Multi-objective optimal water supply scheduling model for an inter-basin water transfer system: the South-to-North Water Diversion Middle Route Project, China

Shuo Ouyang, Hui Qin, Jun Shao, Jiantao Lu, Jianping Bing, Xuemin Wang and Rui Zhang

ABSTRACT

Inter-basin water diversion reallocates water resources by changing their spatio-temporal distribution characteristics between basins. This can effectively relieve water supply and demand conflicts in regions with water resource reserves shortages. However, building inter-basin water diversion projects obviously reduces the inflow from upstream, leading to increasingly conspicuous conflicts between water diversion outside a basin and water utilization inside the basin. To relieve this conflict and explore the optimal scheme of water resource allocation across river basins, this paper chooses the Middle Route Project of the South-to-North Water Diversion Project on the Hanjiang River as a case study. A water supply scheduling model of Danjiangkou Reservoir is built using an integrated inter-basin diversion draw water reservoir regulation (IDR) model to balance multiple conflicting water demands. In the IDR model there are two types of objective sets: aggregate indicators and process matching degree functions. Moreover, six evaluation indexes are selected to analyze the water resource allocation effect of the optimal scheme. The simulation results indicate that the proposed IDR model in this paper is practicable and efficient for water resource allocation across river basins.

Key words | Danjiangkou Reservoir, dispatching scheme, evaluation indexes, Middle Route of South-to-North Water Diversion Project

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INTRODUCTION

In inter-basin water diversion, a large quantity of water is diverted from a water-sufficient basin to a water-deficient basin through large-scale artificial methods to promote economic development in water-deficient areas and relieve water conflicts among people and livestock in the basin. Along with population growth and economic development, water resource issues have become a bottleneck factor restricting humanity's survival and sustainable development in the 21st century (Kanakoudis *et al.* 2017a, 2017b). Inter-basin water diversion is an effective way to develop and utilize water resources, and to optimize the allocation of water resources (Davies *et al.* 1992; Zhu *et al.* 2017). Non-uniform spatio-temporal distribution of water resources and unbalanced water demand make water diversion necessary. Inter-basin water diversion is adopted to reallocate water resources (Snaddon & Davies 1998) and to relieve or resolve urgent demand in water-deficient areas. Since the 1950s many countries have established such projects, including the United States (Feldman 2001), South Africa (Petitjean & Davies 1988), Croatia (Bonacci & Andric 2010), and many others.

However, water diversion projects predictably reduce the downstream runoff, and hydrological characteristics of the source basin's lower reaches will change. In addition,

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because of runoff reduction, the water quality of the lower reaches of the river becomes worse, and the environmental quality of the lower reaches declines (Sun *et al.* 2016). Inter-basin water transfer-supply reservoirs need to optimize the water transfer process, use flood resources in flood seasons, and release water downstream during dry seasons to reduce the impact on downstream areas.

Inter-basin water diversion has a long history in China. The Lingqu Canal Project connecting the Pearl River and Yangtze River basins, and the Grand Canal Project connecting Beijing to Hangzhou, are typical examples of historical inter-basin water diversion. China's largest inter-basin water diversion project, the South-to-North Water Diversion Project (SNWDP), diverts a portion of the Yangtze River's abundant water resources from the Yangtze basin to northern China to relieve water shortages (Liu & Zheng 2002; Peng *et al.* 2015; Guo *et al.* 2018). The Middle Route of the SNWDP (MRP-SNWDP) was officially put into operation on December 12, 2014. Since that time, the Danjiangkou Reservoir has not only handled production, domestic, and ecological water consumption in rural areas and towns downstream, but also addressed water demand in Beijing city, Tianjin, and the Hebei Province.

In recent years, a large number of studies on the operation and management of the MRP-SNWDP have been carried out. These studies focus on a variety of topics, including benefit analysis (Peng *et al.* 2018), comprehensive operation (Wang *et al.* 2016a, 2016b; Li 2017; Yang *et al.* 2017), scheduling rules (Liu *et al.* 2019), flood control (Xie *et al.* 2017), climate impact analysis (Li *et al.* 2015), water regime (Wang *et al.* 2016a, 2016b), water quality (Chen *et al.* 2016), and ecological effects (Wang *et al.* 2011). The studies on water supply optimization scheduling focus mainly on relationships with other scheduling tasks, such as environment requirement, while less attention has been paid to the relationship between multiple water demands. However, this relationship is one of the keys to alleviating the conflict between water supply and demand inside and outside the basin. Previous studies usually select the total water quantity as the index to evaluate the optimal targets of water supply scheduling, and the matching degree of water supply processes is seldom studied.

For the above reasons, the MRP-SNWDP on the Hanjiang River has been chosen as a case study. This paper builds a water supply scheduling model of the Danjiangkou Reservoir, an integrated inter-basin diversion draw water reservoir regulation (IDR) model, to consider the satisfaction of multiple water demands. In an IDR model, there are two types of objectives: aggregate indicators and process matching degree functions. Optimized dispatching of the Danjiangkou Reservoir is simulated by adopting natural runoff patterns of the reservoir from 1956 to 1998. Moreover, six indexes are selected as evaluation indexes to research the impact of different operation objectives on hydrological regimes and water resource balance in downstream regions.

INTER-BASIN WATER TRANSFER SYSTEM (IWT SYSTEM) ON THE HANJIANG RIVER

Hanjiang River basin

The Hanjiang River is the longest tributary of the Yangtze River, with a total length of 1,577 km. The Hanjiang originates south of Qinling Mountain and joins the main stream of the Yangtze River at Dragon King Temple in the city of Wuhan. The basin ranges between 106° and 114° E longitude and 30° and 40° N latitude, covering a watershed area of 159,000 km^2. The Danjiangkou Reservoir is located in Danjiangkou, a city in Hubei Province, approximately 800 m downstream of the confluence of the main stream of the Hanjiang and the Danjiang Rivers. The reservoir provides several water resource utilization benefits, including flood control, water supply, power generation, and shipping. It is a key water conservancy project for the comprehensive utilization and management of the Hanjiang River. It is also the water supply source of the MRP-SNWDP. The catchment area of the Danjiangkou Reservoir is about 95,217 km^2, accounting for about 60% of the Hanjiang River.

Figure 1 shows the geographic location of the Hanjiang River, the Danjiangkou Reservoir, and the MRP-SNWDP. The characteristic parameters of the reservoir are shown in Table 1.

Dispatching operation mode of Danjiangkou Reservoir

The main functions of the Danjiangkou Reservoir are flood control, water supply (including irrigation), power

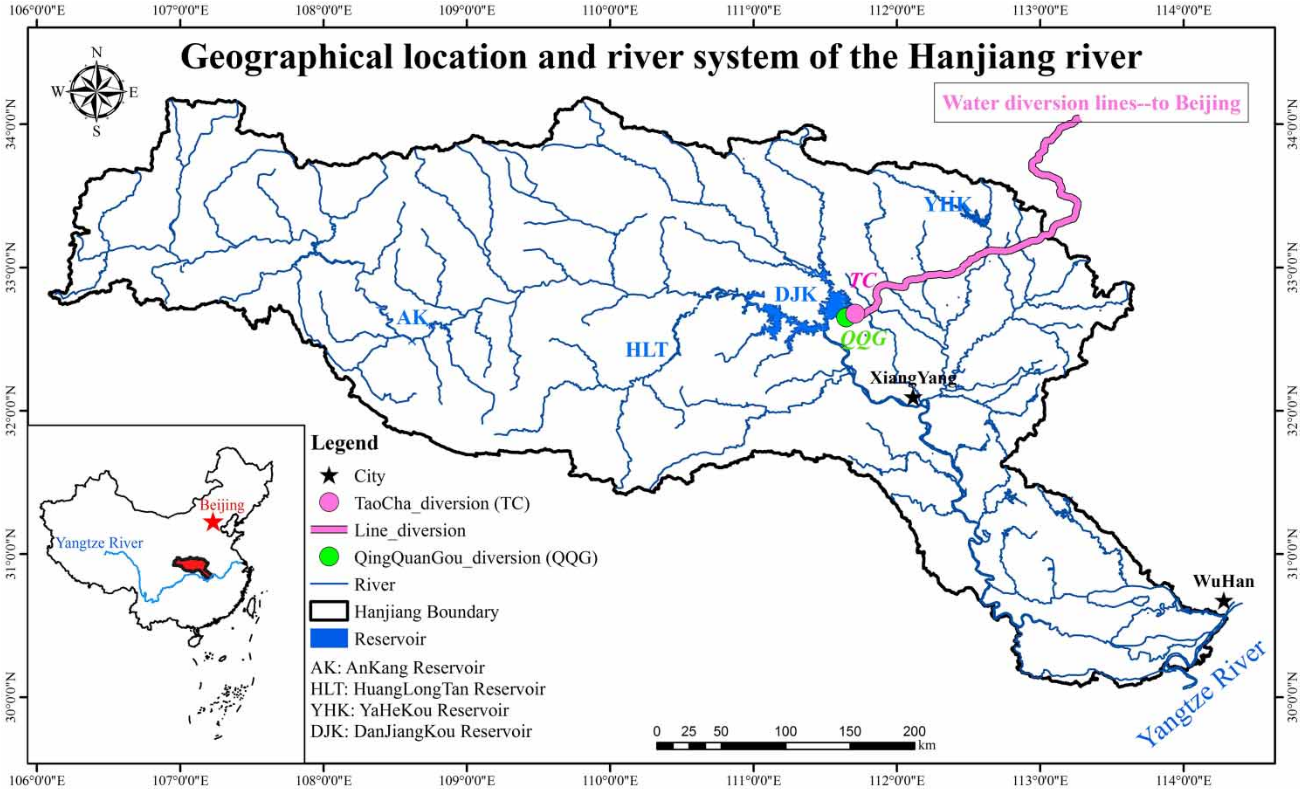

Figure 1 | Geographical location and river system of the Hanjiang River.

Table 1 | Characteristic parameters of the Danjiangkou Reservoir

Characteristic	Unit	Value	Characteristic	Unit	Value
Catchment area	km^2	95,217	Dead water level	m	150.0 (145.0)
Annual average runoff	m^3/s	1,230	Flood limiting water level	m	160.0 (163.5)
Annual average runoff volume	10^8 m^3	381	Water level of design flood	m	172.2
Design flood peak flow	m^3/s	79,000	Water level of check flood	m	174.35
Check flood peak flow	m^3/s	118,000	Normal water level	m	170.0
Total storage	10^8 m^3	339.1	Crest elevation	m	176.6
Regulating storage	10^8 m^3	111.1–140.9	High dam	m	70.6
Dead capacity	10^8 m^3	100–126.9	Firm power	MW	258 (231)
Storage coefficient	%	40–46	Installed capacity	MW	900

generation, and navigation. The operating water levels of the reservoir are as follows: the normal pool level is 170 m and the limited water level in the flood season is 160 m in summer (from June 21 to August 20) and 163.5 m in autumn (from September 1 to September 30). The dead water level is 150 m and the limiting drawdown water level is 145 m. The specific operating and dispatching schemes of the Danjiangkou Reservoir are discussed next.

Flood control dispatching

The reservoir water level is gradually reduced from May 1 to 160 m on June 20. From June 21 to August 20 (the major flood period), the flood control level is 160 m. From August 21 to September 1 (transitional period between the major and autumn flood periods), the flood control level rises gradually from 160 m to 163.5 m. From September 1 to September 30 (the autumn flood period), the flood control level is 163.5 m. After this, the reservoir can gradually store water up to normal pool level of 170 m from October 1 to October 10 (the reservoir refilling period). During the flood period from June 20 to October 10, the discharge of the reservoir shall be not more than 21,000 m^3/s to ensure flood control safety of the downstream area.

Water supply dispatching

The water supply objectives of the Danjiangkou Reservoir include the following: (1) meeting the water demands of cities and irrigated lands located on the middle and lower Hanjiang River; (2) water diversion for the Qingquangou Project; and (3) water diversion for the Middle Route Project (MRP, diversion of the Taocha Canal head). The designed diversion discharge volume is 350 m^3/s and the increased water volume is 420 m^3/s for the Taocha Canal head diversion. At Qingquangou the designed water diversion volume is 100 m^3/s.

The dispatching lines of the Danjiangkou Reservoir's water supply dispatching graph (Figure 2) include the following: (1) a normal pool level line (NPLline); (2) a flood control dispatching line (FCline); (3) a prevent water abandonment line (PWAline); (4) an increased water supply line 2 (IWSline2); (5) an increased water supply line 1 (IWSline1); (6) a reduced water supply line 1 (RWSline1); (7) a reduced water supply line 2 (RWSline2); and (8) limiting drawdown water level (LDWline). These eight water supply dispatching lines divide the Danjiangkou Reservoir dispatching chart into seven zones.

According to the dispatching principles and dispatching graph regulations, the dispatching rules for water supply in different operating conditions of Danjiangkou Reservoir are as follows:

(1) When the reservoir water level is located in the normal water supply zone, the reservoir supplies water to the middle and lower reaches of the Hanjiang River, Qingquangou, and the MRP-SNWDP on the basis of the water dispatching plan.
(2) When the reservoir water level is in the increased water supply zone, the water supply downstream can be increased based on the water dispatching plan, according to the following rules:
    (a) Flood control zone: when the upstream water level of the Danjiangkou Reservoir is higher than the water level line for flood control, the Taocha Canal

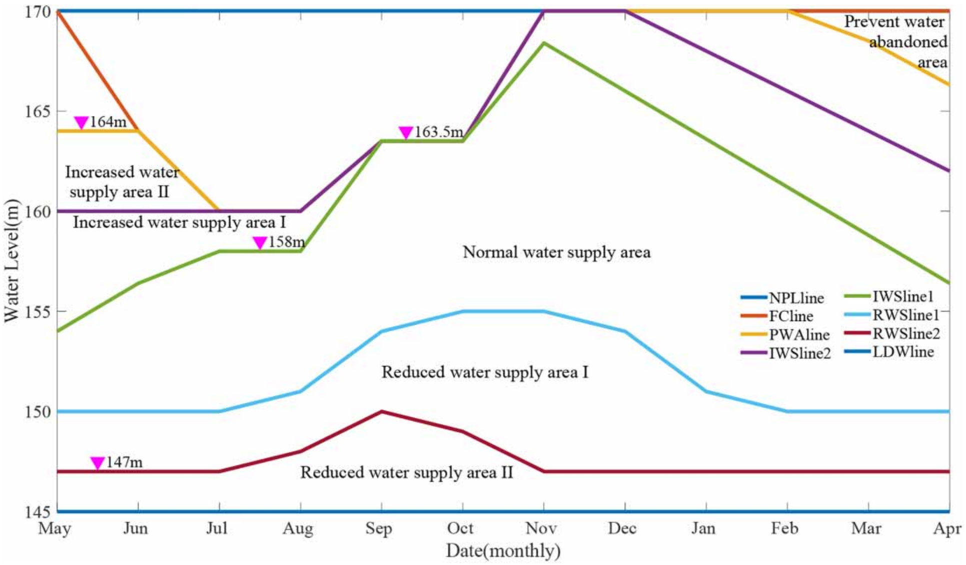

Figure 2 | Water supply dispatching graph of Dangjiangkou Reservoir.

head shall supply water not exceeding the maximum water capacity (420 m^3/s), and carry out water diversion for Qingquangou as needed (mean annual water supply shall not exceed 628 million m^3).

   (b) Increased water supply zone I: when the reservoir water level is in this zone, the added value of the total water supply flow for the middle and lower reaches of the Hanjiang River, Qingquangou, and MRP-SNWDP can be increased by 5% of the planned water supply flow.
   (c) Increased water supply zone II: when the reservoir water level is in this zone, the added value of the total water supply flow can be increased by 15% of the planned water supply flow.
   (d) When the reservoir water level is below IWSline2 (within the 2 m range), if the predicted incoming water flow in the next 1–3 days is significantly greater than the planned water supply flow, the added value of the total water supply flow can be increased by between 5% and 15% of the planned water supply flow, according to the difference between IWSline2 and the reservoir water level.

(3) When the reservoir water level is in the reduced water supply zone, the water supply to the middle and lower reaches of Hanjiang River, Qingquangou, and the MRP-SNWDP may be reduced, according to the following rules:

   (a) Limited water supply zone I: when the reservoir water level is in this zone, the total water supply flow can be reduced by up to 15% of the planned water supply flow.
   (b) Limited water supply zone II: when the reservoir water level is in this zone, the total water supply can be reduced by up to 20% of the planned water supply flow.
   (c) When the water level of the reservoir is lower than 150 m, if the incoming water flow is greater than 350 m^3/s, the water supply of the middle and lower reaches of the Hanjiang River is accordingly reduced to no less than 490 m^3/s. If the incoming water is less than 350 m^3/s, the water supply in the middle and lower reaches of the Hanjiang River is reduced to 400 m^3/s.

Water division scheme for the MRP-SNWDP

Since the MRP-SNWDP was built, the Danjiangkou Reservoir has needed to meet three sets of ecological and economic water requirements: the downstream requirements of the Hanjiang River watershed (using the discharge flow from the reservoir), the water demand of the Yindan Irrigation Project northwest of Xiangyang, and the demand of the MRP-SNWDP. The Yindan Irrigation Project diverts water from the reservoir via the Qingquangou headworks, while the MRP-SNWDP diverts water via the Taocha headworks.

According to the Water Dispatching Scheme for the Middle Route (Phase I) of the SNWDP approved by the State Council of China in 2014, the diverted water from the Danjiangkou Reservoir is to be transported to Henan, Hebei, Beijing, Tianjin, and other water-receiving areas through dedicated canals. Except for a booster pump station near Beijing, the whole route conveys water by gravity. Water delivery and diversion control is conducted through regulating sluices and diversion sluices in the main canal.

The MRP-SNWDP's dispatching follows the following principles: (1) the main canal of the MRP-SNWDP adopts unified dispatching along the whole route and regulating sluices are controlled according to normal water level; (2) the total water diversion flow of all downstream outlets at a given time shall not exceed the water conveyance flow of the canal's cross section; and (3) the sum of water intake of all diversion entrances in each province (or municipalities directly under the central government) shall not exceed the planned water volume for the province (or municipality).

The main monitoring cross-sections of the main MRP-SNWDP canal include Taocha, the Diao River, the Fangcheng Caodun River, the north bank of the Yellow River, the north bank of the Zhang River, the Gangtou Tunnel, the north Juma River, and Wangqingtuo. Figure 3 presents the key indicators of these monitoring cross-sections.

MODEL FORMULATION OF THE IDR MODEL

To analyze the impact of the downstream controlling reservoir operation mode on upstream water diversion, the water supply of mid- and downstream areas, and the water storage

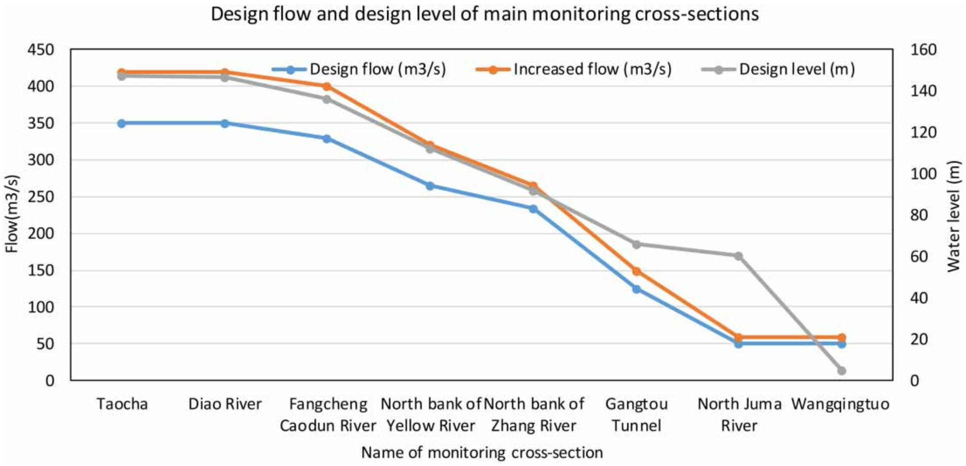

Figure 3 | Design flow and design level of main monitoring cross-sections.

of the reservoir under upstream inter-basin water diversion conditions, the IDR model sets the two types of objectives (aggregate indicators and process matching degree functions). In aggregate indicators, the maximum water utilization ratio, water supply satisfaction of Taocha, and water supply satisfaction of Qingquangou are chosen to meet the needs of the three parties. For process matching degree functions, this paper introduces the Nash–Sutcliffe efficiency coefficient to make the water transfer processes match water requirement processes of Taocha and Qingquangou. The objectives and corresponding constraints of the IDR model are expressed next.

Objective functions

Maximum water utilization ratio (Obj1)

This function takes maximizing the water utilization ratio of the Danjiangkou Reservoir as its main optimization objective, attempts to manage conflicts between upstream inter-basin water diversion and middle and downstream water supply, and fully exploits basin water resources. The specific expression is as follows:

$$\max R_u = \max\left\{1 - \frac{\sum_{t=1}^{T} Q_{t,d} \cdot \Delta t}{\sum_{t=1}^{T} Q_{t,in} \cdot \Delta t}\right\} \quad (1)$$

Here, $Q_{t,in}$ and $Q_{t,d}$ represent inflow and abandoned water flow of reservoir during the period t, respectively; R_u represents water utilization ratio; Δt is the length of each period; and T represents the water supply dispatching period.

Maximum water supply satisfaction of Taocha (Obj2)

This function prioritizes maximizing water supply satisfaction of the reservoir during optimization, fulfilling the water demand of the MRP-SNWDP as far as possible. The specific expression is as follows:

$$\max R_{S-TC} = \max\left\{1 - \frac{\sum_{t=1}^{T} S_{t,TC} \cdot \Delta t}{\sum_{t=1}^{T} D_{t,TC} \cdot \Delta t}\right\} \quad (2)$$

Here, $S_{t,TC}$ and $D_{t,TC}$ represent the water shortage and water demand of Taocha during period t, and R_{S-TC} represent water supply satisfaction of Taocha.

Maximum water supply satisfaction of Qingquangou (Obj3)

Similar to Obj2, this function maximizes the water supply satisfaction of Qingquangou to meet the water demands of Northern Hubei and the Yindan Irrigation Area. The specific expression is as follows:

$$\max R_{S-QQG} = \max\left\{1 - \frac{\sum_{t=1}^{T} S_{t,QQG} \cdot \Delta t}{\sum_{t=1}^{T} D_{t,QQG} \cdot \Delta t}\right\} \tag{3}$$

Here, $S_{t,QQG}$ and $D_{t,QQG}$ represent the water shortage and water demand of Qingquangou during the period t, and R_{S-QQG} represents the water supply satisfaction of Qingquangou.

Maximum Nash–Sutcliffe efficiency coefficient of Taocha water transfer process (Obj4)

This represents the matching degree of the whole water transfer process of Taocha. The specific expression is as follows:

$$\max Ens_{TC} = \max\left\{1 - \frac{\sum_{t=1}^{T} (D_{t,TC} - Q_{t,TC})^2}{\sum_{t=1}^{T} (D_{t,TC} - \overline{D_{TC}})^2}\right\} \tag{4}$$

Here, $Q_{t,TC}$ represents the water transfer of Taocha during a period t; $\overline{D_{TC}}$ represents the average water demand of Taocha; and Ens_{TC} is the Nash–Sutcliffe efficiency coefficient of Taocha's water transfer process.

Maximum Nash–Sutcliffe efficiency coefficient of Qingquangou water transfer process (Obj5)

This, in turn, represents the matching degree of the whole water transfer process of Qingquangou. The specific expression is as follows:

$$\max Ens_{QQG} = \max\left\{1 - \frac{\sum_{t=1}^{T} (D_{t,QQG} - Q_{t,QQG})^2}{\sum_{t=1}^{T} (D_{t,QQG} - \overline{D_{QQG}})^2}\right\} \tag{5}$$

This time, $Q_{t,QQG}$ represents Qingquangou's water transfer during a period t; $\overline{D_{QQG}}$ represents the average water demand of Qingquangou; and Ens_{QQG} is the Nash-Sutcliffe efficiency coefficient of Qingquangou's water transfer process.

Constraint conditions

The constraint conditions of the above-mentioned model are as follows:

(1) Upper and lower constraint of reservoir capacity (water level):

$$\begin{aligned} &Z_t^L \leq Z_t \leq Z_t^U \\ &t = 2, 3, \ldots, T \end{aligned} \tag{6}$$

Here, Z_t^L, Z_t^U, and Z_t are the minimum water level, maximum water level and water level of reservoir during period t, respectively. The constraint includes minimum and maximum reservoir water level limits, the daily amplitude constraint of water level during dispatching period, and the regulated capacity water level constraint set by upstream flood control requirements, and takes the intersection.

(2) Reservoir water balance constraint:

$$\begin{aligned} &V_t = V_{t-1} + (Q_{t,in} - Q_{t,out} - Q_{t,QQG} - Q_{t,TC})\Delta t \\ &\quad t = 2, 3, \ldots, T \end{aligned} \tag{7}$$

Here, V_t and Q_t represent reservoir capacity and reservoir outflow during period t of dispatching.

(3) Reservoir discharge capacity constraint

$$\begin{aligned} &Q_{t,out} \leq Q^U(Z_t) \\ &\quad t = 2, 3, \ldots, T \end{aligned} \tag{8}$$

Here, $Q_{t,out}$ represents the discharge of the reservoir during period t, and $Q^U(Z_t)$ represents the maximum discharge capacity of this reservoir at the corresponding water level.

(4) Reservoir outflow constraint:

$$Q_{t,out} \geq Q^L \quad t = 2, 3, \ldots, T \tag{9}$$

$$|Q_{t,out} - Q_{t-1,out}| \leq \Delta Q \quad t = 2, 3, \ldots, T \tag{10}$$

Here, Q^L represents the minimum discharge capacity of the reservoir during dispatching, and ΔQ represents the maximum amplitude of daily discharge from the reservoir.

Optimization method

With the above objective function and constraints, the IDR model becomes an optimal scheduling model to meet multiple water demands and its solution is a complex nonlinear multi-objective problem. The electromagnetism-like mechanism (EM), proposed by Birbi & Fang (2003), is an optimization algorithm for intelligent methods, originating from the physics of electromagnetism (Ouyang *et al.* 2014). It can be used to maximize the objective function flexibly and effectively (Birbil *et al.* 2004).

The four procedures of the EM model can be modified to solve multi-objective problems more easily, as illustrated by Ouyang *et al.* (2015). This improved multi-objective optimization algorithm, called a multi-objective cultural self-adaptive electromagnetism-like mechanism (MOCSEM), is adopted to solve the proposed IDR model. For simplicity, the details of MOCSEM are not described here, but can be found in the corresponding references.

Evaluation indexes

Six indexes are selected to analyze the impact of the aggregate indicator set and process matching degree function set on upstream water diversion, the supply of middle and downstream, and the reservoir's water storage under upstream inter-basin water diversion conditions. These indexes also enable consideration of the middle and downstream water supplies, water storage in the reservoir, and power generation. The six indexes are as follows: the fill storage ratio (FSR), mean annual full ratio (MFR), mean annual quantity of water supply for downstream (MQS), mean annual abandoned water (MAW), mean annual water consumption for power generation (MWC), and mean annual generated energy (MGE). These are selected as evaluation indexes to carry out a contrastive analysis on conditions before and after the water dispatching of MRP Phase I.

The FSR is calculated by observing whether the reservoir water level can reach the normal pool level at the end of October every year. The mathematical formula for this is as follows:

$$FSR = \frac{n_f}{N} \tag{11}$$

Here, N is the total number of years of long series dispatching and n_f is the total number of years of refill reservoir storage.

The MFR is the ratio of the total storage capacity of the reservoir in the storage period to the storage target, that is:

$$MFR = \sum_{i=1}^{N} V_i / TV \tag{12}$$

Here, V_i is the water storage at the end of refill period of the i-th year and TV refers to the required total water storage of the Danjiangkou Reservoir.

The MQS is calculated based on to the discharged water volume of the Danjiangkou Reservoir, as follows:

$$MQS = \sum_{t=1}^{T} Q_{t,out} \cdot \Delta t \tag{13}$$

The MAW is calculated based on the abandoned water volume of the Danjiangkou Reservoir, as follows:

$$MAW = \sum_{t=1}^{T} Q_{t,d} \cdot \Delta t \tag{14}$$

The mean annual quantity of water diversion (MWD) based on the diverted water volume from the Danjiangkou Reservoir, is calculated as follows:

$$MWD = \sum_{t=1}^{T} S_t \cdot \Delta t \tag{15}$$

Here, S_t is the water diversion volume from the inter-basin water diversion project in the upstream area.

The MWC is calculated according to the water consumption volume of the Danjiangkou Reservoir, as follows:

$$MWC = \sum_{t=1}^{T} Q_{t,e} \cdot \Delta t \tag{16}$$

Here, $Q_{t,e}$ is the water consumption volume taken from the reservoir for power generation during period t.

The MGE is calculated from Danjiangkou Reservoir's power output, as follows:

$$MGE = \sum_{t=1}^{T} N_t \cdot \Delta t \tag{17}$$

Here, N_t is the output of Danjiangkou Reservoir's power station during dispatching period t.

RESULTS AND DISCUSSION

Simulation results of two type objective sets

There are two function sets used in the IWT System: the aggregate indicator set (Set 1) and the process matching degree function set (Set 2). The aggregate indicator set is made up of three aggregate indicators, Obj1, Obj2, and Obj3, which reflect the satisfaction degree of operation

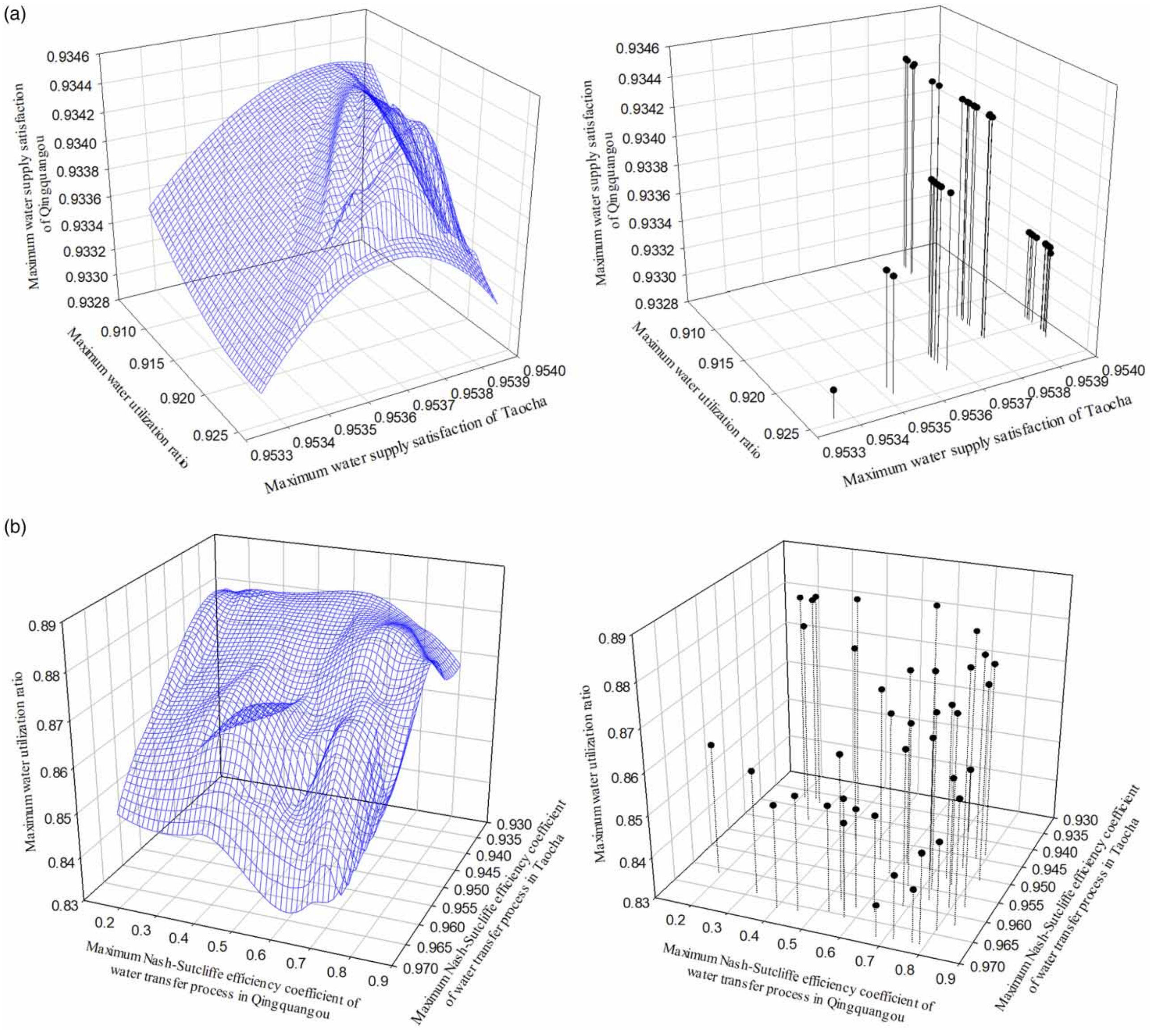

Figure 4 | (a) Optimal solutions obtained by IDR model for Set 1. (b) Optimal solutions obtained by IDR model for Set 2.

schemes to water demands. By contrast, Obj1, Obj4, and Obj5 compose a process matching degree function set, which measures how well operation schemes meet water requirement processes.

The IDR model is implemented to solve the IWT System's problem of water resource allocation across river basins using the MOCSEM method mentioned earlier. Figure 4 displays the optimal solutions and their derivative surface for the two function sets. Moreover, for convenient analysis, Figure 5 details objective function values and evaluation indexes of the obtained solutions.

From Figure 4 three objective values of optimal solutions obtained by IDR model are all found to be in their feasible region. For Set 1, the maximum water utilization ratio (Obj1) is over 0.84, the maximum water supply satisfaction of Taocha (Obj2) is over 0.87, and the maximum water supply satisfaction of Qingquangou (Obj3) is over 0.97. Meanwhile, in Set 2 Obj1 is over 0.82, the maximum Nash–Sutcliffe efficiency coefficient of the water transfer

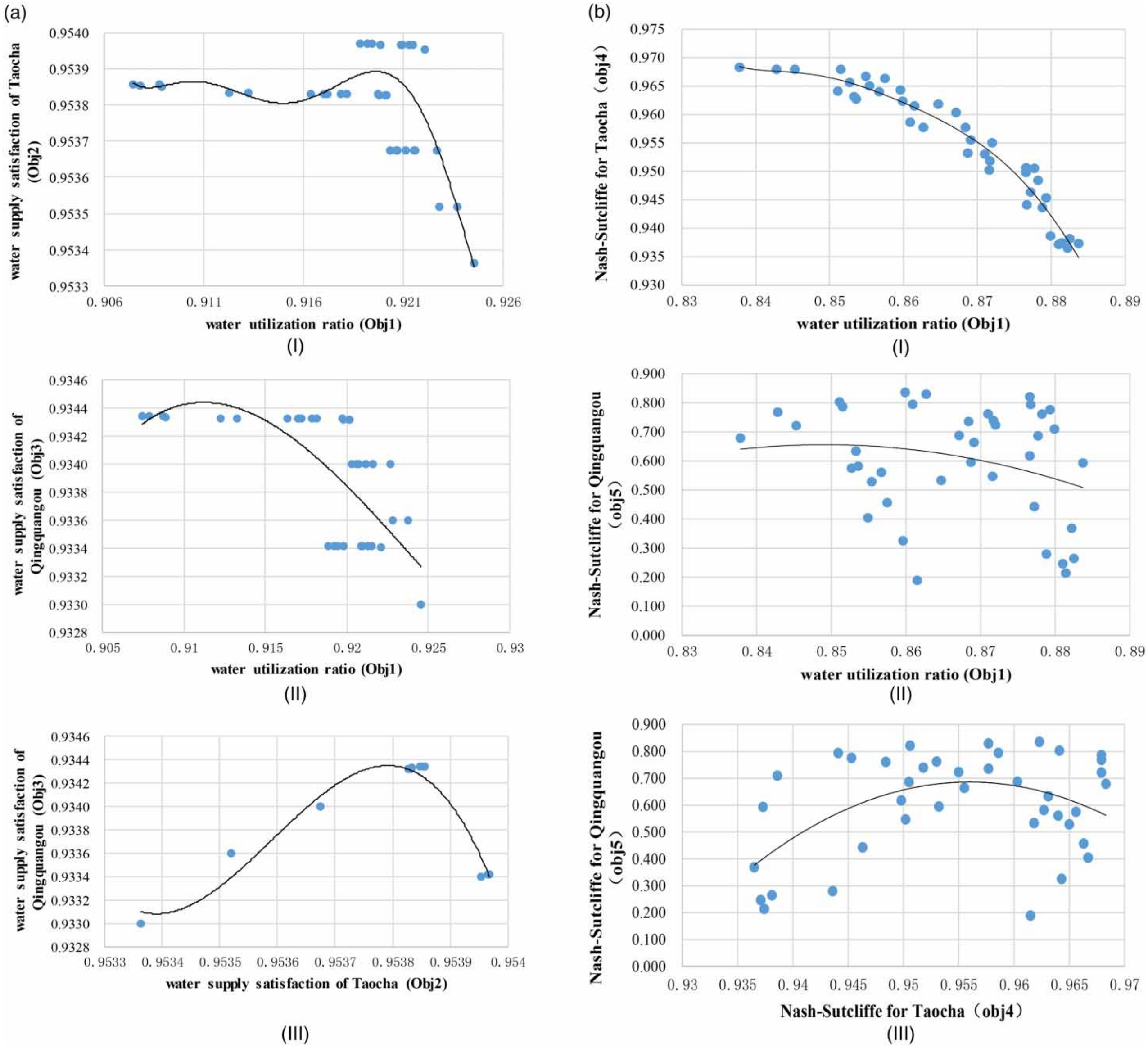

Figure 5 | (a) Relationship between two objectives of optimal solutions for Set 1: (I) Obj1 and Obj2; (II) Obj1 and Obj3; (III) Obj2 and Obj3. (b) Relationship between two objectives of optimal solutions for Set 2: (I) Obj1 and Obj4; (II) Obj1 and Obj5; (III) Obj4 and Obj5.

process of Taocha and Qingquangou (Obj4) is over 0.9, and the efficiency coefficient of water transfer process of Qingquangou (Obj5) is over 0.18. This indicates that all the operation schemes can use water rationally, taking the water demand of the three parties into account.

Relationship between different objectives in two objective sets

After the feasibility analysis, we focus on the relationship between two goals, which are extracted from Figure 4 and displayed in Figure 5. In Set 1 we can see from the figures that Obj1 decreases as rapidly as Obj2 or Obj3 increases because the water supply satisfaction of Taocha and Qingquangou are treated as equally important in IDR model. In Set 2, as Obj1 decreases, Obj4 is increased more strongly than Obj5. This occurs because the process matching degree between the water needs of Qingquangou and the inflow of the Danjiangkou Reservoir is lower than that of Taocha in the IWT System.

On the other hand, by examining the relationship curve between two objective functions of Set 1 and Set 2, a trend is

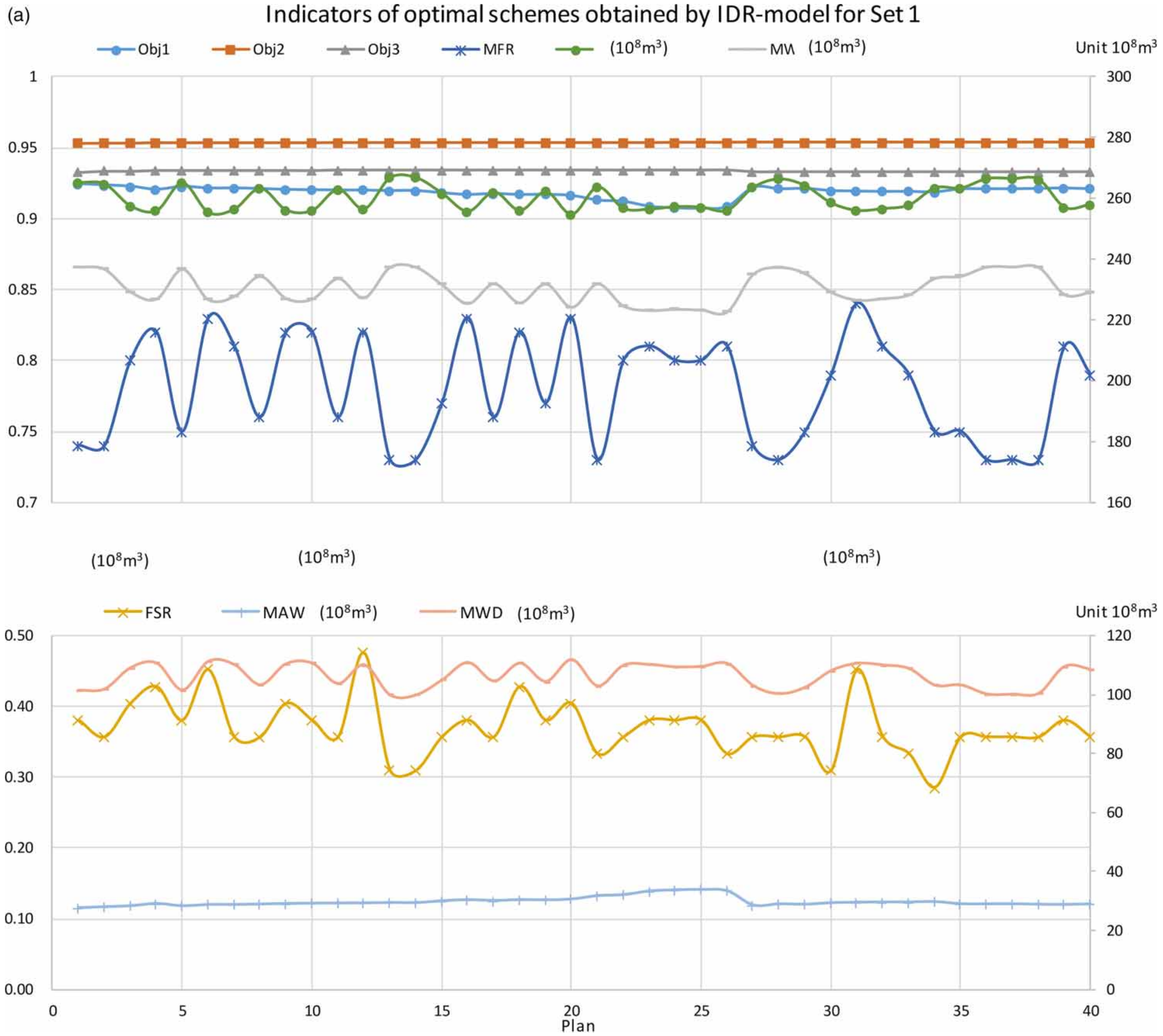

Figure 6 | (a) Indicators of optimal schemes obtained by IDR–model for Set 1. (b) Indicators of optimal schemes obtained by IDR–model for Set 2. *(Continued.)*

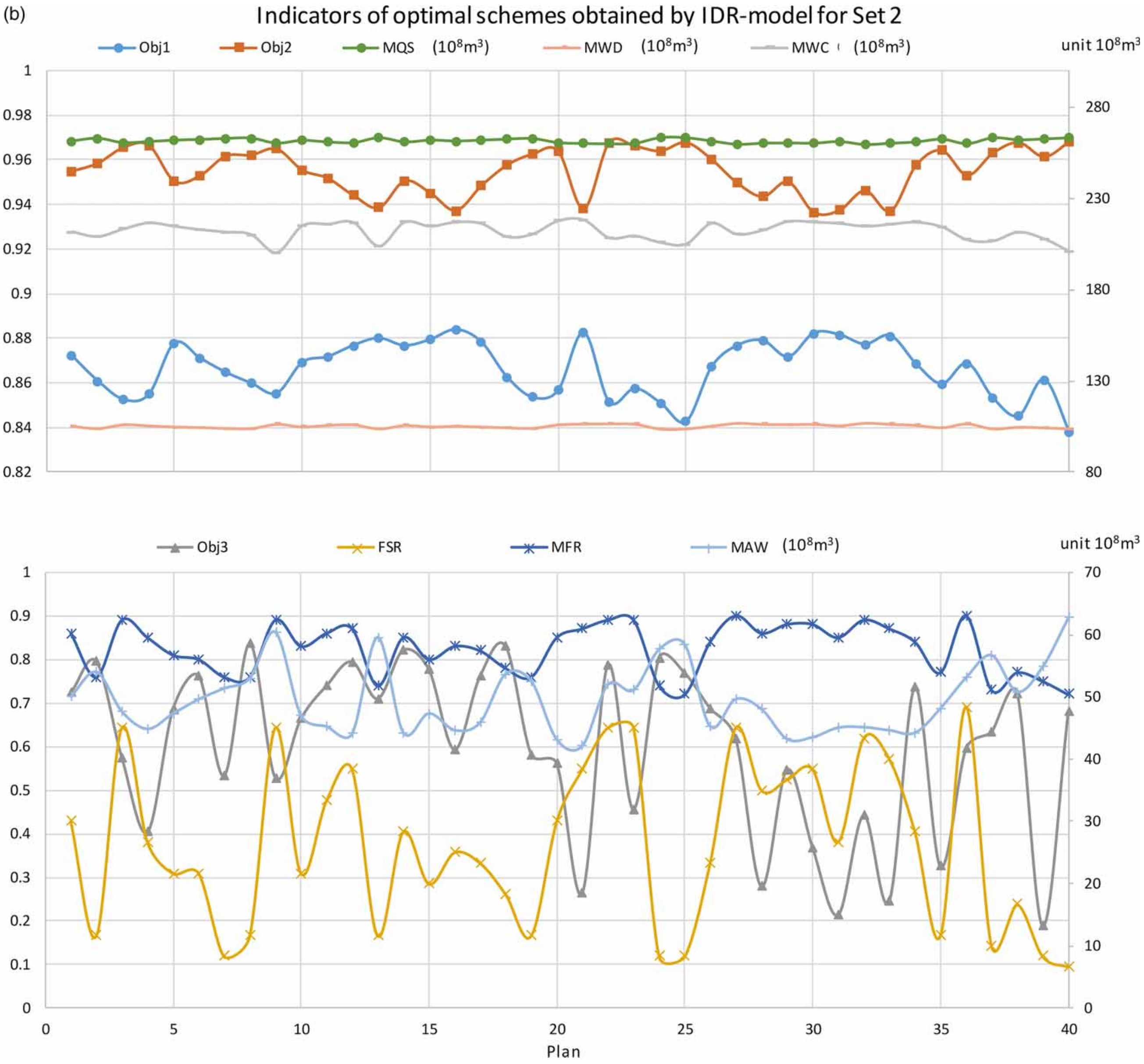

Figure 6 | Continued.

observed whereby Qingquangou's target first increases and then decreases with an increase in Taocha's target. Therefore, the Qingquangou target has a marked peak value. The water supply satisfaction of Taocha has no marked effect on the satisfaction of Qingquangou, but Obj3 first increases with Obj2 and then decreases, reaching a peak value of 0.93435. Similarly, the Nash–Sutcliffe value for Qingquangou appears to change as a function of the Nash–Sutcliffe value for Taocha. This value has a distinctive peak value of 0.8358, with the Nash–Sutcliffe values for Qingquangou increasing and then decreasing as a function of increasing Taocha increase.

Comprehensive benefit comparative analysis for the two objective sets

To analyze the water resource utilization of the two target sets, the performance of the two sets with respect to different evaluation indexes is calculated. The results are detailed in Figure 6 and shown in Figure 7.

From Figure 6, it is clear that for Set 1, the average value of the water utilization ratio (Obj1), MWD, and MWC are 0.92, 106.14, and 230.55, respectively, which are higher values than those of Set 2. Conversely, the average value of the MFR, the MQS, and the MAW are 0.78, 260.33, and 29.78, which are lower than the corresponding values for Set 2. For the convenience of description, MQS, MWD, and MWC are converted to dimensionless values. The normalized values of MQS and MWC are found by dividing those indexes by the total inflow of the reservoir, and by the water availability for power generation, respectively. By contrast, the normalized value of MWD is calculated by subtracting the planned water supply flow from MWD and then dividing by the planned flow.

As illustrated by Figure 7, Sets 1 and 2 provide five-dimensional capability. The Obj1, MFR, MQS, and MWC indexes serve to optimize maximum values. Set 2 outperforms Set 1 in MFR and MQS, which reflects the ability to store water in the flood season impounding period and to supply water downstream. However, Set 2 is outperformed by Set 1 in Obj1 and MWC, which reflects the total water and waterpower utilization. Moreover, for water diversion (embodied by MWD values) Set 2 exhibits slight advantages over Set 1.

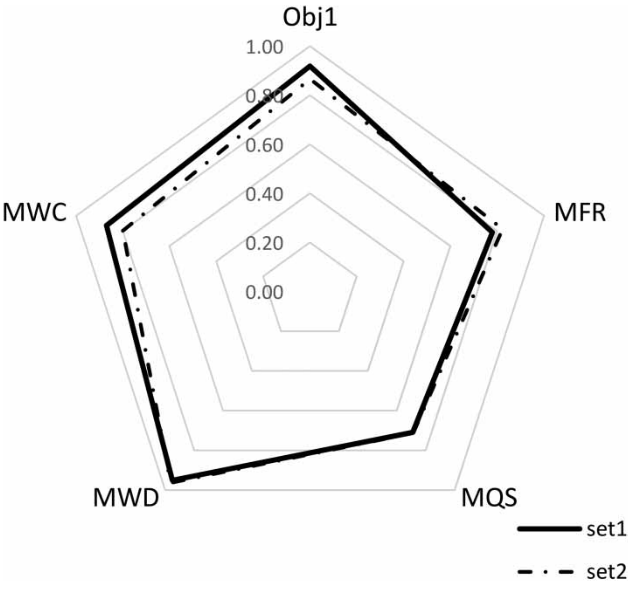

Figure 7 | Joint evaluation of the system's performance based on five-dimensional indexes.

In conclusion, the proposed model as shown generates effective scheduling schemes. The average ranges of Obj1, MWD, MFR, MQS, and MWC in Set 1 and Set 2 are from 0.78 to 0.99. In optimal schemes obtained by the IDR model, the water utilization ratio ranges from 0.837 to 0.925 and the water supply satisfaction of Taocha ranges from 0.953 to 0.954. Furthermore, the optimization scheduling of the IDR model takes into account the water diversion, middle and downstream water demand, and power benefit of a scheduling scheme. For the IWT System, the IDR model is a highly effective method of getting the most out of the Danjiangkou Reservoir's storage capacity.

CONCLUSIONS

The implementation of inter-basin water diversion projects changes the natural geographical distribution of water resources between basins. The hydrological regime in the water source, water diversion area, and water receiving area will change. This can have a favorable impact on local environments, but can also bring negative impacts. The downstream controlling water conservancy project at an inter-basin water diversion water source must comprehensively address conflicts that might arise between regions and alleviate the adverse effects of inter-basin water diversion.

This study chooses the MRP-SNWDP and the Danjiangkou Reservoir as a case study. The aim is to research the optimal schemes of water resource allocation across river basins while meeting the Hanjiang River's water demand, and considering the volume of water diversion in the water receiving area. An optimized dispatching mode with various dispatching objectives is built via the IDR model. On this basis, the 1956–1998 data of natural inflow runoff of the Danjiangkou Reservoir is used to simulate the optimized dispatching. Six indexes (FSR, MFR, MSW, MAW, MWC, and MGE) are selected as evaluation indexes to make a comparison analysis of the impact of different dispatching objectives. This is an attempt to find a dispatching operation mode that can balance water diversion, middle and downstream water demand, water storage, and power generation. The aim is to mitigate the adverse impact of the MRP-SNWDP on the downstream region of water source effectively. Although the proposed model and method are mainly for the MR-SNWDP and Danjiangkou Reservoir, they also have commonality and can be used for the operation of other inter-basin water diversion projects.

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CONFLICT OF INTEREST

None.

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