21	10.5%
	Total	1799	408	650	81	629	1768	32	1.77%		Total	1799	289	650	81	629	1649	151	8.39%

WD: Water Demand; WS: Water Supply; SW: Surface Water; GW: Groundwater; RW: Reclaimed Water; TW: Transferred Water. (The same as below)

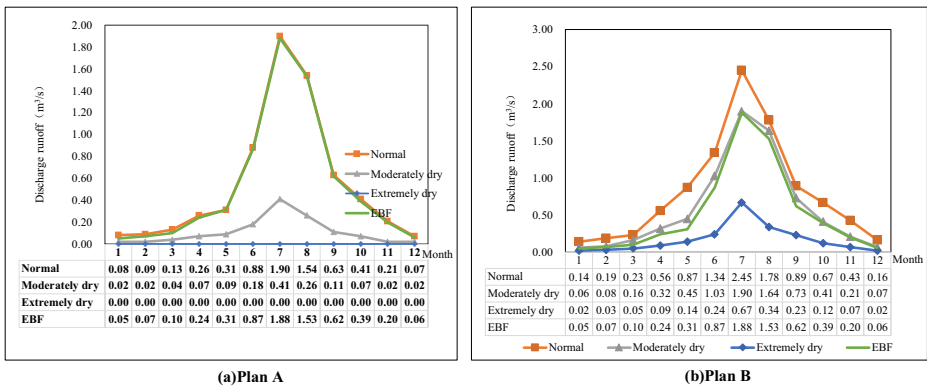


Fig. 5 The discharge runoff of XL Reservoir for short-term planning period: (a) Plan A, (b) Plan B Notes: EBF: Ecological Base flow (The same as below)

4.1.1 Impacts on the off-Stream Water Usage

Table 2 shows that for plan A, the water deficit ratio is 0 in the normal year; while there are some differences in the moderately and extremely dry year. It is noted that the water deficit ratio increases as the precipitation decreases, and different levels of water shortage may occur due to water supply from surface water and groundwater. The water deficit ratio reaches a maximum of 3.97% in the ZQ City in the extremely dry year. Under this circumstance, the water deficit ratio of Jinan is 1.77%. It can be concluded that the water deficit ratio is within a controllable range for plan A.

Similarly, no water shortage occurs in the normal year for plan B, and there are various levels of water shortage in the moderately dry year with the largest water deficit ratio being 6.31% in the ZQ City. However, it is noted that the water shortage becomes more apparent in the extremely dry year with a water deficit ratio of 8.39% in Jinan and > 10% in the ZQ City and SH County. In the moderately dry or normal year, it makes no difference for the off-stream water usage in Jinan whether or not the in-stream ecological water usage is considered; whereas in the extremely dry year, a portion of water originally used for off-stream water usage is now used for in-stream ecological water usage, which is more pronounced in the ZQ

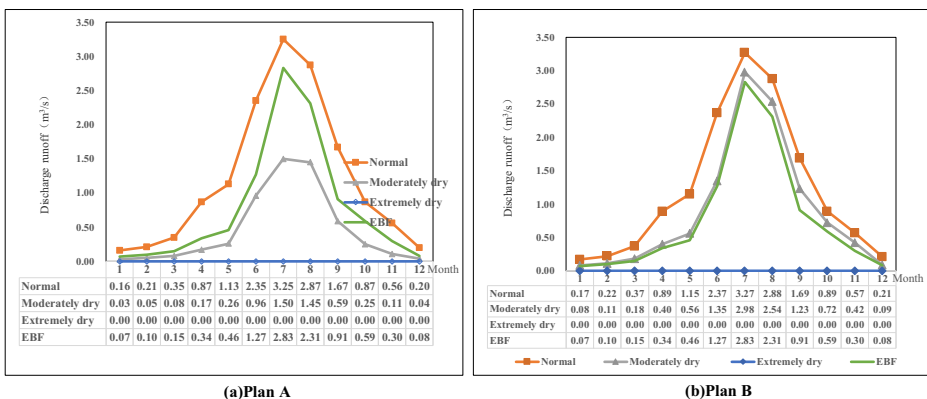


Fig. 6 The discharge runoff of DAZ Reservoir for short-term planning period: (a) Plan A, (b) Plan B

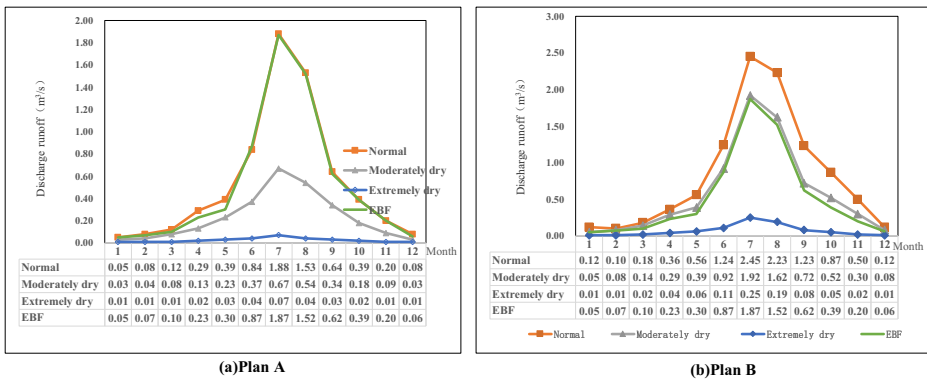


Fig. 7 The discharge runoff of DZ Reservoir for short-term planning period: (a) Plan A, (b) Plan B

City as the water supply project (Donglian) is not completed yet. Thus, for the ZQ City, it is recommended to construct the Donglian water supply project on the basis of ecological scheduling.

4.1.2 Impacts on the in-Stream Ecological Water Usage

Figures 5, 6, 7, 8, 9, 10 show the guarantee rates of the ecological base flow of some main control sections. For plan A, the guarantee rate is 50% and the discharge runoff of upstream key reservoirs can satisfy the demand of the ecological base flow in the normal year but may be insufficient in the moderately and extremely dry years. It is important to note that the discharge runoff of some reservoirs on the Luo River, Xiujiang River, BDS River and NDS River is 0 in the extremely dry year, indicating that no water would be available after supplying the off-stream socio-economic water usage.

For plan B, the guarantee rate is increased to 75%. In normal and moderately dry years, the discharge runoff of upstream key reservoirs can satisfy the demand of the ecological base flow. Figure 8 (b) shows that the discharge runoff of the WHS Reservoir on the Yufu River is 0 in any month of the extremely dry year, which is attributed to the groundwater recharge model operated in the southern mountainous area of Jinan.

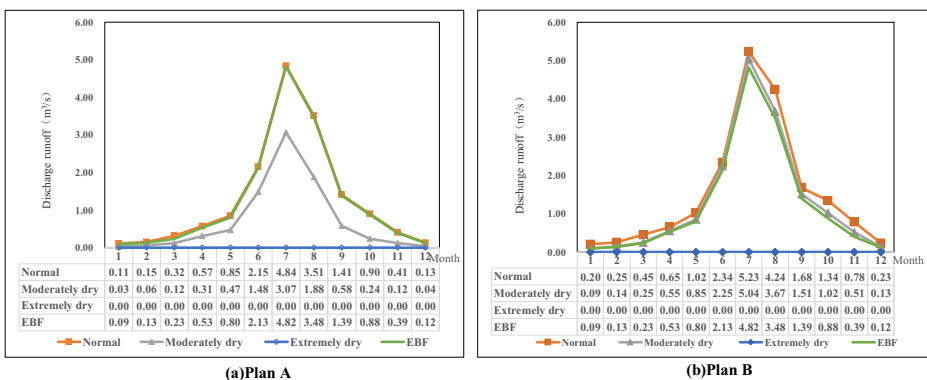


Fig. 8 The discharge runoff of WHS Reservoir for short-term planning period: (a) Plan A, (b) Plan B

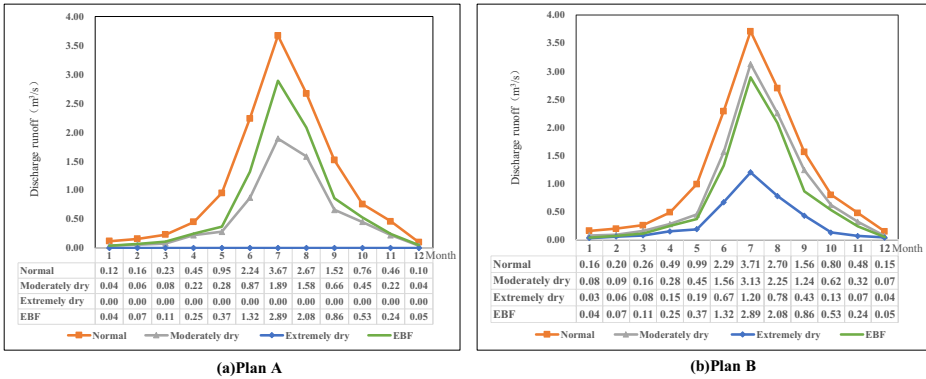


Fig. 9 The discharge runoff of SD Reservoir for short-term planning period: (a) Plan A, (b) Plan B

To sum up, taking the off-stream water deficit ratio and the in-stream guarantee rate of the ecological base flow into consideration, plan B is recommended for normal and moderately dry years; while plan A is recommended for extremely dry year for the short-term planning period.

4.2 WRMIS for Long-Term Planning Period

The off-stream water balance between water supply and demand under normal, moderately dry and extremely dry conditions in 2025 and 2030 is shown in Tables 3 and 4, respectively; and the discharge runoff of DAZ Reservoir and WHS Reservoir in the two scenarios is shown in Figs. 11, 12, 13, 14 to be the representative in the Huaihe Basin and the Yellow River Basin, respectively. Accordingly, the guarantee rates of the ecological base flow in 2025 and 2030 are shown in Figs. 15 and 16, respectively.

4.2.1 Impacts on the off-Stream Water Usage

Tables 3 and 4 show that in 2025 and 2030, there are no effects on the off-stream water usage of Jinan in the normal year, and the water deficit ratio is 0 for all districts and counties. In the moderately dry year, water shortage occurs in Jinan for plan A with a water deficit ratio of 0.49% in 2025 and 0.64% in 2030, respectively. As the ecological base flow is considered in

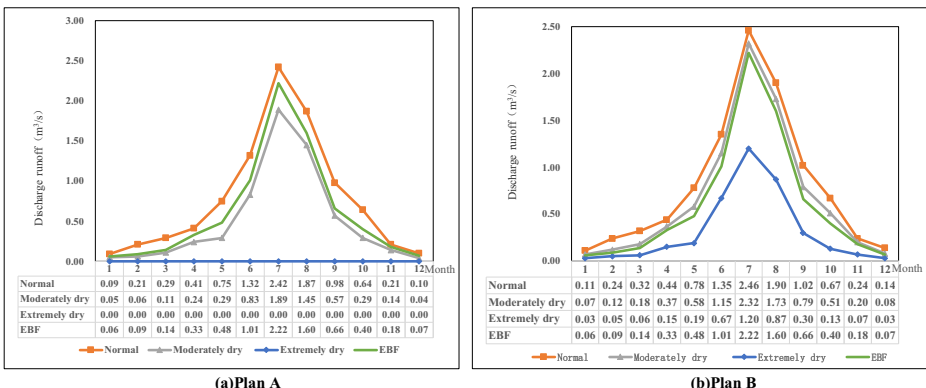


Fig. 10 The discharge runoff of GT Reservoir for short-term planning period: (a) Plan A, (b) Plan B

Table 3 Off-stream water balance between water supply and demand based on the WRMIS model in 2025 (ScenarioII) (million m³)

Plan A													Plan B												
Condition	Admin.	WD	SW	WS	GW	RW	TW	Total WS	Water Deficit	Water Ratio	Condition	Admin.	WD	SW	WS	GW	RW	TW	Total WS	Water Deficit	Water Ratio				
Normal year	Reg.	CW District	814	195	166	138	315	814	0	0.00%	Normal year	Reg.	CW District	814	195	166	138	315	814	0	0.00%				
		CO District	154	67	75	12	0	154	0	0.00%			CO District	154	67	75	12	0	154	0	0.00%				
		ZQ City	353	79	194	28	52	353	0	0.00%			ZQ City	353	79	194	28	52	353	0	0.00%				
		PY County	121	37	68	7	9	121	0	0.00%			PY County	121	37	68	7	9	121	0	0.00%				
		JY County	316	87	78	10	141	316	0	0.00%			JY County	316	87	78	10	141	316	0	0.00%				
		SH County	212	40	107	9	56	212	0	0.00%			SH County	212	40	107	9	56	212	0	0.00%				
Moderately dry year	Total	1970	505	688	204	573	1970	0	0.00%	Moderately dry year	Total	1970	505	688	204	573	1970	0	0.00%						
	Reg.	CW District	832	215	162	138	318	832	0		0.00%	Reg.	CW District	832	215	162	138	318	810	22	2.64%				
		CO District	163	76	71	13	3	163	0		0.00%		CO District	163	72	71	13	3	159	4	2.45%				
		ZQ City	375	75	190	28	82	375	0		0.00%		ZQ City	375	65	190	28	82	365	10	2.67%				
		PY County	134	38	64	7	24	134	0		0.00%		PY County	134	35	64	7	24	131	3	2.24%				
		JY County	336	84	74	10	162	330	6		1.79%		JY County	336	75	74	10	162	321	15	4.46%				
Extremely dry year	Total	2058	523	663	205	657	2048	10	0.49%	Extremely dry year	Total	2058	469	663	205	657	1994	64	3.11%						
	Reg.	CW District	818	205	158	138	316	817	1		0.12%	Reg.	CW District	818	169	158	138	316	37	4.52%					
		CO District	160	74	69	13	3	159	1		0.63%		CO District	160	68	69	13	3	153	7	4.38%				
		ZQ City	361	73	187	28	72	360	1		0.20%		ZQ City	361	59	187	28	72	346	15	4.16%				
		PY County	131	37	62	7	25	130	1		0.76%		PY County	131	33	62	7	25	126	5	3.82%				
		JY County	356	83	76	10	175	344	12		3.42%		JY County	356	73	76	10	175	334	22	6.18%				
	SH County	213	31	96	9	68	204	9	4.23%		SH County	213	26	96	9	68	199	14	6.57%						
	Total	2040	503	648	205	659	2014	26	1.27%		Total	2040	428	648	205	659	1940	100	4.90%						

Table 4 Off-stream water balance between water supply and demand based on the WRMIS model in 2030 (ScenarioII) (million m³)

Plan A												
Condition	Admin.		WD	SW	WS	GW	RW	TW	Total WS	Water Deficit	Water Deficit Ratio	Water Deficit
Normal year	Reg.	CW District	963	195	166	240	362	963	0	0.00%	0	0.00%
		CQ District	176	67	75	27	7	176	0	0.00%	0	0.00%
		ZQ City	378	79	194	49	56	378	0	0.00%	0	0.00%
		PY County	132	47	68	17	0	132	0	0.00%	0	0.00%
		JY County	349	87	78	18	166	349	0	0.00%	0	0.00%
		SH County	241	40	107	34	60	241	0	0.00%	0	0.00%
Moderately dry year	Total	2239	505	688	661	2239	0	0.00%	0	0.00%	0	0.00%
	Reg.	CW District	981	215	162	240	364	981	0	0.00%	0	0.00%
		CQ District	184	76	71	27	10	184	0	0.00%	0	0.00%
		ZQ City	400	75	190	49	85	400	0	0.00%	0	0.00%
		PY County	144	38	64	17	25	144	0	0.00%	0	0.00%
		JY County	364	83	74	18	181	356	8	2.30%	8	2.26%
Extremely dry year	Total	2316	526	663	375	737	2301	15	0.64%	15	0.64%	0.88%
	Reg.	CW District	967	205	158	240	363	966	1	0.10%	1	0.19%
		CQ District	184	72	69	27	15	183	1	0.64%	1	0.84%
		ZQ City	417	74	189	49	104	416	1	0.19%	1	2.24%
		PY County	141	37	62	17	24	140	1	0.84%	1	2.24%
		JY County	360	81	72	18	181	352	8	2.24%	8	3.41%
Plan B		SH County	241	34	101	25	73	233	8	3.41%	8	7.47%
	Total	2310	503	651	376	760	2290	20	0.88%	20	0.88%	5.41%
	Reg.	CW District	963	195	166	240	362	963	0	0.00%	0	0.00%
		CQ District	176	67	75	27	7	176	0	0.00%	0	0.00%
		ZQ City	378	79	194	49	56	378	0	0.00%	0	0.00%
		PY County	132	47	68	17	0	132	0	0.00%	0	0.00%
Plan B		JY County	349	87	78	18	166	349	0	0.00%	0	0.00%
		SH County	241	40	107	34	60	241	0	0.00%	0	0.00%
	Total	2239	505	688	385	661	2239	0	0.00%	0	0.00%	0.00%
	Reg.	CW District	981	188	162	240	364	954	27	2.75%	27	3.26%
		CQ District	184	70	71	27	10	178	6	3.26%	6	3.00%
		ZQ City	400	63	190	49	85	388	12	3.00%	12	2.78%
Plan B		PY County	144	34	64	17	25	140	4	2.78%	4	5.22%
		JY County	364	72	74	18	181	345	19	5.22%	19	5.35%
		SH County	243	32	102	24	72	230	13	5.35%	13	3.50%
	Total	2316	460	663	375	737	2235	81	3.50%	81	4.86%	4.89%
	Reg.	CW District	967	159	158	240	363	920	47	4.86%	47	4.89%
		CQ District	184	64	69	27	15	175	9	4.89%	9	4.56%
Plan B		ZQ City	417	56	189	49	104	398	19	4.56%	19	4.26%
		PY County	141	32	62	17	24	135	6	4.26%	6	7.22%
		JY County	360	63	72	18	181	334	26	7.22%	26	7.47%
		SH County	241	24	101	25	73	223	18	7.47%	18	5.41%
	Total	2310	398	651	376	760	2185	125	5.41%	125	5.41%	5.41%

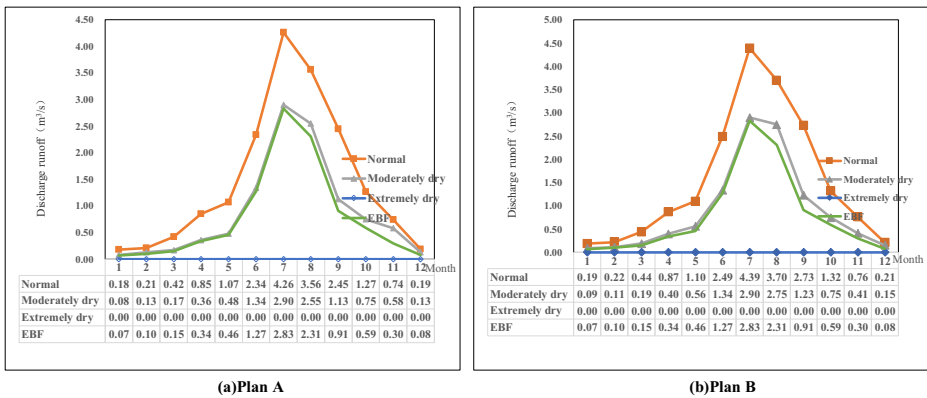


Fig. 11 The discharge runoff of DAZ Reservoir in 2025: (a) Plan A, (b) Plan B

plan B, water shortage becomes more apparent in 2025 and 2030. Specifically, the water deficit ratio of Jinan is increased to 3.11% in 2025 and 3.50% in 2030, respectively. Also, water shortage is more widespread, as it occurs only in the JY County and SH County for plan A but in all districts and counties for plan B. It is concluded that the ecological scheduling for the long-term planning period has an effect on the off-stream socio-economic water usage. The top water deficit ratio reaches a maximum of 5.35% in the SH County in 2030 and it is still within a controllable range.

The water deficit ratio in the extremely dry year is also slightly increased after ecological scheduling, and it is still within a controllable range. Especially for the ZQ City, water shortage would be greatly alleviated in 2025 and 2030 after the completion of the Donglian water supply project. The development of the DH Reservoir may provide another way to supply diverted water to Jinan, making it possible to reduce water supply from the groundwater.

4.2.2 Impacts on the in-Stream Ecological Water Usage

Figures 11, 12, 13, 14, 15, 16 illustrate that the guarantee rates of ecological base flow are improved significantly for plan B. In 2025, the discharge runoff of upstream key reservoirs can satisfy the demand of the ecological base flow after increasing the diverted water and the

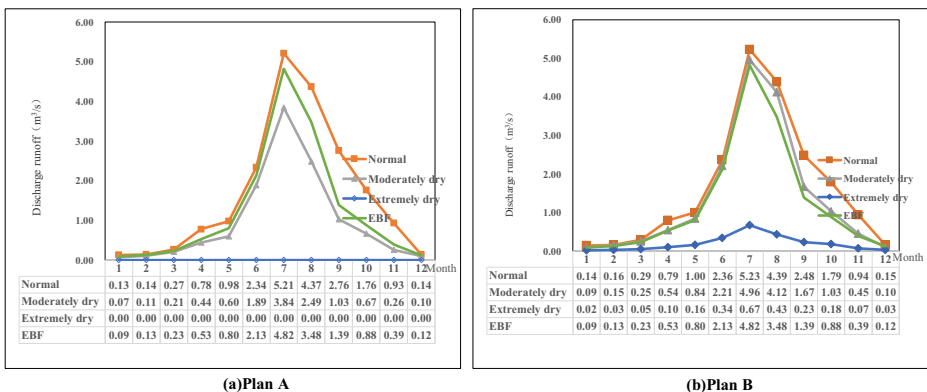


Fig. 12 The discharge runoff of WHS Reservoir in 2025: (a) Plan A, (b) Plan B

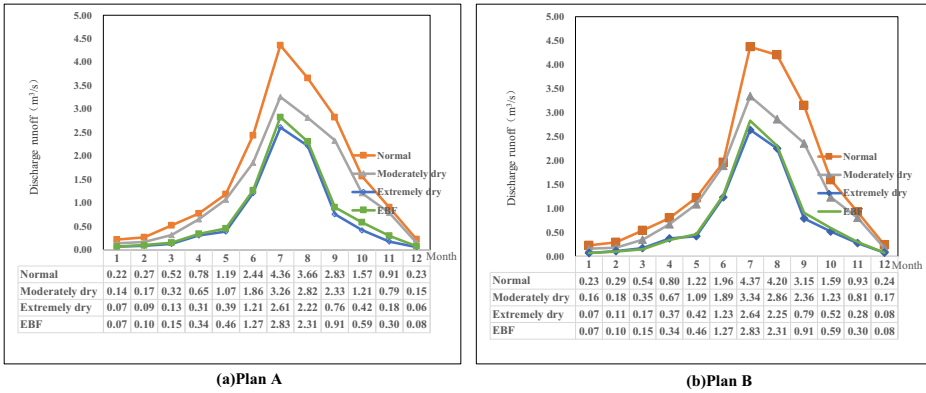


Fig. 13 The discharge runoff of DAZ Reservoir in 2030: (a) Plan A, (b) Plan B

completion of the Donglian water supply project under any conditions except in the extremely dry year. In other words, the guarantee rate of the ecological base flow is 75% in 2025. With the increase of water supply from the Yellow River and Yangtze River, the guarantee rates will be 90% or even higher in 2030.

To sum up, the water deficit ratios of all districts and counties for the long-term planning period are within the controllable range for plan B, and the guarantee rate of the ecological base flow of some main control sections is also significantly improved. Hence, taking the off-stream water deficit ratio and the in-stream guarantee rate of the ecological base flow into consideration, plan B is recommended for the long-term planning period.

5 Conclusions

In this study, a multi-objective and equilibrium scheduling model that combines WRMAA with WRMIS is developed for short-term and long-term water resources scheduling. The WRMAA scheme is taken as the boundary data of the WRMIS model, and some indicators are chosen to couple WRMAA and WRMIS models in terms of objective functions, constraints and time series. RDFEN is brought into the coupling process to reflect the ecological

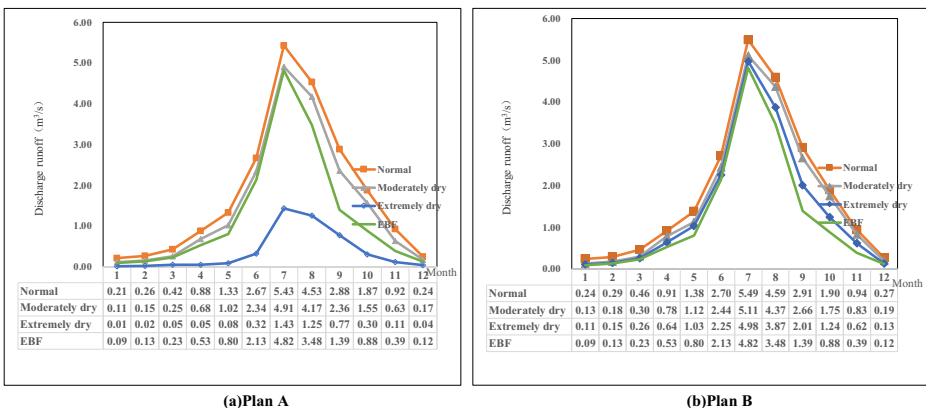


Fig. 14 The discharge runoff of WHS Reservoir in 2030: (a) Plan A, (b) Plan B

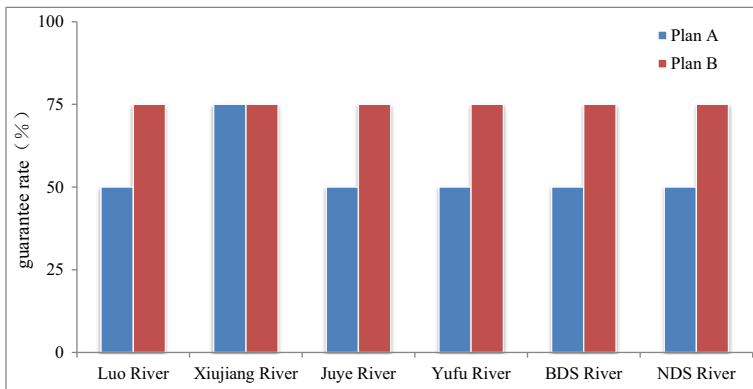


Fig. 15 The guarantee rates of the ecological base flow in 2025: (a) Plan A, (b) Plan B

scheduling effects. The WRMIS models considering or not considering the ecological base flow are simulated under normal, moderately dry and extremely dry conditions on a ten-day basis. At last, the proposed method is successfully applied to regional water resources scheduling in Jinan of Shandong Province, China. The results demonstrate that the WRMIS model results in lower deviation and better allocation of water resources. By the re-expressions of objective functions and constraints, as well as the recoupling of time series, the multi-objective and equilibrium scheduling model of Jinan is constructed and simulated. Then, the multi-objective and equilibrium scheduling plan can be obtained in the normal, moderately dry and extremely dry conditions. The proposed model is applicable to describe water resources scheduling process more accurately in the specific scheduling period, which can be widely used to achieve the coordination of macro planning and micro scheduling management of future water resources.

However, some limitations of this study should be noted. For instance, in addition to RDFEN, some other factors that can affect ecological scheduling plans also need to be considered. Further, each region may have unique aquatic ecological service functions, and thus the water ecological conservation model suitable for a particular region can be incorporated into the multi-objective and equilibrium scheduling model.

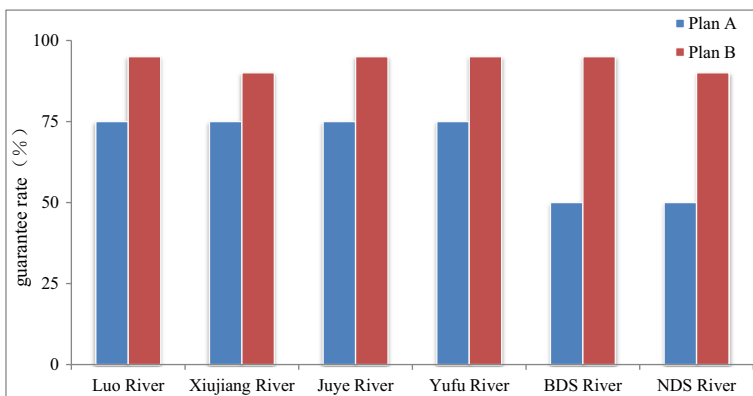


Fig. 16 The guarantee rates of the ecological base flow in 2030: (a) Plan A, (b) Plan B

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Compliance with Ethical Standards

Conflict of Interest None.

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