

Quantifying the resilience of the water-energy nexus for a reservoir-pump station system

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ABSTRACT

Most inter-basin water diversion projects have been constructed to cope with water shortage problems. These projects usually have multiple reservoirs and pump stations connected to each other. Most previous studies focus solely on the operation of reservoirs aiming to supply more water rather than the joint operation of the reservoir-pump station system. Project operations that ignore the pump station may not be cost effective. In addition, future water availability is of great uncertainty that will affect the system's performance. Therefore, the main purpose of this study is to evaluate the tradeoffs between water supply and power net revenue (considering power generation by hydropower stations and power consumption by pump stations) under different water availability scenarios, which can be used to inform policies. A resilience metric is introduced to evaluate the joint system performance. An optimization model including two objectives: social perspective (minimum of total water shortage) and economic perspective (maximum of power net revenue) is considered for the study area: the Hanjiang-to-Weihe River Valley Water Diversion Project. Results mainly show that two objectives are in a contradictory relationship. If future streamflow does not decrease, the water supply sector could at least meet 50% of the water demand in recipient area.

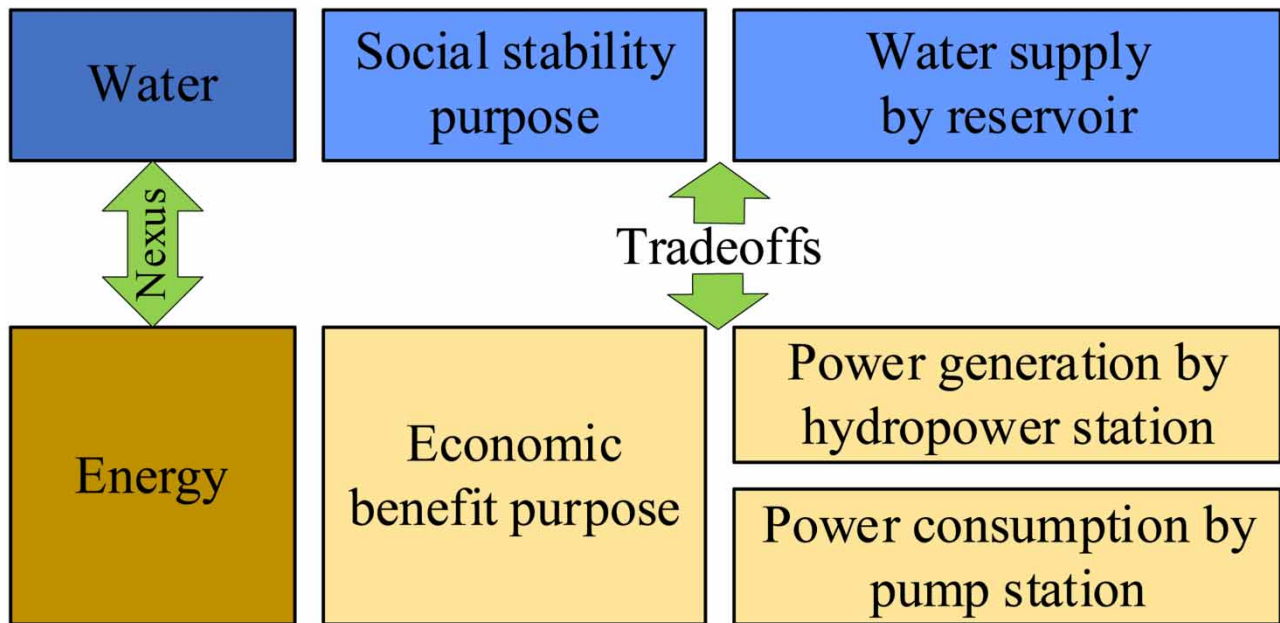
Key words: human priority, multiobjective optimization, social and economic benefit, water resources system analysis

HIGHLIGHTS

- Water-energy nexus tradeoffs of the reservoir-pump station system (RPSS) are evaluated.
- Impact of water availability on the water supply and power net revenue of the RPSS is assessed.
- A resilience metric is introduced to describe the RPSS performance to cope with the deficit.

GRAPHICAL ABSTRACT

Reservoir-Pump station system



1. INTRODUCTION

Uneven distribution of water resources, rapid development, urbanization, population growth, and climate change result in a worldwide growing water demand and water shortage issue (Tsai *et al.* 2019; Salehi 2022). Under this background, surface and groundwater have been overexploited leading to serious environmental problems such as phreatic water pollution and groundwater depression cones (Gude 2018; Portoghese *et al.* 2021). To remit the conflict between water supply and demand, numerous inter-basin water diversion projects have been constructed to transfer water from relatively water abundant area (water source area) to the water shortage area (water recipient area) (Sadegh *et al.* 2010; Yu *et al.* 2018). These include the South-to-North Water Diversion Project (Li *et al.* 2016; Fang *et al.* 2019), the Great Lakes Basin Water Diversion Project (Becker & Easter 1995), the Lesotho Highlands Water Project (Matete & Hassan 2006), and so on. This kind of project has made great contributions to socioeconomic development by increasing water system resilience to cope with water stress (Kumar *et al.* 2005; Zhao *et al.* 2020).

An inter-basin water diversion project can be viewed as a complex water supply system (Zeng *et al.* 2014; Ma *et al.* 2020). It involves many components such as reservoirs, pump stations, pipelines, canals, and water conveyance tunnels (Haimes *et al.* 1998; Vieira & Ramos 2008; Roozbahani *et al.* 2020). Different reservoirs may feature cascade, parallel, or even the combination of cascade and parallel mechanisms (Lund & Guzman 1999; Ma *et al.* 2020). In addition, these reservoirs and pump stations are operated jointly to meet the water demand in the water recipient area. Water can be transferred among different reservoirs by the pump stations to deal with water variability (Davies *et al.* 1992; Wu *et al.* 2020). For example, at off-peak times, water is pumped from lower elevation reservoirs to store in higher elevation reservoirs with higher potential energy. The stored water can be further utilized to generate hydropower at peak time (Ming *et al.* 2017).

Operating strategy is very important for an inter-basin water diversion project. It is beneficial for increasing the system performance and making reasonable policies (Zhu *et al.* 2017; Zhao *et al.* 2021). Analysis of the inter-basin water diversion project operating strategy has gained much attention. For example, Chang *et al.* (2011) established a simulation model to allocate water to different provinces and cities considering the Middle Route of the South-to-North Water Diversion Project. Zhu *et al.* (2013) analyzed the water diversion strategies to efficiently transfer water with the minimum water shortage considering ecological, urban, and agricultural water supplies of the Biliu River Reservoir, China. Xu *et al.* (2016) proposed a bi-level

structure to effectively transfer water to deal with the drought emergency. Arunkumar & Jothiprakash (2017) derived an optimal crop planning for a multi-reservoir system having intra-basin water transfer. Wu *et al.* (2020) explored the tradeoffs between ecological and economic benefits for inter-basin reservoir operation rules determination.

Based on available studies, most inter-basin water diversion project operating strategies emphasize the joint operation of reservoirs (mainly utilized for storing water resources and generating hydropower) and ignore the effect of pump stations (primarily used to pump and distribute water). That means most research focuses on the water supply and hydropower generation without considering the power consumption by pump stations. Although this kind of analysis may supply more water to the water recipient area, which can better satisfy social stable development, it may consume more power in the water supply process and is not cost effective (Ming *et al.* 2017). Therefore, it is very important to quantify the tradeoffs between social benefit (represented by water supply quantity) and economic benefit (represented by power net revenue considering power generation and consumption) for the reservoir-pump station system. The tradeoff analysis of the water-energy nexus contributes to guiding the project operation and facilitating policies.

As water availability is the major uncertainty factor to affect system performance especially with rapid climate change (Steinschneider & Brown 2012; Mehboob & Kim 2021), the main purpose of this study is to quantify the tradeoffs of the water-energy nexus under different water scenarios. A resilience metric defined by Bocchini *et al.* (2013), which is a meaningful probabilistic metric involving certain characteristics that describe the recovery capacity to cope with the deficit, capacity to meet demand, and system supply stability, is chosen to quantify system performance and tradeoffs. This study selects the Hanjiang-to-Weihe River Valley Water Diversion Project (HWWDP; a project under construction), which is composed of two reservoirs and two pump stations, as an illustration. The outcome of this study is expected to shed light on informing the policies of the HWWDP and providing guidance for the operation of other water diversion projects.

2. STUDY AREA, DATA, AND SCENARIOS

2.1. Study area

The Weihe River Basin, especially the Guanzhong area located in Shaanxi Province, is an important industrial and agricultural production site. It plays a significant part in the basin's economic development. With a growing population and industrialization, water demand increases dramatically. At the same time, water availability is showing a downward trend (Yang *et al.* 2018). Therefore, there is an imbalance between water supply and water demand. The water security issue has seriously restricted the basin's further development and triggered severe environmental problems.

Against this background, the HWWDP is proposed to transfer surface water from the Hanjiang to Weihe River Basin for alleviating the water shortage. The Hanjiang is the largest tributary of the Yangtze River, receiving annual precipitation of 800–1,200 mm (Ming *et al.* 2017). Water resources in the Hanjiang are relatively abundant compared to those in the Weihe River, whose annual average precipitation is about 559 mm (Yang *et al.* 2016). Therefore, the Hanjiang is chosen as the water source of the diversion project. The project is proposed mainly for meeting the domestic and industrial water demand, which is relatively stable among different years. According to the current design report, the project is planned to supply $15 \times 10^8 \text{ m}^3$ of surface water to the water recipient areas in 2030. The main water recipient areas include four main cities: Xi'an, Xianyang, Weinan, and Yangling, eleven counties (such as Hu Xian, Zhouzhi Xian, and Wugong Xian) and six industrial parks (Figure 1).

The project is composed of two reservoirs (Huangjinxia and Sanhekou Reservoir; both with hydropower generation capability), two pump stations, and the Qinling Water-conveyance Tunnel. The locations of these reservoirs, the Hanjiang and Weihe River, and some important cities are shown in Figure 1. A node-link structure diagram that highlights the characteristics of the water source and water recipient area of this joint reservoir-pump station system is demonstrated in Figure 2. The Huangjinxia Reservoir (HR) is located in the main stream of the Hanjiang while the Sanhekou Reservoir (SR) is located in the Ziwu River (tributary of the Hanjiang).

Inflow of the HR (multi-year average runoff about $66.4 \times 10^8 \text{ m}^3$ from 1955 to 2009) is larger than that of the SR (multi-year average runoff about $8.6 \times 10^8 \text{ m}^3$ from 1955 to 2009). However, regulated storage of the SR is greater than that of the HR. Considering these two factors and the elevation (Figure 2), the designed water diversion operating rule is as follows: water in the HR is pumped by its Huangjinxia Pump Station (HPS), then is conveyed to the Control gate via the Qinling Water-conveyance Tunnel. If the pumped water cannot satisfy the water demand, the insufficient water will be supplemented from the SR by flowing automatically through the Tunnel to the Control gate. On the other hand, if the pumped water is enough, the

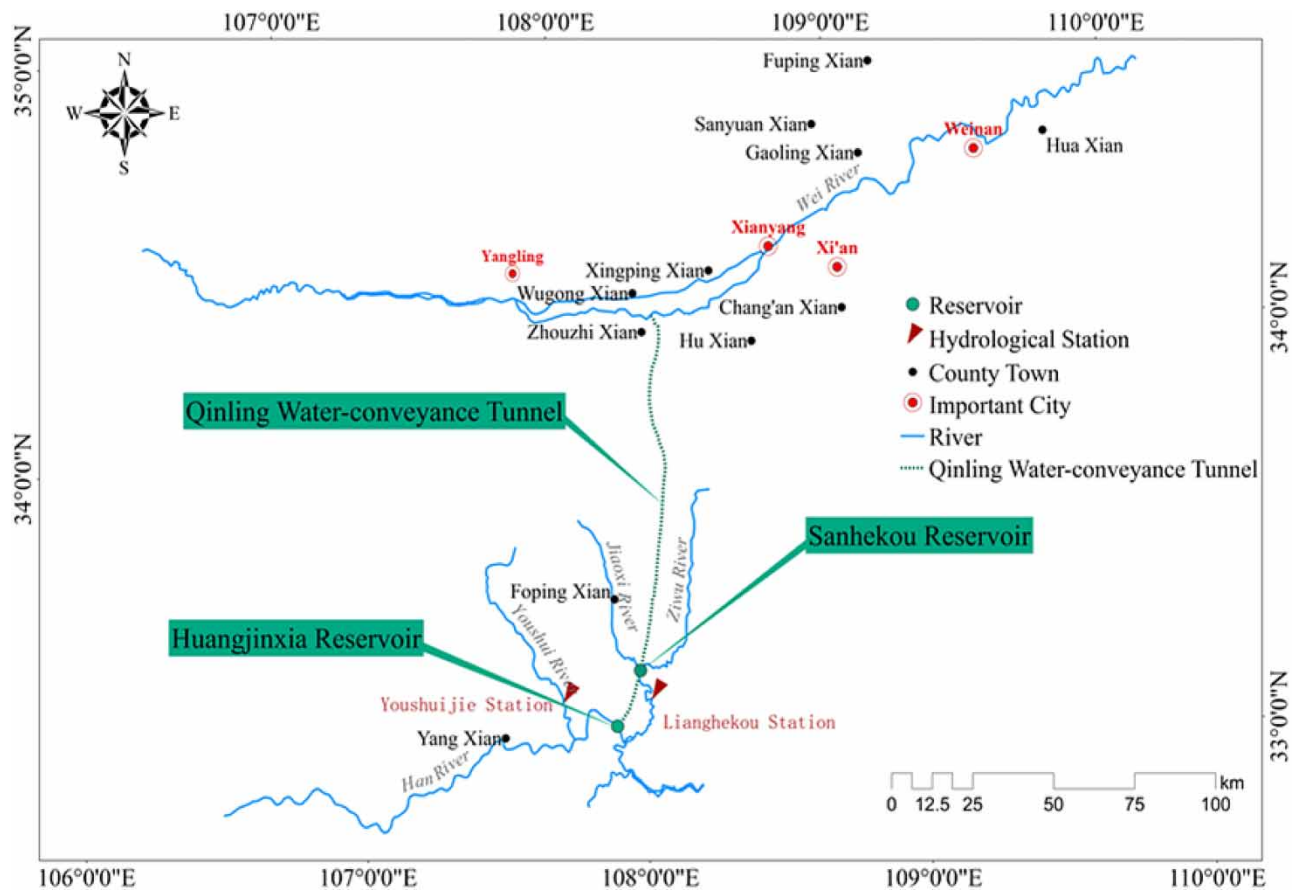


Figure 1 | Geographic positions of Hanjiang, Weihe, and the water diversion project.

surplus water is then pumped by the Sanhekou Pump Station (SPS) to store in the SR for future water use. It is noteworthy that the water pumped from the HR cannot be used to generate hydropower by the Huangjinxia Hydropower Station (HHS), while the water flowing automatically from the SR to the Control gate can be utilized to generate hydropower. In addition, the SPS and the Sanhekou Hydropower Station (SHS) cannot work at the same time.

2.2. Data and scenarios

In this study, monthly inflow to the HR and the SR is provided by the Hanjiang-to-Weihe River Valley Water Diversion Project Construction Company Limited. Date period is from 1955 to 2009. Main characteristics of reservoirs, hydropower stations, and pump stations are listed in Table 1. The Qinling Water-conveyance Tunnel maximum delivery capacity is $70 \text{ m}^3/\text{s}$.

As water availability is the major uncertainty factor to affect system performance especially with rapid climate change (Steinschneider & Brown 2012), this study tests 11 streamflow change scenarios (streamflow +0%, +10%, +20%, +30%, +40%, +50%, -10%, -20%, -30%, -40%, and -50%) to reflect future potential streamflow condition, which facilitates the tradeoffs analysis of the water-energy nexus under uncertainty. Changes in streamflow are applied to monthly data from 1955 to 2009.

3. METHODOLOGIES

3.1. Development of a multiobjective optimization model for the reservoir-pump station system

A multiobjective optimization model is set up for the tradeoffs analysis of the water-energy nexus considering two objectives listed as follows: one for water supply and one for power net revenue. Outputs including water supply, power generation, and consumption are on a monthly time scale.

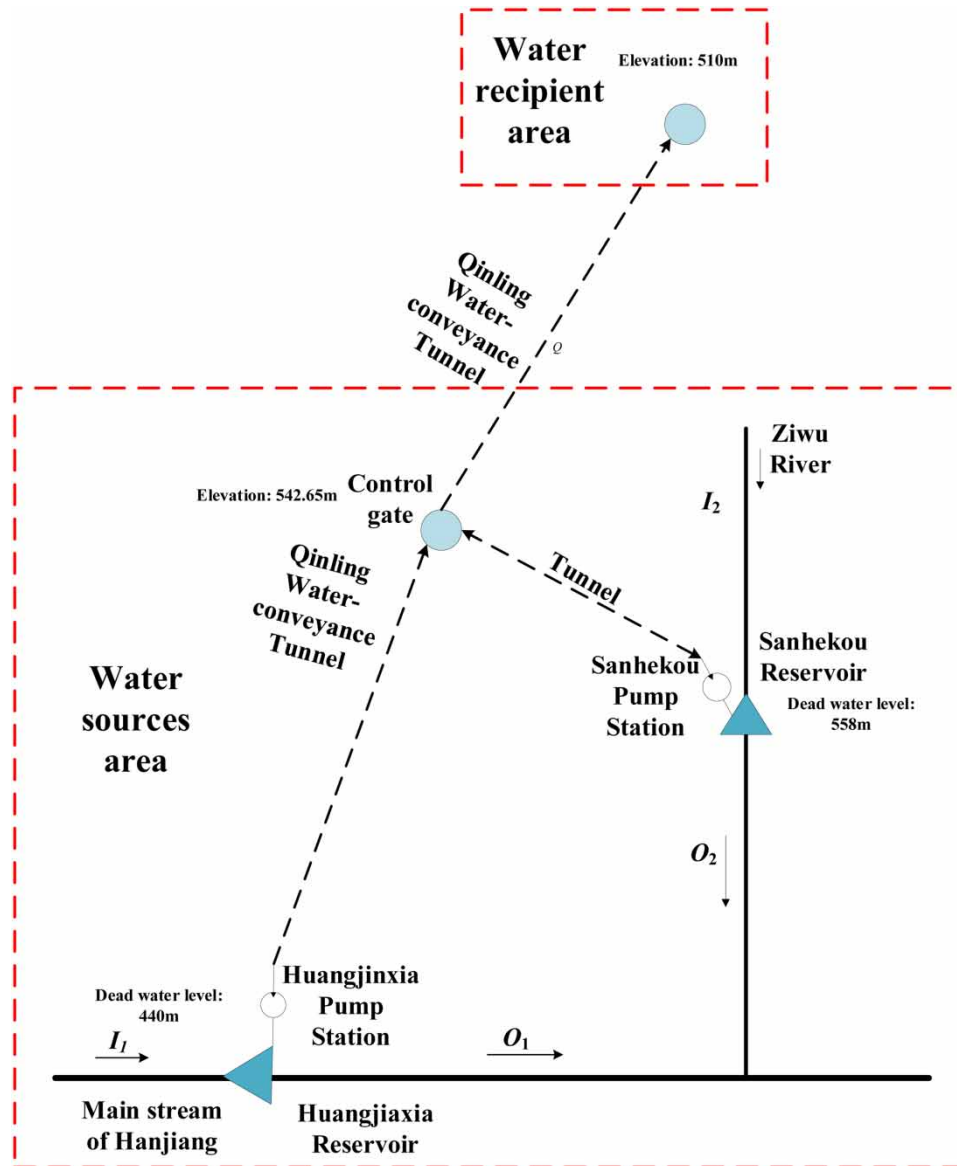


Figure 2 | Node-link structure of the water diversion system.

Table 1 | Main characteristics of reservoirs, hydropower stations, and pump stations

Main characteristics		Units	Huangjinxia	Sanhekou
Reservoir	Normal high water level	m	450	643
	Flood control water level	m	448	642
	Dead water level	m	440	558
	Total storage	10^8 m^3	2.29	7.1
	Active storage	10^8 m^3	0.92	6.49
	Regulation capacity	–	Daily	Multi-year
	Minimum discharge	m^3/s	25	2.7
Hydropower station	Installed capacity	MW	135	45
	Firm power	MW	8.6	2
	Maximum outflow	m^3/s	435.3	72.71
Pump station	Installed capacity	MW	129.5	27
	Maximum outflow	m^3/s	70	18

Objective 1: Minimize the total water shortage for the social stability purpose

$$\min F_1 = \sum_{t=1}^m AWD(t) - \sum_{t=1}^{mn} WS(t) \quad (1)$$

Objective 2: Maximize the power net revenue for the economic benefit purpose

$$\max F_2 = \sum_{i=1}^2 \sum_{t=1}^{mn} [R_1 \times PG_i(t) - R_2 \times PC_i(t)] \quad (2)$$

$$PG_i(t) = K_i Q_i(t) H_i(t) \Delta t \quad (3)$$

$$PC_i(t) = \frac{g q_i(t) h_i(t)}{\eta_i} \Delta t \quad (4)$$

where m is the number of years; n is equal to 12 months in a year; $AWD(t)$ represents the annual water demand (10^8 m^3), in this study, the water diversion is mainly used to meet the domestic water consumption and industrial water use, interannual variation of water demand are not significant, therefore, the annual water demand is equal to $15 \times 10^8 \text{ m}^3$ in the planning year of 2030; $WS(t)$ is on behalf of monthly water supply (10^8 m^3); $i = 2$ for two reservoirs and two pump stations are considered in the project; R_1 is the feed-in tariff (yuan/kWh); $PG_i(t)$ represents the monthly power generation (kWh) by hydropower stations; R_2 denotes the power price (yuan/kWh); $PC_i(t)$ delegates the monthly power consumption (kWh) by pump stations; R_1 and R_2 are set to be 0.3 and 0.5 yuan, respectively. K_i represents power coefficient; $Q_i(t)$ is the streamflow passing through the turbine (m^3/s); $H_i(t)$ means the turbine operating head (m); Δt is the time (h); g delegates the gravitational acceleration; $q_i(t)$ is on behalf of the pumped streamflow (m^3/s); $h_i(t)$ denotes the delivery head (m); η_i refers to the conversion coefficient.

A weighting scheme is an effective way to solve the multiobjective problem, and it is employed in this study (Murata *et al.* 1996; Peng *et al.* 2015). Weights of different objectives reflect different human priorities, and this approach can be employed to analyze the tradeoffs among different objectives. In this study, different combinations of two objectives' weights are tested to analyze the effect of human priorities on the final water supply and power net revenue. The weight of objective 1 is changing from 0 to 1 while the weight of objective 2 is from 1 to 0. As the units of two objectives are different, the first objective is normalized by annual water demand (AWD) equal to $15 \times 10^8 \text{ m}^3$. The second objective is normalized by dividing the benefit of power by its maximal value of the power net revenue (PNR) obtained by the highest weight of objective 2, i.e. $w_2 = 1$.

$$\min F = w_1 \times \frac{\sum_{t=1}^m AWD(t) - \sum_{t=1}^{mn} WS(t)}{m \times AWD} + w_2 \times \frac{\sum_{i=1}^2 \sum_{t=1}^{mn} [R_2 \times PC_i(t) - R_1 \times PG_i(t)]}{PNR} \quad (5)$$

Main constraints of this optimization model are listed as follows:

1. Water balance equation of reservoirs

$$V_i(t+1) = V_i(t) + (I_i(t) - O_i(t) - S_i(t)) \times \Delta t \quad (6)$$

2. Reservoir outflow

$$O_i^{\min} \leq O_i(t) \leq O_i^{\max} \quad (7)$$

3. Reservoir water level

$$Z_i^{\min} \leq Z_i(t) \leq Z_i^{\max} \quad (8)$$

4. Hydropower station output

$$N_i^{min} \leq N_i(t) \leq N_i^{max} \quad (9)$$

5. Pump station output

$$0 \leq Nb_i(t) \leq Nb_i^{max} \quad (10)$$

6. Tunnel flow

$$0 \leq Q_{sd}(t) \leq Q_{sd}^{max} \quad (11)$$

where $V_i(t+1)$ is the storage of i th reservoir in the $t+1$ period (m^3); $I(t)$, $O(t)$, and $S(t)$ represent reservoir inflow, outflow, and water supply, respectively (units are all m^3/s). O^{min} and O^{max} mean the lower limit and upper limit of the reservoir outflow (m^3/s). $Z(t)$, Z^{min} , and Z^{max} are reservoir water level, its corresponding lower limit and upper limit, respectively (m). $N(t)$, N^{min} , and N^{max} delegate the hydropower station output, its corresponding lower limit and upper limit, respectively (MW). $Nb(t)$ and Nb^{max} refer to the pump station power consumption and its upper limit (MW). $Q_{sd}(t)$ and Q_{sd}^{max} denote the tunnel flow and upper limit (m^3/s).

In this study, the cuckoo search algorithm (CS) is utilized to solve the optimization model to obtain the monthly water allocation including pumped water quantity by each pump station and the water supply by each reservoir. Based on these results, the power generation and consumption can be calculated. The CS is a swarm intelligence metaheuristic algorithm introduced by Yang & Deb in 2009. It is inspired based on the cuckoo's brood parasitism behaviors. A cuckoo will lay its egg in the nest of the host bird. If the host bird recognizes that the egg is not its own (with a P_a probability), the egg will be pushed out and abandoned. If not, the egg will be taken care of. The levy flight is a random walk method used by the CS to update the population for searching the global optimal solution. For a detailed description, please refer to Yang & Deb (2009). This algorithm has simple structure, few parameters, excellent search capacity, and strong robustness (Nguyen *et al.* 2014). Due to these characteristics, it has been employed in water resources issues (Hosseini-Moghari *et al.* 2015; Shamshirband *et al.* 2015; Ming *et al.* 2017; Mohammadrezapour *et al.* 2019). However, there is still a limited literature that has utilized this algorithm in the reservoir optimal operation field. To enrich the useability and potential of the algorithm, this study applies it to solve the optimization model to further analyze the tradeoffs of the water-energy nexus.

3.2. Calculation of the resilience metric

A resilience concept is an important basis for quantifying the system performance. This study selects the resilience defined by Bocchini *et al.* (2013) as a demonstration. The resilience is defined as the deficit recovery path, also called the 'resilience triangle.' It can be calculated by the integrating functionality $F(t)$, i.e. the ratio between supply and demand or the ratio between actual production and target. In this study, the resilience metric is calculated at the annual time step. The assumption is that the interannual variations of water demand (mainly for domestic and industrial use) are the same in different years. Therefore, the annual water demand target is $15 \times 10^8 m^3$ in the planning year of 2030. As there is no instructional power net revenue target for the under-construction project, the highest annual power net revenue equal to the maximal value of power net revenue (PNR) divided by the number of years (m) is selected as the target for the energy purpose. The author acknowledges that this assumption is rather simple and has certain limitations. Although with the target limitation, the resilience metric value variation trend can basically reflect the system performance about the energy part. Based on these assumptions, the functionalities of water supply ($F_{ws}(t)$) and power net revenue ($F_{pnr}(t)$) are expressed in Equations (12) and (13), respectively.

$$F_{ws}(t) = \begin{cases} AWS(t)/AWD(t) & \text{if } AWS(t) < AWD(t) \\ 1 & \text{if } AWS(t) \geq AWD(t) \end{cases} \quad (12)$$

$$F_{pnr}(t) = \begin{cases} (AHS(t))/(PNR/m) & \text{if } AHS(t) < (PNR/m) \\ 1 & \text{if } AHS(t) \geq (PNR/m) \end{cases} \quad (13)$$

where $AWS(t)$ is the annual water supply; $AHS(t)$ denotes the annual power net revenue.

After that, the resilience metric value of the water supply (R_{ws}) and power net revenue (R_{pnr}) can be computed by Equation (14) at the annual time step.

$$R = \frac{\int_{t_0}^T F(t)dt}{T} \quad (14)$$

4. RESULTS

4.1. Impact of water uncertainty on water supply and power net revenue quantity

Based on the cuckoo search algorithm, the author first calculated the monthly water diversion process, power generation and consumption with the water supply weight equal to 1 (focusing on social perspective) under the historical streamflow condition (streamflow +0%). Figure 3 shows the integrated annual results.

For the water source area, by the least square method (Giudice *et al.* 2018), the 1983 and 1971 are identified to be the typical high- and low-flow year (whose precipitation cumulative probability distribution function is basically close to 95 and 5%, respectively). In Figure 3(a), the HR basically transfers more water to the water recipient area due to its higher inflow. It is especially true under the low-flow year compared to the high-flow year. The reason is that: water in the SR flows automatically to the recipient area, using the water from the SR is more economical.

Figure 3(b) also proves the above findings. In the high-flow year, more power generation tends to be generated. Also, more water transferred from the SR leads to lower power consumption thus leading to higher net power generation.

Ming *et al.* 2017 found that when the water supply is equal to $15 \times 10^8 \text{ m}^3$, total power generation (considering HHS and SHS) and consumption (considering HPS and SPS) are basically around $5 \times 10^8 \text{ kWh}$. Solid blue and red line also fluctuate around $5 \times 10^8 \text{ kWh}$. The comparison basically proves the correctness of the results.

The annual average results under different weight combinations are further calculated and visualized in Figure 4 (water supply) and Figure 5 (power generation and consumption).

Figure 4 basically shows that the water supply priority tipping point is about 0.73. When the water supply priority is smaller than 0.73, the total water supply is only provided by the SR while no water is pumped from the HR. Since using water from the SR is cheaper (water flowing automatically to the water recipient area without using the pump station), when priority of water supply is low, which means policy makers pay more attention to the economy, it makes perfect economic sense to use a cheaper water source. In this case, the total water supply can only satisfy about 50% of the water demand as the inflow of the SR is relatively smaller. It is hard to meet demand using only water supplied by the SR.

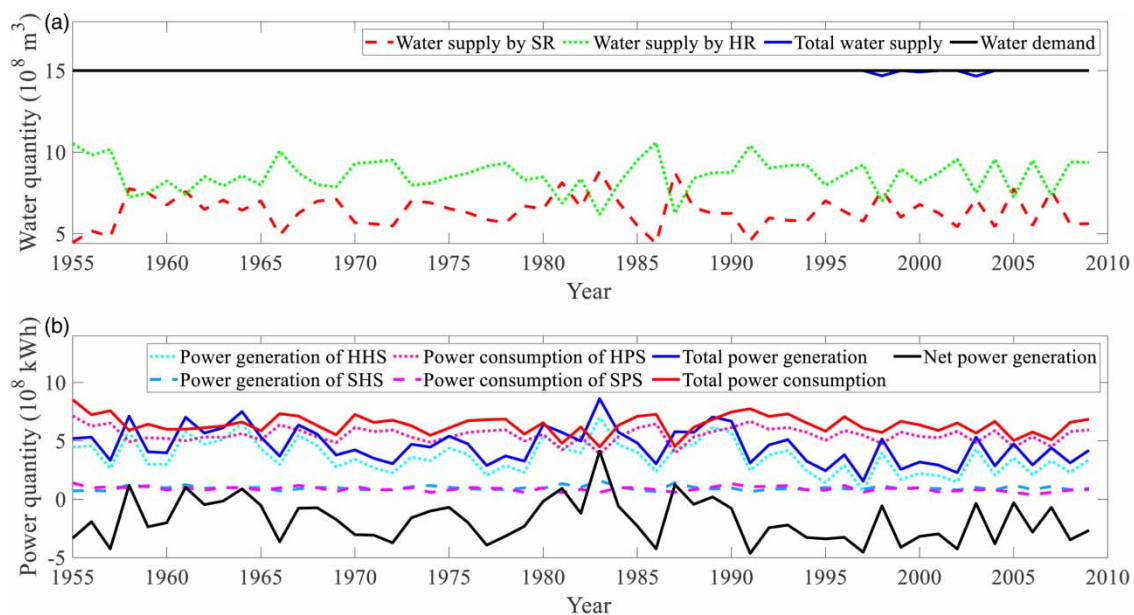


Figure 3 | Model results focusing on water supply under the historical condition.

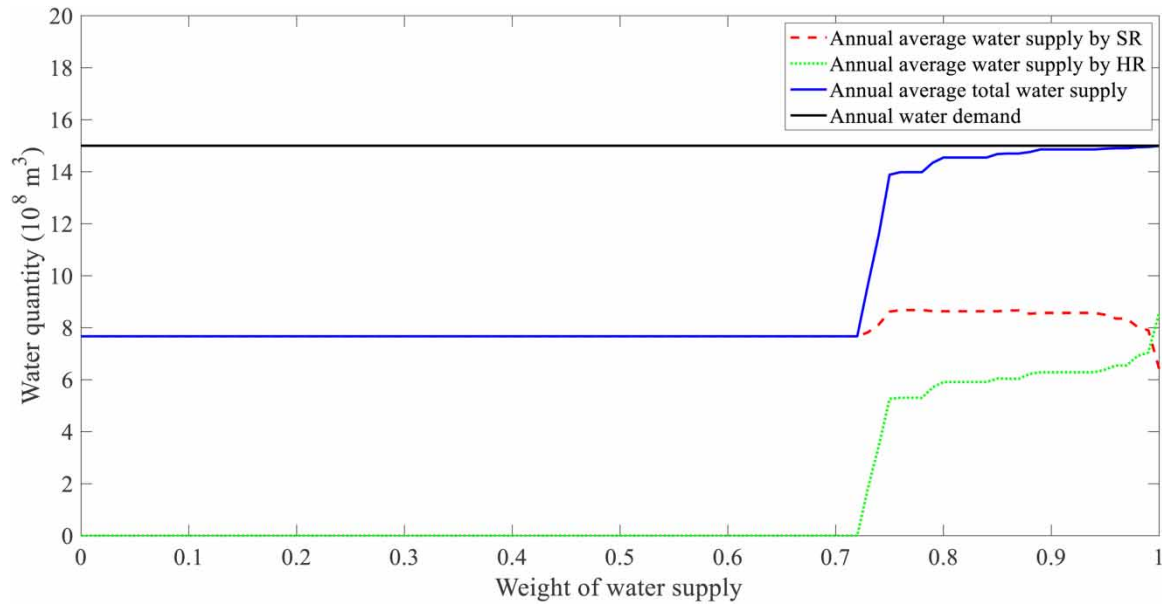


Figure 4 | Impact of human priority on water supply.

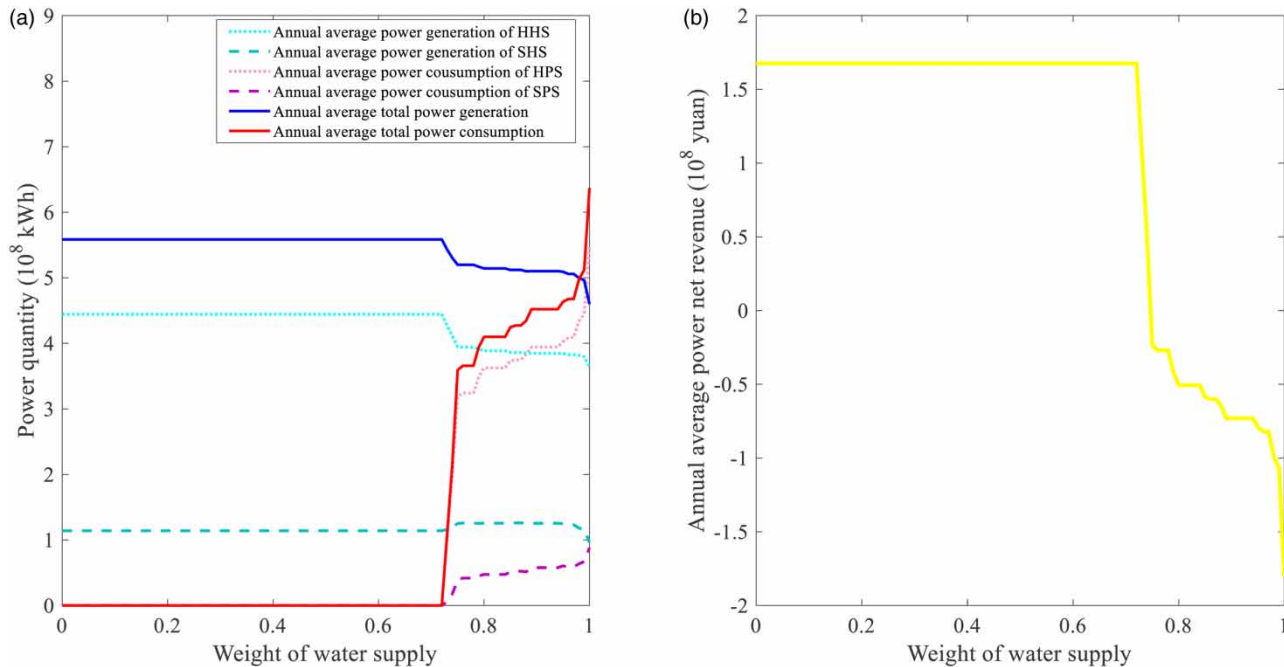


Figure 5 | Impact of human priority on power net revenue.

When the water supply priority gradually increases, the water pumped by the HPS increases. Water supplied by the SR increases first and then decreases. The overall water supply is showing an increasing trend. Higher water supply priority leads to higher total water supply to maintain social stability without doubt. Intuitively, the annual average water supply is over $14 \times 10^8 \text{ m}^3$ when the water supply priority is over 0.8.

Figure 5(a) illustrates that when the water supply weight is smaller than 0.73, two pump stations do not both operate to reduce the power consumption for the purpose of economic benefit maximization. With the continued increase of the water supply weight, two pump stations are put into operation, and the power consumptions of these two pump stations

rise. The SPS mainly works to store more water in the SR. It is noteworthy that the power consumption of the HPS remarkably increases to better meet the water demand due to its higher inflow than the SR. As the water pumped by the HPS cannot be used for power generation, more water pumped by the HPS also leads to a decrease of the power generation of the HHS. Overall, with the water supply weight increase, total power generation and consumption present a decreasing and increasing trend, respectively. These trends result in the corresponding decrease of the power net revenue exhibited in Figure 5(b). Intuitively, the annual average power net revenue is varying from about 1.7×10^8 (yuan) to -1.8×10^8 (yuan). The annual average power net revenue is negative and lower than -0.5×10^8 (yuan) when the water supply weight is over 0.8.

Then, the results under other 10 streamflow change levels are tested. The impact of water uncertainties on the annual average water supply and annual average power net revenue is demonstrated in Figure 6.

In Figure 6, black colors represent streamflow unchanged levels. Blue colors (from light to dark) represent streamflow increase levels. Red colors (from light to dark) represent streamflow decrease levels. It is also suitable for the following figures.

Figure 6(a) and 6(b) demonstrate that water availability will significantly affect the water supply and power net revenue. Different colors represent different water availabilities. More water availability tends to result in higher social and economic benefits. The variation trend of water supply and power net revenue under different future streamflow scenarios is consistent with that under historical streamflow conditions. The highest water supply (with $w_1 = 1$) varies from $15 \times 10^8 \text{ m}^3$ to $12.5 \times 10^8 \text{ m}^3$, the lowest water supply (with $w_1 = 0$) varies from $10.7 \times 10^8 \text{ m}^3$ to $3.5 \times 10^8 \text{ m}^3$ with water availability changing from the highest (+50%) to the lowest (−50%). If no streamflow decrease occurred, the water supply can always meet half of the water demand ($7.5 \times 10^8 \text{ m}^3$). Similarly, the highest power net revenue (with $w_1 = 0$) varies from 2.2×10^8 (yuan) to 1.0×10^8 (yuan), the lowest power net revenue (with $w_1 = 1$) varies from -0.3×10^8 (yuan) to -1.9×10^8 (yuan) with water availability changing from the highest (+50%) to the lowest (−50%).

The tradeoffs between water supply and power net revenue quantity under 11 streamflow conditions are further plotted in Figure 7, which can be utilized to inform policies. It intuitively displays how the annual average power net revenue varies with the annual average water supply under different water availability scenarios. For the project, maximizing the social and economic benefits are contradictory. The finding is consistent with Ming *et al.* 2017 and Wu *et al.* 2020. These researchers also found this conflicting relationship. Higher water supply triggers lower power net revenue under no matter which water availability condition. Here, tradeoffs under three given power net revenue conditions: -1 , 0 , and 1×10^8 (yuan) are listed as a demonstration shown in Table 2.

In Table 2, when the project bears an economic loss of about 1×10^8 (yuan), the water demand can be fully satisfied when the streamflow remains unchanged or increases. Under no matter which water availability conditions, over 2/3 of the water demand can also be supplied. On the balance of the revenue, the water supply can meet the water demand at the guaranteed rate of 80% except when the streamflow decreases by over 10%. At the lowest water availability condition (−50%), water supply is less than half of the demand. In the pursuit of economic benefit of 1×10^8 (yuan), only a water increase of over 20% can satisfy the water demand at the guaranteed rate of 80% while 2/3 of the demand cannot be sustained at the streamflow decrease condition.

4.2. Impact of water uncertainty on water-energy nexus resilience

System resilience quantification offers another layer of information for system performance analysis. Based on the optimization model output results and Equations (12)–(14), resilience metric values for water-energy nexus under 11 water conditions are calculated and displayed in Figure 8.

Figure 8(a) and 8(b) display that the resilience trends of water supply and power net revenue are like those demonstrated in Figure 6, and more water availability leads to higher resilience for both water and energy sectors. The highest water supply resilience (with $w_1 = 1$) varies from 1 to 0.84, the lowest water supply (with $w_1 = 0$) varies from 0.72 to 0.23 while water availability changing from the highest (+50%) to the lowest (−50%). In study, resilience value is further divided into four grades. Resilience values smaller than 0.2, between 0.2 and 0.5, between 0.5 and 0.8, and higher than 0.8 are defined as the low, relatively low, medium, and high level grade reflecting the system performance to meet the targets of either water or energy sector. Therefore, if the water availability remains unchanged or increases, the water supply resilience will always be higher than 0.5, and the water sector has at least a medium level grade to meet the water demand. The highest power net revenue resilience varies from 0.98 to 0.58 (with $w_1 = 0$), the lowest (with $w_1 = 1$) varies from 0.12 to 0 while water availability changing from the highest to the lowest.

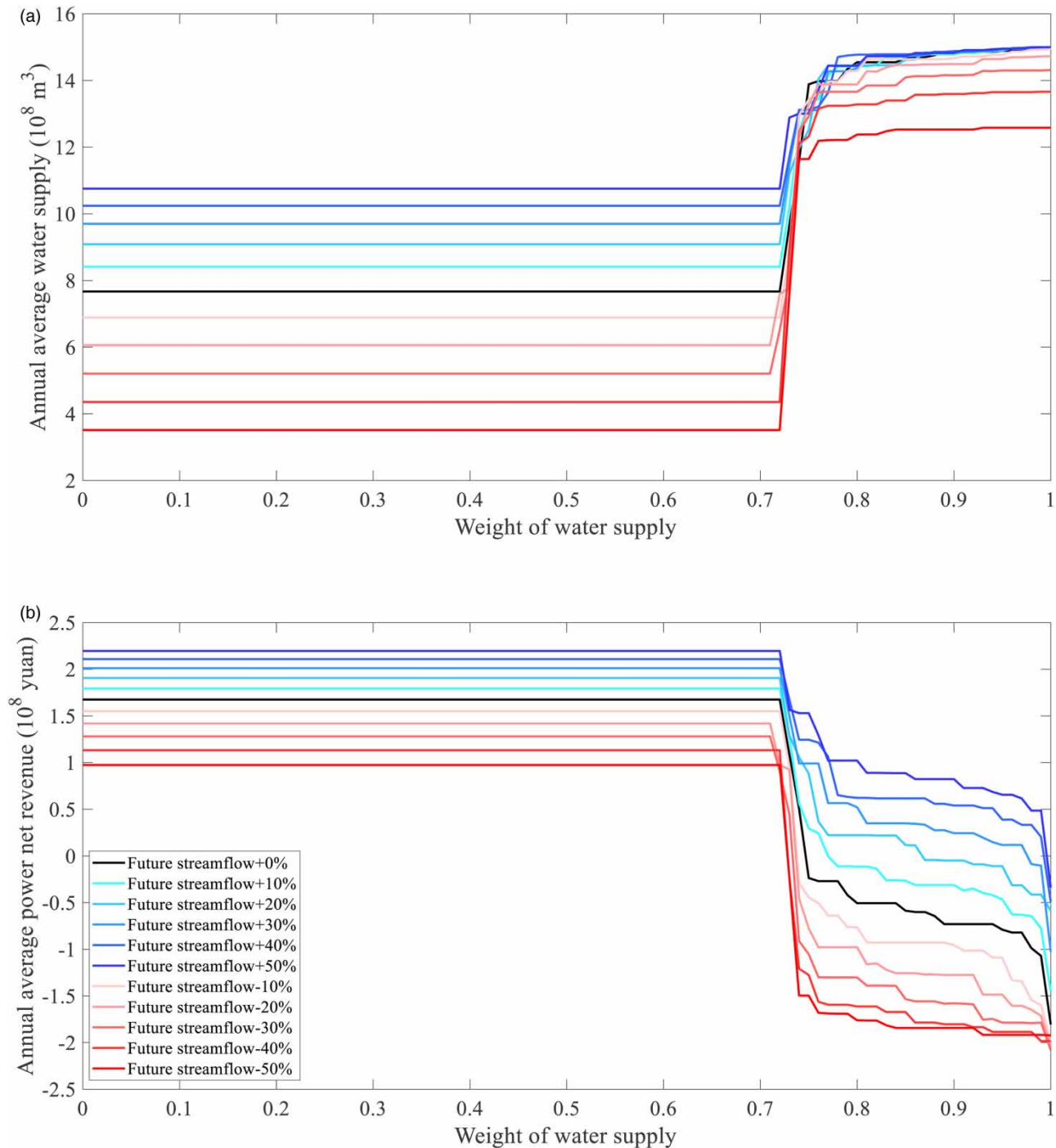


Figure 6 | Impact of streamflow uncertainties on the water-energy nexus: (a) for annual average water supply, and (b) for annual average power net revenue.

The resilience tradeoffs between water and energy sector under 11 water availability conditions are visualized in Figure 9. This figure also shows the contradictory relationship between the water and energy sector resilience similar to the trend in Figure 7. Based on this figure, the tradeoffs under three given power net revenue resilience conditions: 0.2, 0.5, and 0.8 are demonstrated as examples in Table 3.

In Table 3, when the project only needs to keep the resilience for energy sector at about 0.2, i.e. low-level grade to meet the energy demand, water sector resilience with streamflow increase equal or over 20% is 1, indicating the 'optimal' water supply

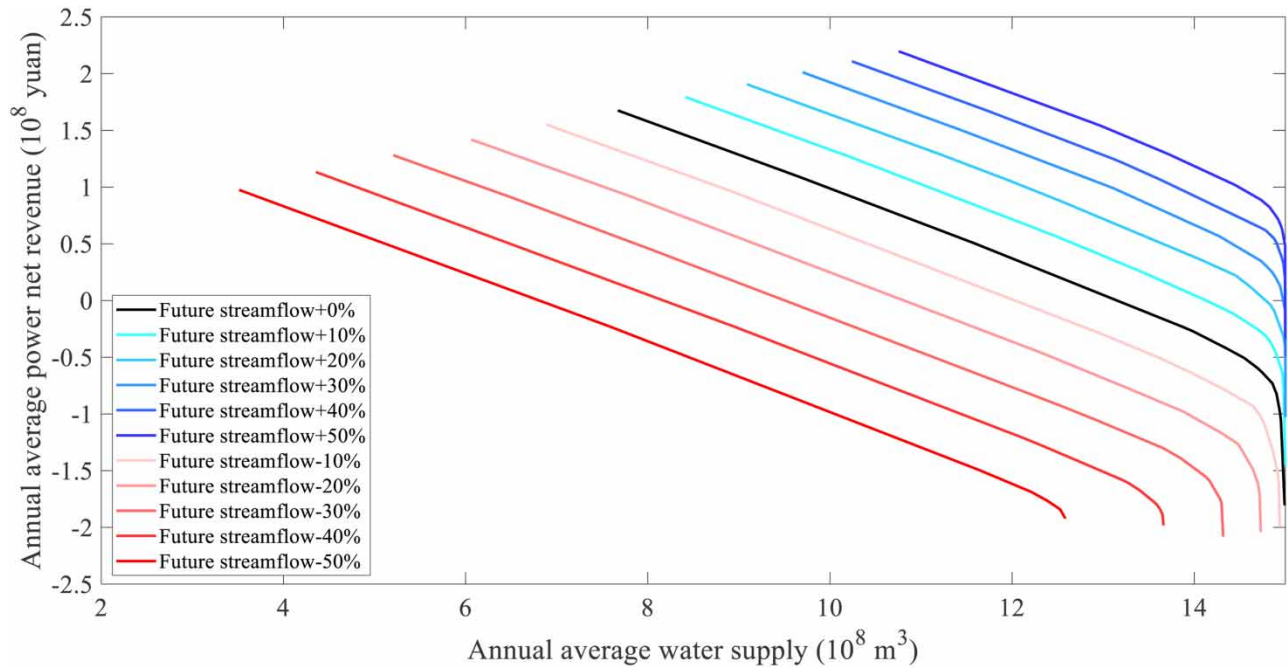


Figure 7 | Tradeoffs between water supply and power net revenue quantity.

Table 2 | Water supply quantity under three given power net revenue conditions

Streamflow condition	Annual average power net revenue (10 ⁸ yuan)		
	– 1	0	1
–50%	10.0	6.8	3.5
–40%	11.4	8.2	4.8
–30%	12.8	9.5	6.2
–20%	13.9	10.8	7.5
–10%	14.7	12.1	8.8
+0%	15.0	13.2	10.0
+10%	15.0	14.2	11.1
+20%	15.0	14.8	12.2
+30%	15.0	15.0	13.1
+40%	15.0	15.0	13.8
+50%	15.0	15.0	14.5

resilience. That means the project can recover from the water deficit shock very well. If water streamflow decreases no more than 10%, water sector will at least remain a high-level grade. Overall, the resilience of the water sector is over 0.5 (except at the streamflow –50% scenario) indicating the medium level recovery capacity.

When the medium-level resilience is required for the energy nexus, under no matter which water availability scenario, no ‘optimal’ resilience will be achieved for water system. Streamflow decreases no less than 20% can maintain at least the medium-level water system resilience, while streamflow increases no less than 10% can ensure high-level water system resilience.

When the streamflow decreases by 30% or more, high-level resilience (0.8) of the energy sector will not achieved. At high-level resilience (0.8) of the power net revenue condition, the decrease of the water availability cannot reach the

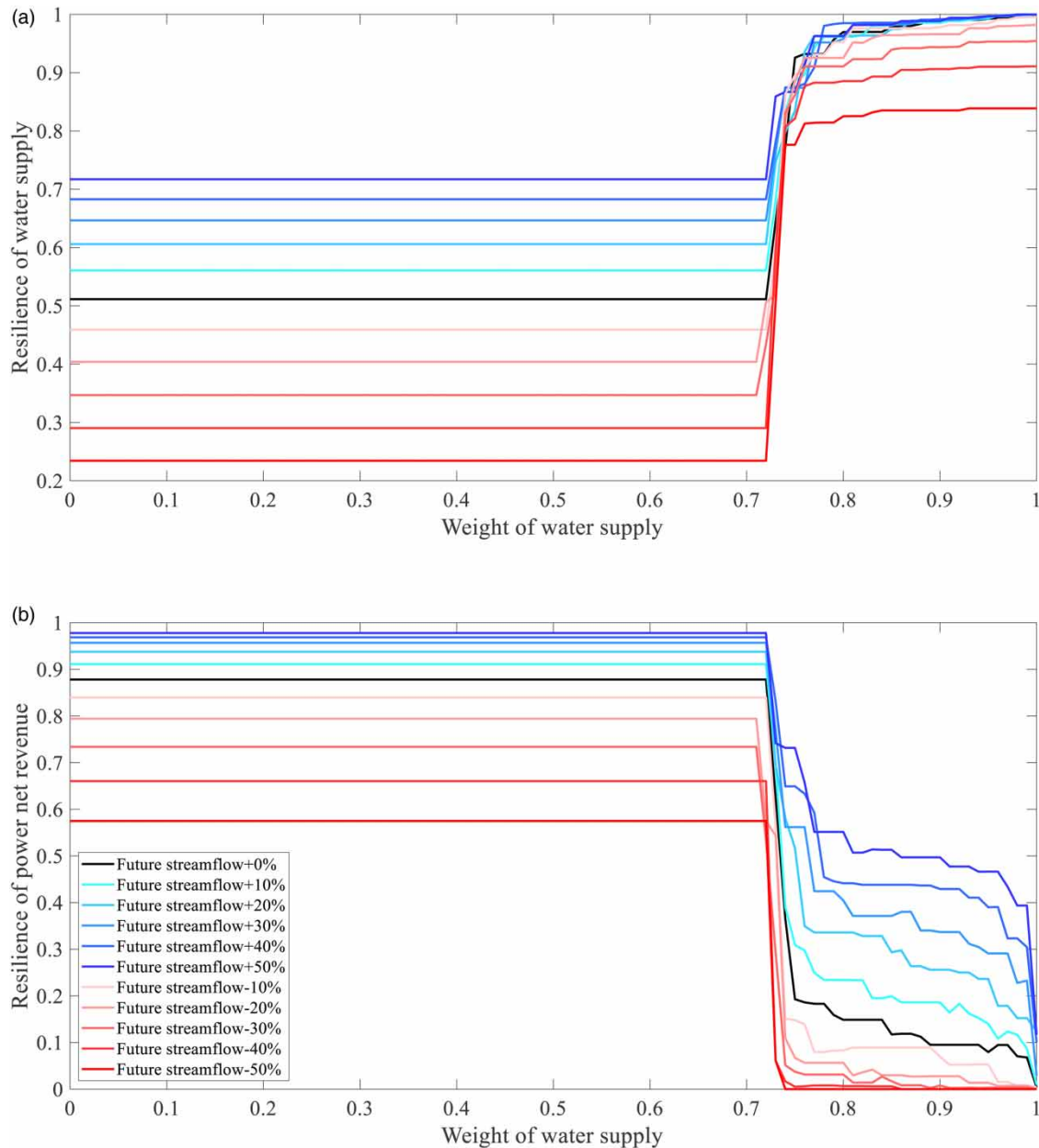


Figure 8 | Impact of streamflow uncertainties on the water-energy nexus resilience: (a) for annual average water supply, and (b) for annual average power net revenue.

medium-level water supply resilience. Only a water availability increase of more than 40% can lead to high-level water supply resilience.

5. DISCUSSIONS

5.1. Limitations and potential future work

This study assesses the tradeoffs between water and energy sectors under different water availability scenarios for guiding the inter-basin water diversion project operation. Reasonable project operation could promote the social and economic development in an integrated way that is also consistent with the ‘Sustainable Development Goals’ (SDGs) (UN 2015). For example, objective 1 in this study, trying to minimize the total water shortage, coincides with SDG6: ensure water availability. Objective 2, maximizing the power net revenue, is in accordance with SDG7: ensure access to affordable, reliable, sustainable, and

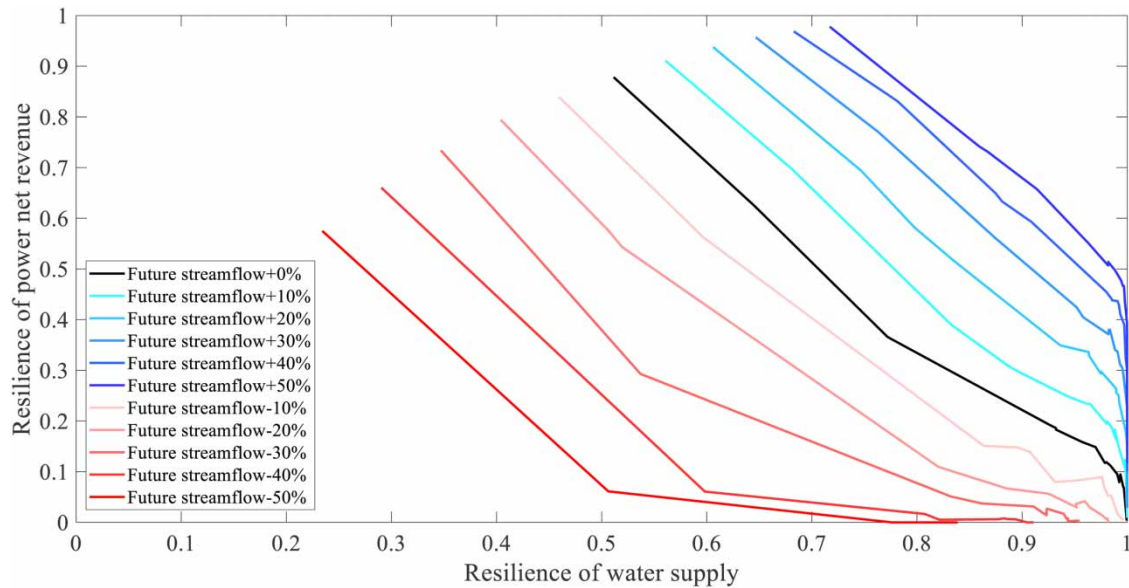


Figure 9 | Tradeoffs between water supply and power net revenue resilience.

Table 3 | Water supply resilience under three given power net revenue resilience conditions

Streamflow condition	Power net revenue resilience		
	0.2	0.5	0.8
–50%	0.43	0.27	–
–40%	0.53	0.37	–
–30%	0.65	0.45	–
–20%	0.76	0.55	0.41
–10%	0.83	0.64	0.48
+0%	0.92	0.71	0.55
+10%	0.98	0.78	0.63
+20%	1.00	0.85	0.69
+30%	1.00	0.91	0.74
+40%	1.00	0.96	0.80
+50%	1.00	0.99	0.82

The symbol '–' means power net revenue resilience cannot be achieved under the corresponding water availability conditions.

modern energy for all. Assessing the water availability impact is closely related to SDG13: clear understanding of climate change impact. Therefore, the analysis in this study has a certain significance in practical engineering.

However, the author acknowledges several limitations exist and need to be focused on in the future for better policy implications:

- (1) In this study, only impact of water availability uncertainty on the water-energy nexus is assessed. Other uncertainties such as industrial expansion, population growth, and land use change will also affect the system performance (Haasnoot *et al.* 2011). They are ignored in this study. Future research directions can be explored related to these uncertainties.
- (2) The resilience of the water supply and power net revenue is evaluated at the annual time step. Water and energy demand vary with the seasons, months, days, or even shorter time scales during a year (Tso & Yau 2007). Shortening the time scale will better reflect the tradeoffs.

- (3) The tradeoffs are evaluated from the diversion project perspective by considering social (water supply) and economic (power net revenue) benefits. A water diversion project is characterized by multiple departments and different types of impacts involved (Zhuang 2016). Tradeoffs can be further evaluated from the basin perspective while taking more factors such as more benefits and negative impacts into consideration.

For example, the diversion project (a new water supply source) will bring some difficulties for the original water allocation in the water recipient area. The changing water supply quantities of different types of local water resources (such as surface water, groundwater, and reused water) will affect the benefits of different cities and companies (Wang *et al.* 2019). In addition, the water price of the transferred water is higher compared to local resources, many water-using departments may be unwilling to use the higher-cost transferred water (Yu *et al.* 2018). For the water source area, the diminished water quantity may affect the water quantity of some industries (Moore 2014). This may cause certain social and economic conflicts.

Construction of the water diversion project may also cause several types of environmental impacts. It may reduce the water shortage in the water recipient area (Sadegh *et al.* 2010). Therefore, it may mitigate ecological water shortages, protect biology diversity, improve water quality, and control land subsidence (Yang *et al.* 2012). However, long-distance water diversion may also result in the spread of disease (Smakhtin *et al.* 2001). For the water source area, the water quality, salinization, and fish and wildlife habitat may also be affected due to the decreasing water availability (Getches 2003).

A comprehensive tradeoff among social, economic, and environmental sectors is desired but challenging. Only by thinking from a nexus perspective can the project better play its role and gain more benefits. This will have significant advantages for the basin's social, economic, and sustainable environmental development.

5.2. Government policy implications

Efficient water resources and project operation management should also consider the law and administration. Government should make reasonable unified management policies to coordinate the stakeholder benefit tradeoffs among multiple water-using departments, water supply departments, and cities for the basin's economic development and environmental protection. Water utilization orders and water supply guaranteed rates of different water-using departments, water supply orders among different water resources should be reconciled.

A stricter water licensing system should be also made to relatively reduce the exploitation of local water resources especially the groundwater to enhance the environment. On the premise of basic water supply, improper water use structure or water use habitat should be modified to gradually transfer water to areas or industries that have a higher water use efficiency. Water prices for different types of water resources should be formulated considering the engineering cost (the cost to exploit the water) and environmental cost (potential environmental loss resulted by water exploitation).

Water prices for local water should be increased due to the current higher environmental cost. Government subsidies on transferred water price may be a choice to reduce the transferred water price. Reasonable water price is beneficial for avoiding the transferred water being much abandoned and the environmental protection.

Furthermore, basin should strengthen the water resource monitoring, long-term and short-term water demand and water availability prediction for better formulating water allocations especially for an advanced plan for low-flow years or seasons.

6. CONCLUSIONS

Currently, numerous inter-basin water diversion projects have been built to mitigate the water shortage. Inter-basin water diversion projects can be seen as a complex system composed of many reservoirs and pump stations, constituting the reservoir-pump station system. Most available research concerns the operation of reservoirs rather than the joint operation of reservoirs and pump stations, which may not be economically optimal. Therefore, the main purposes of this study include (1) evaluating the water-energy nexus tradeoffs of the reservoir-pump station system, (2) assessing the impact of water availability on the water supply and power net revenue (considering both power generation by reservoir and consumption by pump station), and (3) quantifying the system performance to cope with the deficit via a resilience metric (sharing some characteristics with risk) for potential policy makings especially under the water availability uncertainty condition.

To address this issue, this study develops a multiobjective optimization model for the reservoir-pump station system with two objectives: minimizing the total water shortage for social benefit and maximizing the power net revenue for economic

benefit. Results solved by the cuckoo search algorithm and a weighting scheme mainly show that: two objectives are incompatible. By visualizing the tradeoffs between water supply and power net revenue, if the system could bear the losses about 1×10^8 (yuan), it would ensure at least 2/3 water demand. However, if the system would like to achieve about 1×10^8 (yuan), ensuring at least 2/3 water demand is only possible in streamflow not decrease condition.

The target determination is critical for the results. A constant target setting no matter what it is for water or energy sector in this study has its drawbacks as demand vary at any time. Also, this study only assesses the impact of water availability basically at the annual time step from the diversion project perspective. Suggested follow-up directions include (1) determining the target from a shortened time scale; (2) considering more uncertainties for more reliable impact analysis such as population, and industrial expansion as well as better simulating the future climate change through hydrological models and General Circulation Models; (3) conducting a more comprehensive tradeoffs analysis by fully considering social, economic, and environmental benefits and losses; and (4) establishing the optimal real-time system considering both water diversion from the water source area as well as the water distribution in the water recipient area to better achieve integrated water resources regulation and water supply.

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DECLARATION OF COMPETING INTEREST

The author declares that no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

- Arunkumar, R. & Jothiprakash, V. 2017 Optimal crop plans for a multi-reservoir system having intra-basin water transfer using multi-objective evolutionary algorithms coupled with chaos. *Computers and Electronics in Agriculture* **140**, 34–47.
- Becker, N. & Easter, K. W. 1995 Water diversions in the great lakes basin analyzed in a game theory framework. *Water Resources Management* **9** (3), 221–242.
- Bocchini, P., Frangopol, D. M., Ummenhofer, T. & Zinke, T. 2013 Resilience and sustainability of civil infrastructure: toward a unified approach. *Journal of Infrastructure Systems* **20** (2), 04014004.
- Chang, J. X., Wang, Y. M. & Huang, Q. 2011 Water dispatch model for middle route of a South-to-North Water Transfer Project in China. *JAWRA Journal of the American Water Resources Association* **47** (1), 70–80.
- Davies, B. R., Thoms, M. & Meador, M. 1992 An assessment of the ecological impacts of inter-basin water transfers, and their threats to river basin integrity and conservation. *Aquatic Conservation: Marine and Freshwater Ecosystems* **2** (4), 325–349.
- Fang, G., Zhu, X. & Huang, X. 2019 Risk analysis of floodwater resources utilization along water diversion project: a case study of the Eastern Route of the South-to-North Water Diversion Project in China. *Water Supply* **19** (8), 2464–2475.
- Getches, D. H. 2003 Spain's Ebro river transfers: test case for water policy in the European Union. *International Journal of Water Resources Development* **19** (3), 501–512.
- Giudice, D. D., Muenich, R. L., Kalcic, M. M., Bosch, N. S., Scavia, D. & Michalak, A. M. 2018 On the practical usefulness of least squares for assessing uncertainty in hydrologic and water quality predictions. *Environmental Modelling & Software* **105**, 286–295.
- Gude, V. G. 2018 Desalination of deep groundwater aquifers for freshwater supplies—Challenges and strategies. *Groundwater for Sustainable Development* **6**, 87–92.
- Haasnoot, M., Middelkoop, H., Van Beek, E. & Van Deursen, W. P. A. 2011 A method to develop sustainable water management strategies for an uncertain future. *Sustainable Development* **19** (6), 369–381.
- Haines, Y. Y., Matalas, N. C., Lambert, J. H., Jackson, B. A. & Fellows, J. F. 1998 Reducing vulnerability of water supply systems to attack. *Journal of Infrastructure Systems* **4** (4), 164–177.
- Hosseini-Moghari, S. M., Morovati, R., Moghadas, M. & Araghinejad, S. 2015 Optimum operation of reservoir using two evolutionary algorithms: imperialist competitive algorithm (ICA) and cuckoo optimization algorithm (COA). *Water Resources Management* **29** (10), 3749–3769.
- Kumar, R., Singh, R. D. & Sharma, K. D. 2005 Water resources of India. *Current Science* **89** (5), 794–811.

- Li, Y., Xiong, W., Zhang, W., Wang, C. & Wang, P. 2016 Life cycle assessment of water supply alternatives in water-receiving areas of the South-to-North Water Diversion Project in China. *Water Research* **89**, 9–19.
- Lund, J. R. & Guzman, J. 1999 Derived operating rules for reservoirs in series or in parallel. *Journal of Water Resources Planning and Management* **125** (3), 143–153.
- Ma, Y., Chang, J., Guo, A., Wu, L., Yang, J. & Chen, L. 2020 Optimizing inter-basin water transfers from multiple sources among interconnected River basins. *Journal of Hydrology* **590**, 125461.
- Matete, M. & Hassan, R. 2006 Integrated ecological economics accounting approach to evaluation of inter-basin water transfers: an application to the Lesotho Highlands Water Project. *Ecological Economics* **60** (1), 246–259.
- Mehboob, M. & Kim, Y. 2021 Effect of climate and socioeconomic changes on future surface water availability from mountainous water sources in Pakistan's Upper Indus Basin. *Science of the Total Environment* **769** (15), 144820.
- Ming, B., Liu, P., Chang, J., Wang, Y. & Huang, Q. 2017 Deriving operating rules of pumped water storage using multiobjective optimization: case study of the Han to Wei Interbasin Water Transfer Project, China. *Journal of Water Resources Planning and Management* **143** (10), 05017012.
- Mohammadrezapour, O., Yoosefdoost, I. & Ebrahimi, M. 2019 Cuckoo optimization algorithm in optimal water allocation and crop planning under various weather conditions (case study: Qazvin plain, Iran). *Neural Computing and Applications* **31** (6), 1879–1892.
- Moore, S. M. 2014 Modernisation, authoritarianism, and the environment: the politics of China's South–North Water Transfer Project. *Environmental Politics* **23** (6), 947–964.
- Murata, T., Ishibuchi, H. & Tanaka, H. 1996 Multi-objective genetic algorithm and its applications to flowshop scheduling. *Computers and Industrial Engineering* **30** (4), 957–968.
- Nguyen, T. T., Vo, D. N. & Truong, A. V. 2014 Cuckoo search algorithm for short-term hydrothermal scheduling. *Applied Energy* **132**, 276–287.
- Peng, Y., Chu, J., Peng, A. & Zhou, H. 2015 Optimization operation model coupled with improving water-transfer rules and hedging rules for inter-basin water transfer-supply systems. *Water Resources Management* **29** (10), 3787–3806.
- Portoghese, I., Giannoccaro, G., Giordano, R. & Pagano, A. 2021 Modeling the impacts of volumetric water pricing in irrigation districts with conjunctive use of surface and groundwater resources. *Agricultural Water Management* **244**, 106561.
- Roozbahani, A., Ghased, H. & Shahedany, M. H. 2020 Inter-basin water transfer planning with grey COPRAS and fuzzy COPRAS techniques: a case study in Iranian Central Plateau. *Science of the Total Environment* **726** (15), 138499.
- Sadegh, M., Mahjouri, N. & Kerachian, R. 2010 Optimal inter-basin water allocation using crisp and fuzzy Shapley games. *Water Resources Management* **24** (10), 2291–2310.
- Salehi, M. 2022 Global water shortage and potable water safety; today's concern and tomorrow's crisis. *Environment International* **158**, 106936.
- Shamshirband, S., Amirmojahedi, M., Gocić, M., Akib, S., Petković, D., Piri, J. & Trajkovic, S. 2015 Estimation of reference evapotranspiration using neural networks and cuckoo search algorithm. *Journal of Irrigation and Drainage Engineering* **142** (2), 04015044.
- Smakhtin, V., Ashton, P., Batchelor, A., Meyer, R., Murray, E., Barta, B., Bauer, N., Naidoo, D. & Terblanche, D. 2001 Unconventional water supply options in South Africa: a review of possible solutions. *Water International* **26** (3), 314–334.
- Steinschneider, S. & Brown, C. 2012 Dynamic reservoir management with real-option risk hedging as a robust adaptation to nonstationary climate. *Water Resources Research* **48** (5), 106561.
- Tsai, W. P., Cheng, C. L., Uen, T. S., Zhou, Y. & Chang, F. J. 2019 Drought mitigation under urbanization through an intelligent water allocation system. *Agricultural Water Management* **213**, 87–96.
- Tso, G. K. & Yau, K. K. 2007 Predicting electricity energy consumption: a comparison of regression analysis, decision tree and neural networks. *Energy* **32** (9), 1761–1768.
- United Nations (UN) 2015 *Transforming our World: the 2030 Agenda for Sustainable Development*.
- Vieira, F. & Ramos, H. M. 2008 Hybrid solution and pump-storage optimization in water supply system efficiency: a case study. *Energy Policy* **36** (11), 4142–4148.
- Wang, Y., Yang, J. & Chang, J. 2019 Development of a coupled quantity-quality-environment water allocation model applying the optimization-simulation method. *Journal of Cleaner Production* **213**, 944–955.
- Wu, L., Bai, T. & Huang, Q. 2020 Tradeoff analysis between economic and ecological benefits of the inter-basin water transfer project under changing environment and its operation rules. *Journal of Cleaner Production* **248**, 119294.
- Xu, J., Ma, N. & Lv, C. 2016 Dynamic equilibrium strategy for drought emergency temporary water transfer and allocation management. *Journal of Hydrology* **539**, 700–722.
- Yang, X. S. & Deb, S. 2009 *Cuckoo Search via Lévy Flights*. IEEE Publications, USA.
- Yang, Y., Li, G. M., Dong, Y. H., Li, M., Yang, J. Q., Zhou, D., Yang, Z. S. & Zheng, F. D. 2012 Influence of South to North Water Transfer on groundwater dynamic change in Beijing plain. *Environmental Earth Sciences* **65** (4), 1323–1331.
- Yang, J., Wang, Y., Chang, J., Yao, J. & Huang, Q. 2016 Integrated assessment for hydrometeorological drought based on Markov chain model. *Natural Hazards* **84** (2), 1137–1160.
- Yang, J., Chang, J., Wang, Y., Li, Y., Hu, H., Chen, Y., Huang, Q. & Yao, J. 2018 Comprehensive drought characteristics analysis based on a nonlinear multivariate drought index. *Journal of Hydrology* **557**, 651–667.

- Yu, M., Wang, C., Liu, Y., Olsson, G. & Wang, C. 2018 Sustainability of mega water diversion projects: experience and lessons from China. *Science of the Total Environment* **619**, 721–731.
- Zeng, X., Hu, T., Guo, X. & Li, X. 2014 Water transfer triggering mechanism for multi-reservoir operation in inter-basin water transfer-supply project. *Water Resources Management* **28** (5), 1293–1308.
- Zhao, P., Li, Z., Zhang, R., Pan, J. & Liu, Y. 2020 Does water diversion project deteriorate the water quality of reservoir and downstream? a case-study indanjiangkou reservoir. *Global Ecology and Conservation* **24**, e01235.
- Zhao, S., Liu, W., Zhu, M., Ma, Y. & Li, Z. 2021 A priority-based multi-objective framework for water resources diversion and allocation in the middle route of the South-to-North Water Diversion Project. *Socio-Economic Planning Sciences* **78**, 101085.
- Zhu, X., Zhang, C., Yin, J., Zhou, H. & Jiang, Y. 2013 Optimization of water diversion based on reservoir operating rules: analysis of the Biliu River reservoir, China. *Journal of Hydrologic Engineering* **19** (2), 411–421.
- Zhu, X., Zhang, C., Fu, G., Li, Y. & Ding, W. 2017 Bi-Level optimization for determining operating strategies for inter-basin water transfer-supply reservoirs. *Water Resources Management* **31** (14), 4415–4432.
- Zhuang, W. 2016 Eco-environmental impact of inter-basin water transfer projects: a review. *Environmental Science and Pollution Research* **23** (13), 12867–12879.

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