



Hydrological Response and Ecological Flow Optimization in Water Diversion Area of Inter-basin Water Diversion Project

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Abstract

This article investigates the hydrological response and ecological flow in the diversion area from the Hanjiang River to the Weihe River. Quantifies the impact of the inter-basin diversion project on the hydro-ecological environment of the downstream river. MIKE BASIN is initially utilized in this research to create the multi-year reservoir operating model of Sanhekou Reservoir. Then Indicators of Hydrologic Alteration (IHA) and Range of Variability Approach (RVA) are used to evaluate the change degree of hydrological indicators. Secondly, set seven different ecological flow process schemes considering ecological demand and inter-annual wetness and dryness variability. Finally, evaluate the optimization scheme by Analytic Hierarchy Process (AHP). According to the hydrological response results, suggestions are put forward from the perspective of engineering and non-engineering. The results show that the simulation results of the MIKE BASIN have a high degree of fitting with the design results, which verifies the rationality of the model. Under the design scheme, the overall hydrological change of the river is 72.91% and the hydrological response of the river is high changed. Scheme 6 can reduce the overall hydrological change to (56.63%) moderate change under the premise of less impact on economic benefits, and scheme 6 is the optimal scheme. The research results not only guarantee the ecological function of the river but also provide guidance and reference significance for the actual operation of the reservoir.

Keywords Hydrological response · Ecological flow · Hydrological indicators · Reservoir scheduling · Hanjiang River to Weihe River inter-basin water transfer project

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1 Introduction

The large-scale development of urbanization and industrialization intensifies the contradiction of water shortage. This series of problems caused by water shortage seriously threaten the sustainable development of the regional economy and the virtuous cycle of the ecological environment. Human beings develop water resources by constructing large-scale water conservancy projects upstream of rivers to reduce the economic losses caused by water shortage. On the one hand, as critical engineering, the development of these reservoirs has successfully relieved the water shortage, enhanced the efficiency of water resource usage, and delivered considerable advantages. On the other hand, it is difficult to guarantee the seasonal ecological basic flow, and the diversity of river species is seriously damaged (Han 2014; Cui et al. 2014; Zhang 2017).

Exploring the impact of a dam built and operation on river channel ecology is a hot issue studied abroad. By evaluating the indicators in IHA, they found that hydrological indicators of the river have generally changed more than moderate changes. For instance, the trend of annual extreme flow change (Costigan et al. 2012; Ashraf et al. 2016; Liu 2019; Cui et al. 2020), Changes in natural runoff patterns due to changes in monthly average flow (Al-Farajet and Scholz 2014; Li et al. 2020; Hunt et al. 2020), change of connectivity and related ecological service functions caused by high and low flow pulses and seasonal law of flow downstream (Ibraitim et al. 2015; Gao et al. 2018). Apart from this, there are other indicators beyond IHA indicators, for example, deterioration of water quality, disconnection of the river, and decrease of riparian vegetation outside rivers, phytoplankton and fish community biodiversity in the river channel (Natália et al. 2018; Oscar et al. 2013; Swapan and Swades 2019; Romero et al. 2021).

Domestic scholars have done massive research on the impact of water conservancy projects in different basins to explore the influence on river ecology. The findings show that the construction and maintenance of water conservation projects will have a negative impact on the river ecosystem. For example, after the completion of the Jinjiang Reservoir, ecological flow in the Jinjiang river fell and caused drying days to rise in the downstream channel (Chen et al. 2015). The hydrological situation in the Three Outlets of Jingjiang river changed after the Three Gorges Project was built and operated, such as decreased outflow downstream, shorted flood season, and reduced day maximum flow (Gao et al. 2020). The Three Gorges Dam has changed the ecological and hydrological conditions, thus adversely affecting the spawning and reproduction of four common fish species (Guo et al. 2018). The storage of Danjiangkou Dam increases the flow of the downstream river in the dry season and decreases the flow in the wet season. Climate change leads to the reduction of rainfall, the reduction of monthly average flow and annual maximum flow in each month, and the increase of the number of low flow pulses. Affected by backwater, the monthly average flow and annual minimum flow rate of Huangjiagang Hydrological Station located downstream of Danjiangkou Dam increase (Ban et al. 2020).

Reservoirs must release the appropriate ecological flow within a particular time and space to prevent or relieve the negative impact of water conservancy construction and operation on river ecology. However, at present, the vast majority of reservoir operation schemes only meet the minimum ecological base flow of the river and lack the consideration of natural runoff response and ecologic demand. In summary, the Hanjiang-to-Weihe River Diversion Project has definite ecological base flow requirements for ecological environment water use, but it lacks relevant scientific and technical support. Therefore, studying hydrological response and ecological flow optimization of rivers in the water transfer

area of the inter-basin water transfer project has important theoretical significance and application value.

2 Study Area and Data

2.1 Study Area

As critical basic engineering to alleviate the shortage of water resources and improve the utilization efficiency of water resources in Shaanxi Province, the construction of the inter-basin water transfer project from Hanjiang to Weihe is not only of great significance to promoting the economic and social development of Shaanxi Province, but also has a profound impact on the ecological and environmental protection of the province. Sanhekou Reservoir is operated independently in the early stages of the Hanjiang-to-Weihe Inter-basin water diversion project to optimize the economic advantages. The main task of the reservoir is water supply, followed by power generation. The hydropower station adopts the power generation mode of determining electricity by water, which mainly uses the water supply, ecological water, and the water head between the dam and the tail water level of the hydropower station. At the same time, the reservoir also carries out the task of ecological water intake downstream. Taking the Ziwu River basin, a tributary of the Hanjiang River, as the study area, this paper analyzes the influence of the initial operation of the project on the hydrological process in the Ziwu river basin. Ziwu River is between $N33^{\circ}18' \sim N33^{\circ}44'$ and $E107^{\circ}51' \sim E108^{\circ}30'$ and belongs to a major tributary of the northern bank of the upper Hanjiang River (Fig. 1).

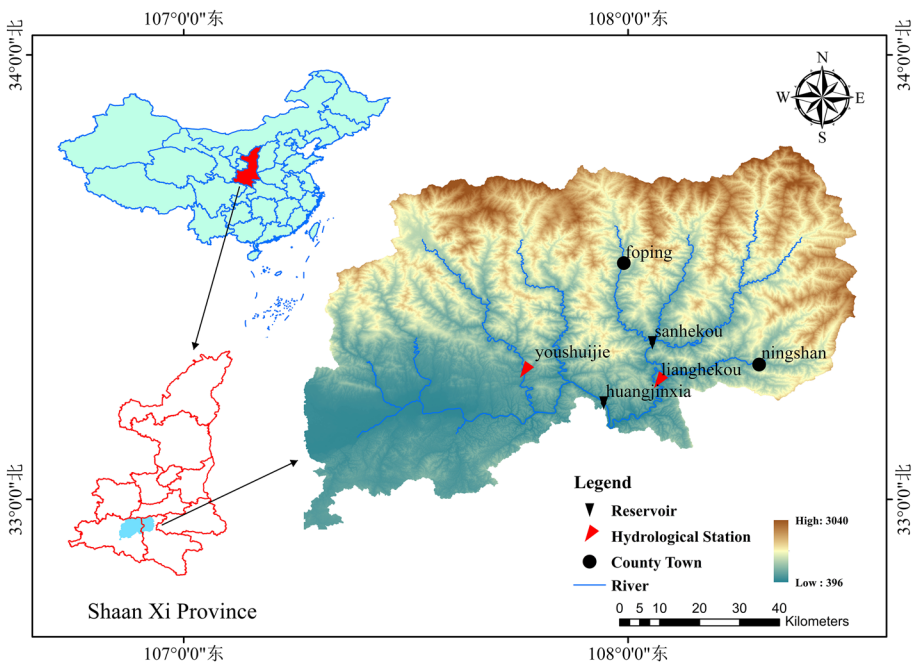


Fig. 1 The distribution diagram of reservoirs and hydrological stations in the water diversion area of Hanjiang to Weihe inter-basin water transfer project

Ziwu river is subordinate to Ningshan county and Foping County, with a river length of about 160 km and a watershed control area of more than 3000 square kilometers. Ziwu river has many tributaries, the most important of which are the Wenshui River, Pujiang River, and Jiaoxi River. The reservoir dam site locates 2 km downstream from the confluence of three tributaries.

2.2 Study Data

Data required for this paper include reservoir power station data, runoff data, and water demand data. Reservoir power station data includes characteristic parameters of the Sanhekou Water Control Project in the Ziwu River Basin. This paper collects the daily measured flow data of the Lianghekou hydrological station. Since there is no hydrological station in Sanhekou Reservoir, this paper used the area analogy method to obtain the daily discharge series of the dam site from 1964 to 2013. The supply and demand of water resources in the initial operation of the Hanjiang-to-Weihe River Basin Water Diversion Project is relatively simple, mainly including water supply in the receiving area and ecological water demand in the downstream river. Wherein receiving area water supply for industrial and living water, water demand is more stable, therefore, can be satisfied by equal-delivery. According to planning, the ecological water demand of downstream rivers designs 10% of the annual average runoff, which is $2.71\text{m}^3/\text{s}$. The data are as follows in Tables 1 and 2, and the technical route is shown in Fig. 2.

3 Methodology

3.1 MIKE BASIN Model

MIKE BASIN is a mathematical simulation software developed by the Danish Hydraulic Institute (DHI) for water resources distribution and water resources supply and demand balance affected by spatial and temporal factors on the basin scale. Based on the existing digital basin elevation map (DEM), the model can automatically generate channels, construct river networks, and divide sub-basins by adding reservoir performance, river network tracking, scheduling rules, and water users. Simulation of water resources distribution in a watershed using the steady water balance equation. Water balance is the core calculation program, and water balance calculation formulas are usually different in different scales and regions.

Table 1 Date information

Data category	Runoff data
Data source	Sanhekou Hydrological Station
Data type	Runoff
Length of time	1964–2013
Time scale	Day
Data format	Site data

Table 2 Characteristic parameters of Sanhekou water conservancy project

Reservoir	Dead water level (m)	Normal high water level (m)	Adjust storage capacity ($10^8 m^3$)	Regulating storage	Installed capacity (MW)	Regulation ability
Sanhekou	558	643	6.49	7.10	60	Multi-year

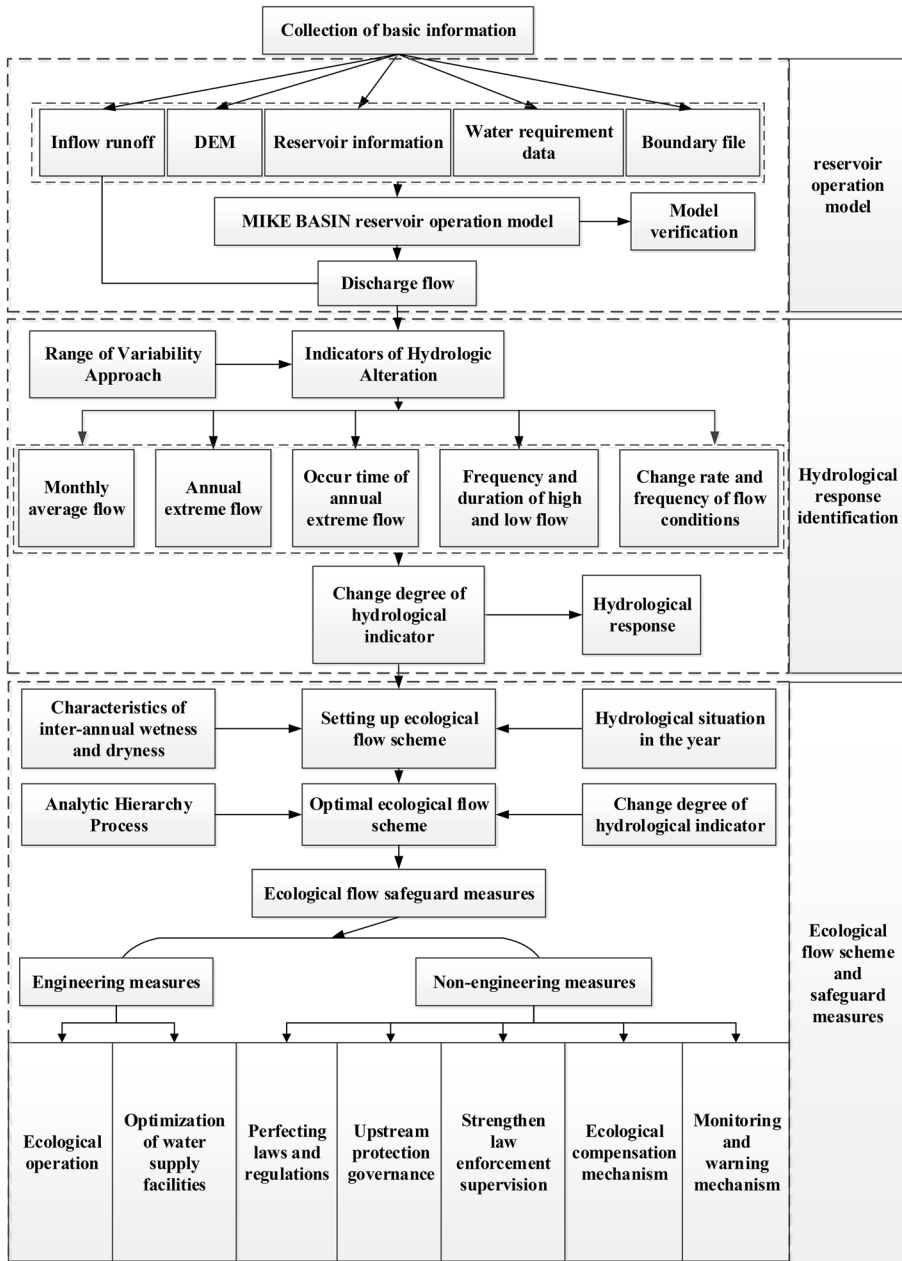


Fig. 2 Technology roadmap

For closing watersheds without inter-basin water transfer, the water balance formula is:

$$P = ET + R + \Delta S \tag{1}$$

In formula: P represents rainfall in the basin; ET represents vertical evapotranspiration; R represents the sum of lateral surface water and groundwater outflows; ΔS represents the sum of changes in soil water, surface water, and groundwater storage.

MIKE BASIN provides two benefits over the classic reservoir optimum operation model. (1) MIKE BASIN considers not only the influence of time factors but also the influence of spatial factors, which is suitable for case studies on different time scales (years, months, days, hours, et al.) and spatial scales (basins, water users, nodes, rivers). (2) MIKE BASIN has powerful functions such as result display, data interaction, and portability.

In the actual model construction, select modules and attributes according to the characteristics of the basin and water demand. Up to now, MIKE BASIN has been used to solve water resources allocation and reservoir operation cases in multiple basins (e.g., Li 2013; Zhang and Shan 2019; Qi et al. 2018; Meng et al. 2014; Liu et al. 2021; Lu 2016; Kumar et al. 2018; Hassaballah et al. 2012). In this study, the MIKE BASIN scheduling model of the Ziwu River basin establishes based on MIKE software.

3.2 Verification of MIKE BASIN Model

So far, the Sanhekou reservoir has not been officially put into operation. According to the initial reservoir operation process in the design report, simulation results of the MIKE BASIN model are as consistent as possible with the design process through multiple operation models, parameter adjustment, and optimization. Finally, the parameters of the MIKE BASIN operation model of Sanhekou Reservoir are determined and selected. This article assembles measured runoff data from 1964 to 2014. This article used wavelet analysis to do a multi-time scale analysis of input runoff series in Sanhekou Reservoir. The findings reveal that the middle periodic of the observed runoff series is six years. Different periods of runoff change trend is the same, does not affect the simulation results, only verify the fitting degree of the design value and simulation value. Therefore, this article selects the measured runoff process from 1964 to 1969, and compares the water level change process, ecological water discharge process, and water supply process of the Sanhekou reservoir simulation and design report, as shown in Figs. 3, 4 and 5.

From Figs. 3, 4 and 5, it is clear that the simulation results of MIKE BASIN and the design results are consistent with the trend of change, and the model better simulates the dynamics of water resources change at the early stage of reservoir operation. Further

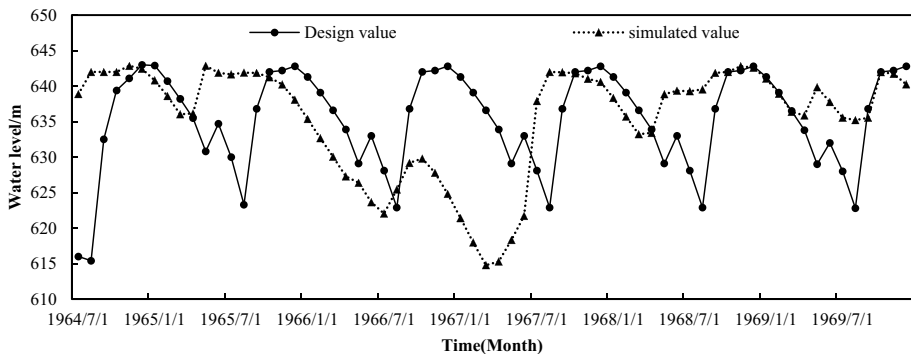


Fig. 3 Sanhekou Reservoir simulation water level and design water level process line

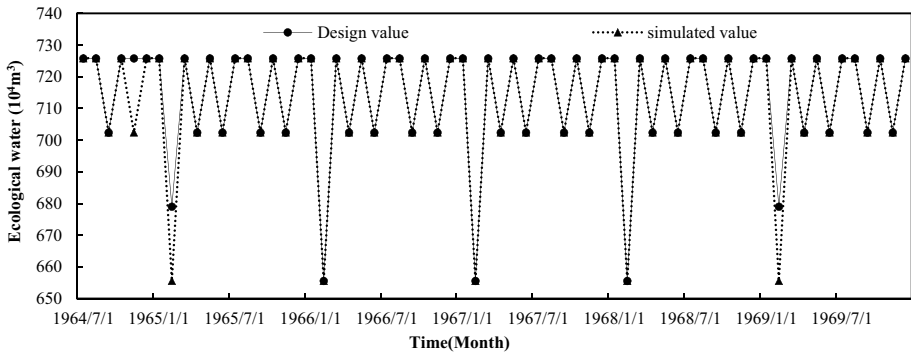


Fig. 4 Sanhekou Reservoir simulation ecological water quantity and design ecological water quantity process line

calculations show that the multi-year average error of the water level process is 1.21%, the multi-year average error of ecological water volume of discharge is 0.15%, and the multi-year average error of water supply is 0.38%. The results show that the simulation results of the MIKE BASIN model fit the design results very well. The rationality of the model is satisfied, and the model can be used for ecological effect evaluation and calculation.

3.3 Ecological Effect Evaluation Method

3.3.1 IHA Method

As the core factor guarantee the health and integrity of water ecosystems such as rivers and lakes, the hydrological situation determines the biological composition of the water ecosystem to a certain extent. Community structure and ecological function. Hydrological situation research generally needs to be characterized by specific hydrological indicators. The qualitative or quantitative description of hydrological situation indicators is a crucial content of ecological hydrological process research. So far, scholars at home and abroad have done a lot of research on the impact of human activities on the hydrological situation. A series of indicators are selected to characterize hydrological changes. On this basis, summarize 33 hydrological change indicators (IHA, Indicators of Hydrologic Alteration). The above indicators can be divided into five groups according to the monthly average flow,

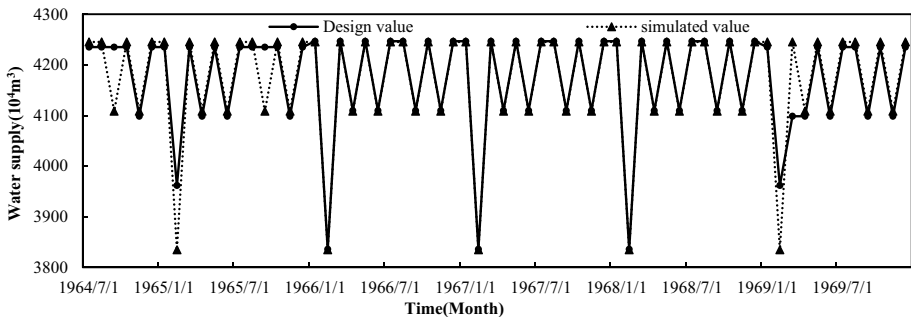


Fig. 5 Sanhekou Reservoir simulation water supply and design water supply process line

annual extreme flow, occur time of annual extreme flow, frequency and duration of high and low flow, and change rate and frequency of flow conditions to evaluate the changes in river hydrological situation before and after the impact of human activities. At the same time, based on a large amount of field monitoring data, the response relationship between indicators and river ecosystems is summarized as shown in Table 3. (Richter et al. 1996). Hydrological change indicators affect the structure and function of the ecosystem, reflecting the degree of change in the ecological environment before and after activities.

3.3.2 RVA Method

To calculate the change degree of each hydrological indicator in IHA. The Range of Variability Approach (RVA) proposes based on IHA (Richter et al. 1997). The RVA method is based on the analysis of the IHA index to quantify the change in the indicators. Assess river hydrological changes affected by human activities and provide comprehensive ecological statistical characteristics related to river system flow. The RVA method can provide reference value and data support for quantifying the degree of river hydrological change caused by reservoir construction in water diversion areas. RVA requires high accuracy of runoff series and generally requires daily runoff data of more than 20 years. Calculate the IHA indicator before reservoir construction and divide the sorting percentage of each indicator into three intervals: R1 = [0,25%], R2 = [25%,75%], and R3 = [75%,100%], R2 is also called RVA threshold as the interval to meet ecological needs. Sort out the runoff process acquired from the MIKE BASIN model and calculate the 33 IHA indicators before and after reservoir construction. Compare the frequency that the IHA flow indicator falls within the RVA range before and after reservoir construction. If most of the flow indicator values fall within the RVA threshold after the reservoir construction, it indicates that the change range of the river hydrological regime is acceptable. On the contrary, it shows that the building of the reservoir has a detrimental effect on the ecological environment.

Richter et al. proposed an evaluation method that can quantify the change degree of hydrological indicators. The specific changes of each hydrological indicator are as follows:

$$D_i = \left| \frac{N_i - N_0}{N_0} \right| \times 100\% \quad (2)$$

$$N_0 = rN_T \quad (3)$$

where: D_i indicates the degree of change of the i th hydrological indicator; N_i and N_0 indicate the number of years after reservoir construction when the IHA indicator falls within the RVA threshold and the number of years when the IHA indicator falls within the RVA threshold as expected, respectively; r indicates the proportion of years before the construction that the IHA falls within the RVA threshold; and N_T indicates the total number of years affected.

Richter set an objective judgment standard for the change degree of hydrological indicators. The standards are as follows: $0 \leq D_i < 33\%$ indicates the low change in the hydrological indicator; $33\% \leq D_i < 67\%$ represents moderate changes in the hydrological indicator; $67\% \leq D_i < 100\%$ represents high changes in the hydrological indicator.

Based on the degree of change of each indicator D_i , the overall degree of change of the hydrological indicators after the change (D_0) is calculated as follows:

Table 3 IHA indicator System and Its Ecological Significance

IHA Group (33 indicators)	Content	Ecological Implications
Monthly average flow (12 indicators)	Average of monthly flow	Aquatic habitat range; soil moisture required for plant growth; drinking water for terrestrial organisms; migration demand of carnivores; Food for life in mammals; Influence of water temperature, dissolved oxygen, and photosynthesis in water
Annual extreme flow (12 indicators)	Annual minimum flow on 1-day, 3-day, 7-day, 30-day and 90-day of year Annual maximum flow on 1-day, 3-day, 7-day, 30-day and 90-day of year	satisfying vegetation expansion; Biological competition and tolerance balance; constructing river channel landform; Form natural habitat; pressure on anaerobic plants; Duration of poor water environment; the Nutrient exchange between rivers and floodplains; The demand of community distribution in lakes, ponds, and floodplains;
Occur time of annual extreme flow (2 indicators)	Date of annual 1-day maximum flow Date of annual 1-day minimum flow	Provide a natural life cycle for all kinds of fish that need to swim back to spawn and cycle reproduction; habitat requirements during biological reproduction; Diachronic exchange of life
Frequency and duration of high and low flow (4 indicators)	Days of annual high flow Days of annual low flow High annual flow duration Annual low flow duration	Frequency and scale of soil moisture required by plants; Support water bird habitat; meeting the needs of sediment transport in flood areas and rivers; Nutrition and organic matter exchange between rivers and flood areas
Change rate and frequency of flow conditions (3 indicators)	Average increase rate of flow Average decrease rate of flow Annual fluctuation times	Plant drought stress; Low-speed organism drought stress; Encouraging organic trapping on islands and floodplains

$$D_o = \sqrt{\frac{1}{3} \sum_{i=1}^{33} D_i^2} \tag{4}$$

The overall degree of change of hydrological indicators definition: If $0 \leq D_o < 33\%$, the overall is a low change or no change; $33 \leq D_o < 67\%$, the overall is moderate change; $67\% \leq D_o < 100\%$, the overall is high change.

3.4 Ecological Flow Scheme Setting

Sanhekou Reservoir locates in the middle valley of the Ziwu River at the junction of Foping County and Ningshan County, Shaanxi Province. Runoff at the dam site includes three tributaries of Wenshui River, Pu River, Jiaoxi River, and slope overland flow. After built of Sanhekou Reservoir, downstream discharge is directly affected by the reservoir regulation. The flow sequence can reflect the flow variation of the river section below the dam site. At the same time, considering the current situation that the reservoir has not yet been in operation, this article takes the dam site as the representative section to analyze Ziwu river downstream runoff variation law before and after the reservoir was built. The day runoff process at the dam site from 1964 to 2013 takes as the runoff process before the reservoir construction and taking reservoir discharge process simulated by MIKE BASIN software as the ecological flow process after reservoir construction in the design scheme. The process of reservoir inflow and outflow is shown in Fig. 6.

As can be seen from Fig. 6: the maximum flow rate before the construction of the reservoir is 1532.30 m³/s, and the minimum flow rate is 0.47 m³/s. The maximum flow rate after reservoir construction is 1516.45 m³/s, and the minimum flow rate is 2.71 m³/s, which satisfies the minimum ecological flow constraint. From the inter-annual scale, the flow is less volatile after the construction of the reservoir than before. The multi-year regulating capacity of the reservoir plays the role of storing abundant and replenishing dryness. The reason is that the reservoir meets the water supply guarantee rate to implement a smooth water supply process, and the non-flood season follows the ecological water demand flow.

River ecological flow in the current operating scheme is 10% (2.71 m³/s) of the annual average flow. The results of the IHA-RVA method show that under this scheme, the hydrological indicator of downstream river changes is high. According to earlier

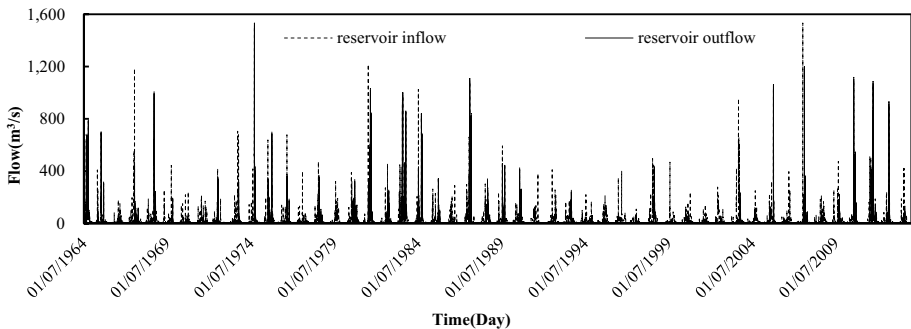


Fig. 6 Sanhekou Reservoir inflow runoff and outflow runoff

research on the ecological flow of the Ziwu River (Li et al. 2017; Chang et al. 2007), the existing ecological flow plan includes the following glaring flaws and defects:

1. The overall ecological flow is relatively small.
2. Ecological flow does not reflect changes in different periods of the year.
3. The ecological flow does not reflect the inter-annual abundance and dryness characteristics.

Numerous studies have revealed that the stability of river ecosystems and species reproduction have varying needs for hydrological processes at different times of the year. When calculating ecological flow, we should fully reflect the characteristics of the river hydrological process (Kang et al. 2010). At the same time, different frequencies of annual flow correspond to different river health standards. For example, 10% of an annual flow corresponds to flow degradation or barren conditions (Xu et al. 2003).

Up to now, ecological flow calculation methods include habitat method, integral method, hydraulic method, and hydrology method. This article uses the hydrological method to calculate the ecological flow of rivers. At the same time, taking into account that the runoff time scale of this study is the day, the article uses the multi-year daily discharge data frequency method to calculate (Yang et al. 2013). The calculation idea is to arrange the frequency of daily flow data for many years and select different frequencies in different periods.

To ensure the ecological health and biological reproduction of rivers, the flow requirements of rivers are different at different stages between and within years. When designing the ecological flow, it should fully reflect the characteristics of inter-annual wetness-dryness variation of river hydrological processes and the demands of different stages within the year. Based on the above analysis, this article takes the design scheme as scheme 1, sets the ecological flow process as a fixed value, and sets multiple ecological flow scheduling schemes. Scheme 2~4 does not consider the characteristics of inter-annual wetness and dryness, and uses 90%, 80%, and 70% of annual flow frequency as ecological flow; Scheme 5~7, considering the characteristics of inter-annual wetness and dryness, sets different ecological flow for wetness and dryness years. The Scheme settings are shown in Table 4.

Table 4 Ecological flow scheme

Scheme	Ecological flow regime (m ³ /s)		
1	2.71		
Scheme	Frequency of multi-year daily traffic (%)		
2	90		
3	80		
4	70		
	Wet year ($P_e \geq 25\%$)	Median water year ($25\% > P_e > 75\%$)	Low flow year ($P_e \leq 75\%$)
5	70	80	90
6	60	80	90
7	60	70	90

4 Analysis of Results

Utilized the indicators in IHA to assess the overall change in hydrological indicators before and after reservoir building. Setting ecological flow scheme 2 to scheme 7, considering the various characteristics of wetness and dryness in different years, setting different daily flow frequencies, calculating and comparing the water supply, power generation, and ecological water guarantee rate of each scheme.

4.1 River Hydrological Response Analysis

Collect the runoff data by the MIKE BASIN model, and calculate the corresponding 33 IHA indicators. The hydrological change degree calculation formula (1) is selected to quantify the change degree of each indicator before and after reservoir building. The calculation results are shown in Table 5.

Before the construction of the reservoir, the average annual flow was 54.81 m³/s in flood season and 12.10 m³/s in non-flood season. After the establishment of the reservoir, the annual average flow in flood season is 26.03 m³/s, and that in non-flood season is 2.95 m³/s.

The changes in indicators for each group can be seen in Table 5.

1. Since the reservoir undertakes the water supply task of 500million m³ at the initial stage of the project, the average monthly flow decreases to varying degrees. Among them, the average monthly flow in flood season (July to October) changes moderately, and the average monthly flow in non-flood season (November to June of the next year) changes highly.
2. The 1-day and 3-day minimum flow show an increasing trend compared with that before construction. The 7-day, 30-day, and 90-day minimum flows show a decreasing trend compared with that before the construction of the reservoir. Indicating that the multi-year storage performance of the Sanhekou Reservoir has improved the minimum flows on the daily time scale but has limited effects on the minimum flows on the weekly, monthly, and seasonal time scales. There was no cutoff scenario before and after reservoir building, and the base flow indicator grew from 0.12 before to 0.51 after reservoir construction.
3. The minimum and maximum flows occurred earlier than before the reservoir was constructed, and the trend of decreasing maximum flows on different time scales did not change.
4. Except for basic flow, annual extreme flow and occurrence time show moderate or above changes. The occurrence times of low flow after reservoir construction are decreasing. But the average duration of low flow increases from 15.49 days before reservoir construction to 232.90 days after reservoir construction. The occurrence frequency of high flow rates after reservoir construction is also decreasing. High flow duration increased from 3.17 days before construction to 3.81 days after construction.
5. The average increase rate of flow increased from 19.73(m³/(s·d)) to 73.95(m³/(s·d)) after the building of the reservoir; the average flow reduction rate changed from -9.38(m³/(s·d)) to 28.46(m³/(s·d)) after reservoir built. Annual flow reversals decreased from 104.90 to 13.45 after the reservoir was constructed.

Table 5 Changes in IHA indicator before and after reservoir built

IHA Indicators	Before Built	After Built	RVA		Hydrological Variability (%)	Degree Of Change
			Upper Limit	Lower Limit		
The first group of indicators						
Monthly average flow in January	4.97	2.74	6.69	3.26	0.98	high
Monthly average flow in February	4.30	2.75	5.55	3.05	0.97	high
Monthly average flow in March	6.48	2.74	10.32	3.85	0.97	high
Monthly average flow in April	16.23	2.76	29.55	7.67	1.00	high
Monthly average flow in May	23.60	3.43	40.90	6.29	0.95	high
Monthly average flow in June	21.70	3.32	45.47	7.04	0.94	high
Monthly average flow in July	65.73	21.79	111.40	20.06	0.54	moderate
Monthly average flow in August	51.70	25.73	93.02	10.38	0.62	moderate
Monthly average flow in September	65.12	37.96	123.90	24.76	0.55	moderate
Monthly average flow in October	36.67	18.66	69.21	14.73	0.60	moderate
Monthly average flow in November	15.90	4.24	28.88	2.91	0.87	high
Monthly average flow in December	7.41	2.90	10.99	3.83	0.95	high
The second group of indicators						
1-day minimum flow	2.43	2.69	3.66	1.20	0.53	moderate
3-day minimum flow	2.61	2.70	3.84	1.37	0.58	moderate
7-day minimum flow	2.85	2.71	4.12	1.57	0.63	moderate
30-day minimum flow	3.56	2.74	4.78	2.33	0.44	moderate
90-day minimum flow	4.87	2.74	6.49	3.25	0.97	high
1-day maximum flow	588.60	388.30	964.90	212.40	0.45	moderate
3-day maximum flow	398.90	263.70	629.10	168.70	0.39	moderate
7-day maximum flow	253.30	170.10	397.70	108.90	0.34	moderate
30-day maximum flow	119.80	70.96	181.60	58.06	0.42	moderate

Table 5 (continued)

IHA Indicators	Before Built	After Built	RVA		Hydrological Variability (%)	Degree Of Change
			Upper Limit	Lower Limit		
The first group of indicators						
90-day maximum flow	69.39	33.97	104.90	33.88	0.57	moderate
Flow breaking days	0	0	0.00	0.00	0.00	low
Base-flow coefficient	0.12	0.51	0.17	0.06	0.60	moderate
The third group of indicators						
Minimum flow time	101.8	2.471	171.80	31.85	0.97	high
Maximum flow appearing time	226	157	258.00	193.90	0.35	moderate
The fourth group of indicators						
Number of low flow occurrences	7.27	2.24	11.79	2.74	0.47	moderate
Low flow average duration	15.49	232.90	30.28	6.13	0.97	high
Frequency of high flow	5.96	2.28	8.37	3.55	0.60	moderate
Average duration of high flow	3.17	3.81	4.47	1.87	0.41	moderate
The fifth group of indicators						
Average increase rate of flow	19.73	75.95	31.57	7.90	0.92	high
Average decrease rate of flow	-9.38	-28.46	-4.37	-14.39	0.92	high
Annual flow reversal times	104.90	13.45	130.00	79.81	1.00	high

significantly changed based on the operation of the designed scheduling scheme. Because the Sanhekou Reservoir is the largest constructed water conservancy project on the Ziwu River with a wide range of influence. The Sanhekou reservoir is a large water conservancy project dominated by water supply, which affects the discharge process to a large extent.

4.2 Change of Hydrological Indicators Under Each Scheme

4.2.1 Changes in Hydrological Indicators

The daily runoff data from 1964 to 2013 are taken as the daily runoff sequence before the construction of Sanhekou Reservoir. MIKE BASIN simulated the discharge process as the daily runoff sequence after the construction of the Sanhekou Reservoir and calculated the change degree of the IHA hydrological indicators in schemes 2–7.

1. Change in average monthly traffic

The monthly average flow change process of different schemes is shown in Fig. 8. The average flow of each month following reservoir construction indicates a decreased trend compared with before. The distribution of yearly inner diameter flow at the Sanhekou dam site is exceedingly irregular under natural conditions, with noticeable seasonal features. After the construction of the reservoir, the reservoir plays a role in regulation and storage, and the flow in flood season decreases significantly compared with that in non-flood season.

2. Annual extreme flow

The minimum and maximum flow processes of different schemes are shown in Figs. 9 and 10. With the increase in time scale, the minimum flow process shows an increasing trend, and the maximum flow process shows a decreasing trend, which is the same as the changing trend before the construction of the reservoir. Except for Scheme 2, the minimum 1-day flow and the minimum 3-day flow of each scheme are better than the natural runoff process. It shows that under this scheme, reservoir construction has a promotion

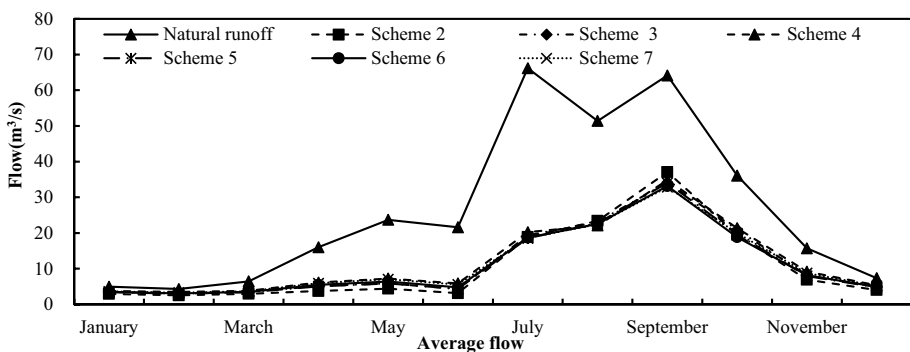


Fig. 8 The change process of monthly average traffic under different schemes after Sanhekou Reservoir operation

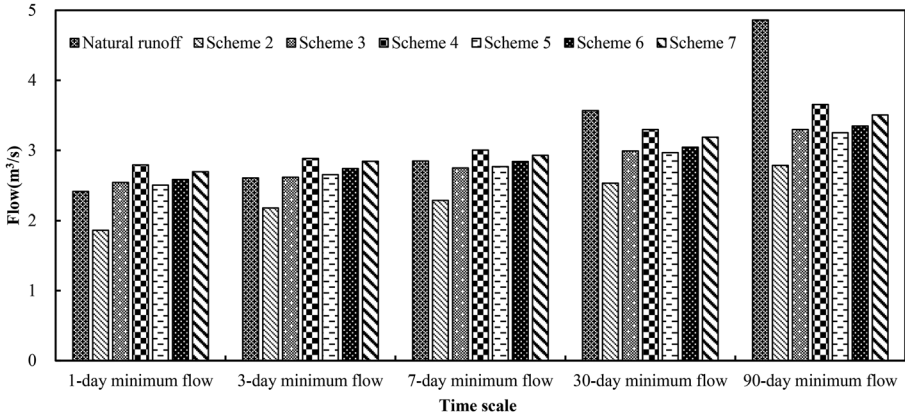


Fig. 9 Minimum flow change process under different schemes after Sanhekou Reservoir operation

and improvement effect on extremely low flow rate, but its effect on a large time scale is limited. The difference between minimum flow and natural runoff in each scheme group is small, and the difference between maximum flow and natural runoff is large.

3. Annual extreme flow occurrence time

The minimum flow occurrence time of each scheme is earlier than the natural runoff process before the construction of the reservoir, and each scheme has a moderate change. The maximum flow occurrence time of the schemes after the construction of the reservoir is not much different from the natural runoff process before the construction of the reservoir, and each scheme has a low degree of change. After the reservoir is built, the minimum flow of each scheme occurrence time is earlier than the natural runoff process before the construction of the reservoir and changes moderately. When compared to the natural runoff process before reservoir building, the occurrence time

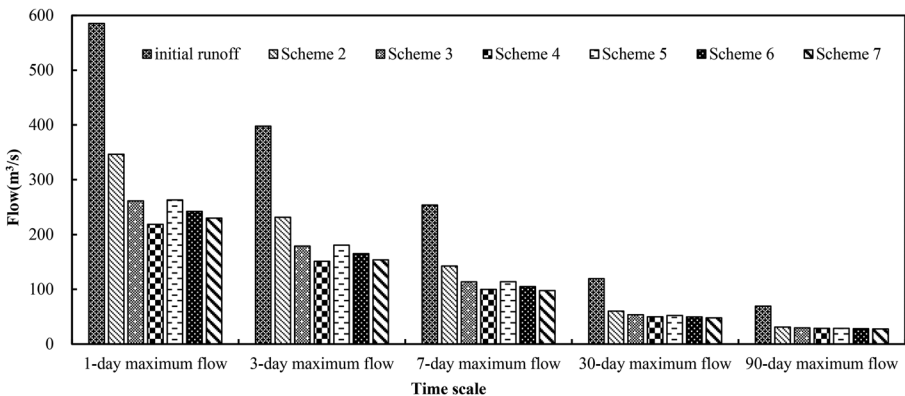


Fig. 10 Maximum flow change process under different schemes after Sanhekou Reservoir operation

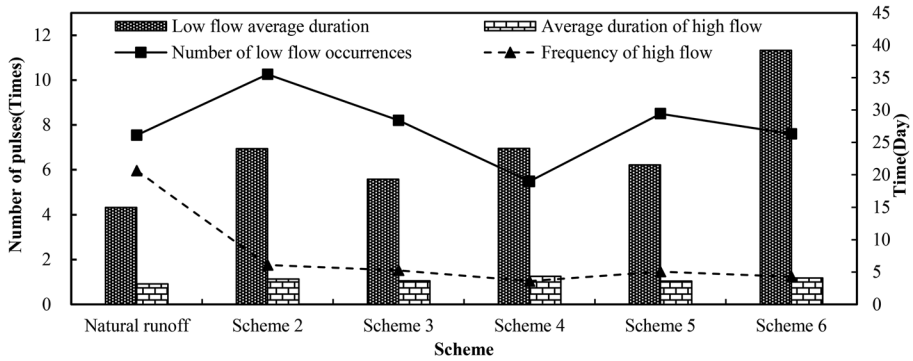


Fig. 11 Pulse flow indicators under different schemes after Sanhekou Reservoir operation

of the maximum flow of the scheme after reservoir construction is delayed, and a low degree of change occurs.

4. High and low flow indicators

It can be observed in Fig. 11 that the occurrence time of low flow varies with different schemes, but the average duration of low flow increases significantly. The occurrence frequency of high flow showed a significant decreasing trend, while the duration of high flow showed an increasing tendency.

5. Rate and frequency of change of water flow conditions

Figure 12 depicts the flow change rate, frequency change process, and hydrological change degree of several schemes. Compared with the natural state before reservoir building, the average growth rate and decline rate of the flow after reservoir construction indicate a reduction tendency, except for the moderate change of scheme 2, the other schemes have a high change degree.

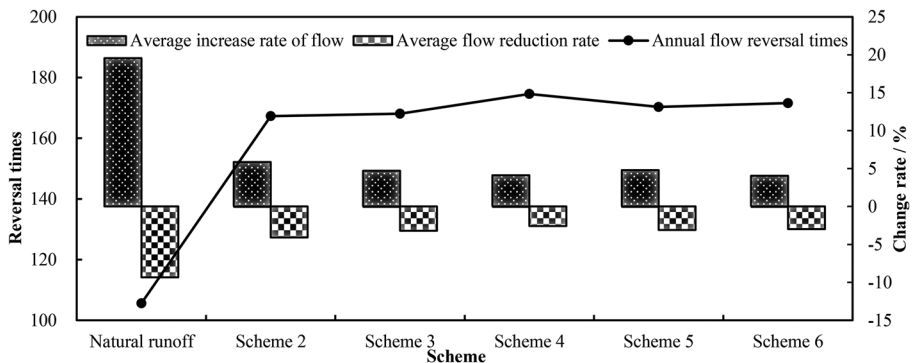


Fig. 12 Flow change rate under different schemes after Sanhekou Reservoir operation

4.2.2 Overall Change

Changes in 33 hydrological indicators of each scheme are summarized as shown in Fig. 13.

1. The construction of the reservoir has caused changes in the hydrological indicators of various schemes to varying degrees. Analyzing the features of 33 indicators across all schemes reveals a significant discrepancy in the variance of hydrological indicators across different ecological flow schemes. The fluctuation trend of hydrological indicators is inconsistent, showing that diverse ecological flow processes influence reservoir operating mode.
2. In all schemes, the high flow indicators (1-day, 3-day, 7-day, 30-day, and 90-day), the average increase rate of flow, the average decrease rate of flow, and the number of reversals all have moderate and high changes. It shows that different ecological flow schemes may face challenges in high flow regulation and flow change rate regulation.

4.3 Results Analysis of Ecological Flow Scheme

Count the number of changes in hydrological indicators in different schemes, and calculate the overall change degree of hydrological indicators in each scheme. From Table 6, we can see that the overall degree of hydrological alteration of Schemes 2 to 7 decreases in order, and the fluctuation range is between 0.53 and 0.66, which all belong to moderate alteration, compared with the high alteration of Scheme 1. The ecological flow of schemes 2–7 is substituted into the MIKE BASIN model, and the daily runoff data from 1964 to 2013 are selected in the warehousing process (Table 7). Table 7 shows the average annual water supply, average annual power output, and ecological water usage assurance rate under each dispatching strategy.

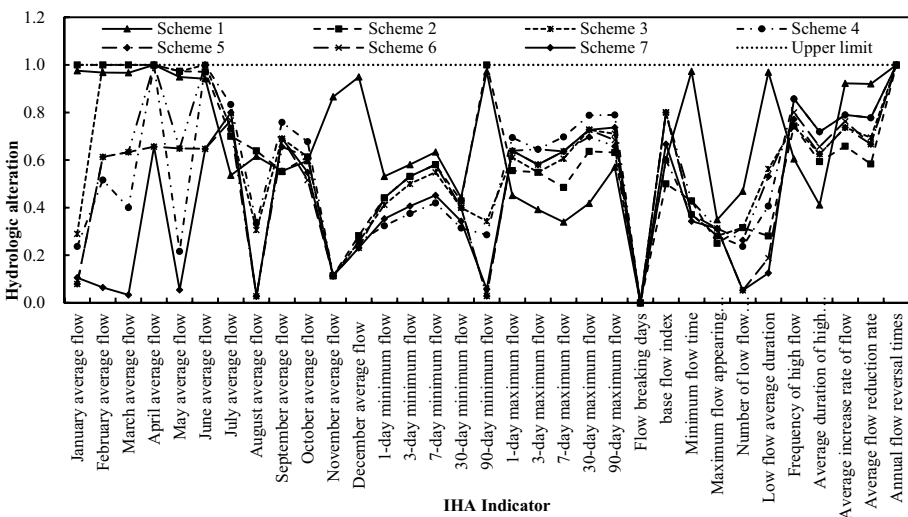


Fig. 13 IHA indicators change degree under different schemes after Sanhekou Reservoir operation

Table 6 Changes in hydrological indicators under different operating modes

Scheme	Indicator change number			Overall change/%	
	High	Moderate	Low		
2	10	17	6	66.42	Moderate
3	14	12	7	64.91	Moderate
4	14	8	11	60.19	Moderate
5	9	16	8	60.29	Moderate
6	8	17	8	56.63	Moderate
7	10	11	12	53.22	Moderate

As can be seen from Table 7: In terms of the average annual water supply, the guaranteed rate of water supply for Schemes 2 to 7 reservoirs is reduced, and the average annual water supply is less than the designed 500 million m³. Because according to the report, the design water demand at the beginning of the project is 500 million m³ per year, which is more stringent than the multi-year average of 500 million m³. However, except for Scheme 4, the guaranteed rate of water supply for all Schemes is above 90%, among which, the guaranteed rate of Scheme 2 is the highest and the guaranteed rate of Scheme 4 is the lowest. In terms of average annual power generation, the multi-year average power generation of each Scheme decreases compared to the design value, and the power generation of each Scheme fluctuates between 119 and 129 million kW·h. Compared to the design power generation, the power generation of Scheme 2 decreases by 2.18%, Scheme 3 decreases by 9.06%, Scheme 4 decreases by 9.65%, Scheme 5 decreases by 9.06%, and Scheme 6 decreases by 3.42%, and Scheme 3 decreases by 6.01%. In terms of ecological water guarantee rate, Scheme 2 is the highest, and Scheme 4 is the lowest.

4.4 Optimal Selection of Ecological Flow Schemes

The results show that there is a contradictory relationship between ecological dispatching and power generation and water supply. For example, power generation and water supply in Scheme 2 are the best in all schemes, but the degree of ecological change is the highest. The ecological change degree of Scheme 7 is the lowest, but the calculation result is not optimal. As a result, all affecting aspects must be thoroughly considered, and an appropriate scheme must be evaluated and chosen. Analytic Hierarchy Process (AHP)

Table 7 Reservoir operation results of different schemes

Scheme	Water requirement (10 ⁸ m ³)	Average annual water supply (10 ⁸ m ³)	Water supply guarantee rate (%)	Design power generation (10 ⁸ kW·h)	Average annual power generation (10 ⁸ kW·h)	Guarantee rate of ecological water (%)
1		5.00	100		1.34	100.00
2		4.95	98.17		1.29	99.67
3		4.80	94.00		1.20	96.00
4	5.00	4.62	89.00	1.32	1.19	92.67
5		4.87	96.33		1.28	97.00
6		4.86	96.00		1.27	96.83
7		4.76	93.00		1.24	95.00

is selected in this article to assess each scheme (Tharme 2003; Deng et al. 2012). In the early stages of the Hanjiang-to-Weihe River Diversion Project, Sanhekou Reservoir primarily relieves the burden on production and living water in the Guanzhong area, as well as power generation and downstream ecological water usage. Scheme 2–7 reduces the degree of hydrological change under the condition of as low damage to water supply efficiency as possible, so this article constructs evaluation indicators from three aspects of water supply, power generation, and ecology. In the water supply scheme: select the annual water supply C_1 and water supply guarantee rate C_2 ; in the power generation area, select the average annual power generation C_3 ; on the ecological side, select the ecological water guarantee rate C_4 and hydrological overall change C_5 .

1. Construction of hierarchical judgment matrix A

The comparison matrix A is constructed by comparing the two targets, based on the numbers 1–9 as the indicator scale (Deng et al. 2012).

$$A = \begin{bmatrix} & C_1 & C_2 & C_3 & C_4 & C_5 \\ C_1 & 1 & 1/2 & 7 & 1/4 & 1/2 \\ C_2 & 2 & 1 & 5 & 1/3 & 1/2 \\ C_3 & 1/7 & 1/5 & 1 & 1/7 & 1/8 \\ C_4 & 4 & 3 & 7 & 1 & 3 \\ C_5 & 2 & 2 & 8 & 1/3 & 1 \end{bmatrix}$$

2. Consistency test

The maximum eigenvalue of the matrix is calculated as follows:

$$\lambda_{\max} = 5.08$$

Eigenvector:

$$w = (0.131, 0.161, 0.035, 0.441, 0.232)T.$$

The consistency metric for matrix A CI is calculated as follows:

$$CI = \frac{\lambda_{\max} - n}{n - 1} = \frac{5.08 - 5}{5 - 1} = 0.021$$

Query the random consistency table to get $RI = 1.12$ and further calculate the consistency ratio CR as follows:

$$CR = \frac{CI}{RI} = \frac{0.025}{1.12} = 0.019 < 0.1$$

After calculating from the above formula: $CR < 0.1$. It shows that the consistency test is satisfied and the consistency of the judgment matrix is reasonable.

According to the indicator weight and normalization matrix, the calculation results of each scheme are as follows:

$$W = (0.502, 0.490, 0.484, 0.505, 0.511, 0.509) T.$$

The priority ranking them is: Scheme 6 > Scheme 7 > Scheme 5 > Scheme 2 > Scheme 3 > Scheme 4, so the ecological flow of Scheme 6 is chosen as the preferred Scheme in this paper.

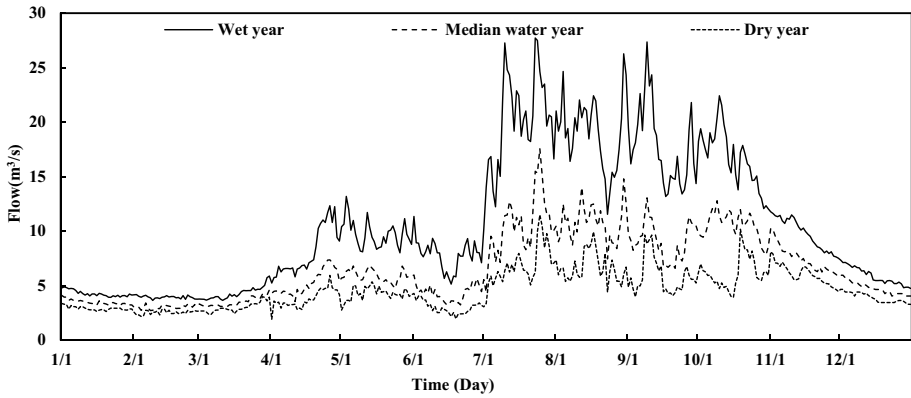


Fig. 14 Ecological flow process of Scheme 6

As can be seen from Table 7: In the recommended Scheme 6, the water supply and power generation benefits of the hydropower plant are less affected, and the overall degree of hydrological alteration is reduced from high altered (72.91%) to moderate altered (56.63%) in the current scheduling scheme, with a 16.28% reduction in the overall degree of hydrological alteration. The ecological water demand of Scheme 6 is shown in Fig. 14, and the corresponding multi-year reservoir scheduling process is shown in Fig. 15.

Even if the overall change degree of hydrology is reduced to moderate change, its water supply assurance rate and power generation still cannot reach the design value compared with that before the construction of the reservoir. The average value of the flow series decreases significantly, and the flow cycle shortens, affecting the life rhythm of aquatic animals in the river. Because the reservoir dispersion of flow and the frequency of tiny flow events grow after its construction, precautions must be taken to safeguard it.

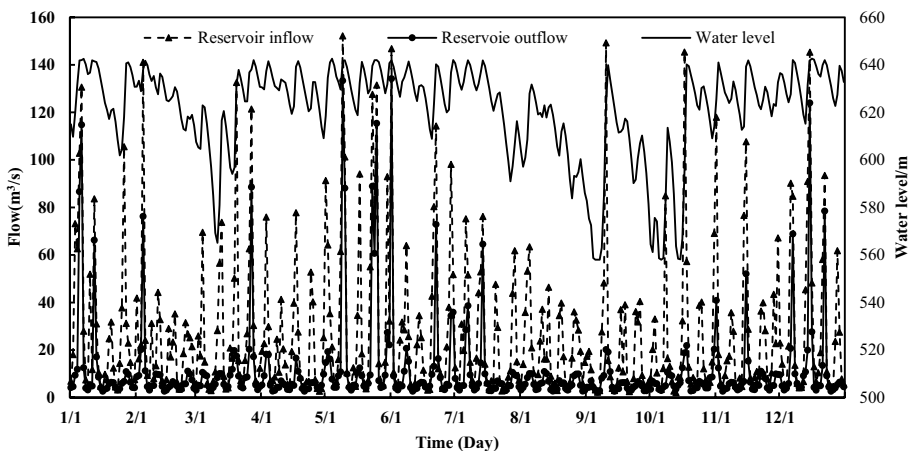


Fig. 15 Multi-year reservoir operation process of Scheme 6

4.5 Ecological Flow Safeguard Measures

It can be seen from the above results that built of the reservoir has already affected the ecological function of the downstream river, so it is necessary to take engineering and non-engineering measures to protect downstream ecology.

4.5.1 Engineering Measures

1. Ecological scheduling, which takes ecological factors into account in reservoir scheduling to reduce the impact of reservoir operation on river ecology, can optimally regulate water quantity without changing the total water quantity in the basin and reduce the interference and stress of human activities on rivers. Get more ecological flow opportunities by changing reservoir operation mode.
2. Sanhekou Reservoir is a water supply type reservoir. Damming and water diversion is the fundamental reason for the reduction of ecological water use. Water loss in the water conveyance tunnel of the Hanjiang-to-Weihe River diversion project is very large. So, optimizing water supply tunnel facilities, making technological innovations, and improving water supply efficiency to reduce water loss are effective measures to ensure ecological water use of rivers.

4.5.2 Non-engineering Measures

1. It is urgent to create and improve relevant laws and regulations to provide the basis and guidance for river ecological flow protection to solve the problem of weak environmental protection awareness of water users. In practical work, it is necessary to continue to improve relevant laws and regulations and establish an investment system for ecological flow protection funds.
2. In order to ensure that the Sanhekou water conservancy project can meet the ecological flow demand of the downstream river in the long term, it is necessary to increase human and financial investment in ecological environment protection and construction.
3. To ensure that the Sanhekou water conservancy project can protect the overall interests of the whole basin, the development of industry and agriculture in the middle-upper reaches of the Ziwu River is limited, resulting in economic backwardness. River basin ecological compensation mechanism should be built to speed up social, economic, and environmentally sustainable development of the whole river basin.
4. Establishing the monitoring and early warning mechanism for the downstream flow of the Sanhekou reservoirs, determining the ecological flow early warning level system, and defining the early warning release process. Use information technology to establish a basin early warning response platform to comprehensively improve the ecological flow monitoring and early warning mechanism of the basin.
5. Establish a sound management system and strengthen monitoring and supervision; establish sound law enforcement mechanisms; establish a river ecological flow law enforcement and supervision consultation system and rapid response mechanism. Severely crack down on the destruction of the river ecological environment and the illegal behavior of occupying river ecological water.

5 Conclusions

1. The reservoir scheduling model was established based on MIKE BASIN. The rationality of the model is confirmed by comparing the design water supply, ecological water amount, water level change process, and the river flow process after reservoir construction was obtained.
2. The range of variation (RVA) method is selected to calculate the degree of change of 33 hydrological indicators following reservoir building. The results demonstrate that reservoir operation has a large impact on the hydrological situation of the downstream river, and the overall degree of hydrological indicators is 72.91 percent, which has a moderate change.
3. The shortcomings of the current flow scheme are analyzed, and various river ecological flow schemes are formulated considering the hydrological situation within the year and the inter-annual changes of wetness and dryness seasons. Evaluate the scheme set based on the analytic hierarchy process. The overall change degree of hydrology is lowered to 56.63 percent under scheme 6, with little influence on the assurance rate of water supply, power production, and ecological water usage. Using the reservoir operation mode under this scheme, the research results provide technical support for reducing the impact of reservoir construction.
4. To propose ecological flow guarantee measures from engineering and non-engineering measures for the possible difficulties of ecological flow management in the Ziwu River.

This paper investigates the hydrological response of the river during the initial operation of the Hanjiang-to-Weihe inter-basin water transfer project and has achieved certain results. However, due to the high uncertainty of the hydrological response and the limitations of the authors' research level and the data of the study area, there are some shortcomings in this paper, which need further in-depth research and improvement.

Authors Contribution **Tao Bai:** Term, Software, Resources, Writing–Original Draft, Visualization, Project administration, Funding acquisition. **Xian-ge Sun:** Investigation, Data Curation, Writing–Review & Editing. **Jian Wei:** Validation, Formal analysis. **Lianzhou Wu:** Conceptualization, Supervision.

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Availability of Data and Materials The dataset on which this paper is based is too large to be retained or publicly archived with available resources. Documentation and data used to support this study are available from Geospatial Data Cloud and hydrological station data.

Declarations

Ethics Approval There are no relevant waivers or approvals.

Consent to Participate Authors consent to their participation in the entire review process.

Consent to Publication Authors allow publication if the research is accepted.

Competing Interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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