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Evaluation of instream ecological flows based on hydrological alteration in the Upper Huai River, China

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ABSTRACT

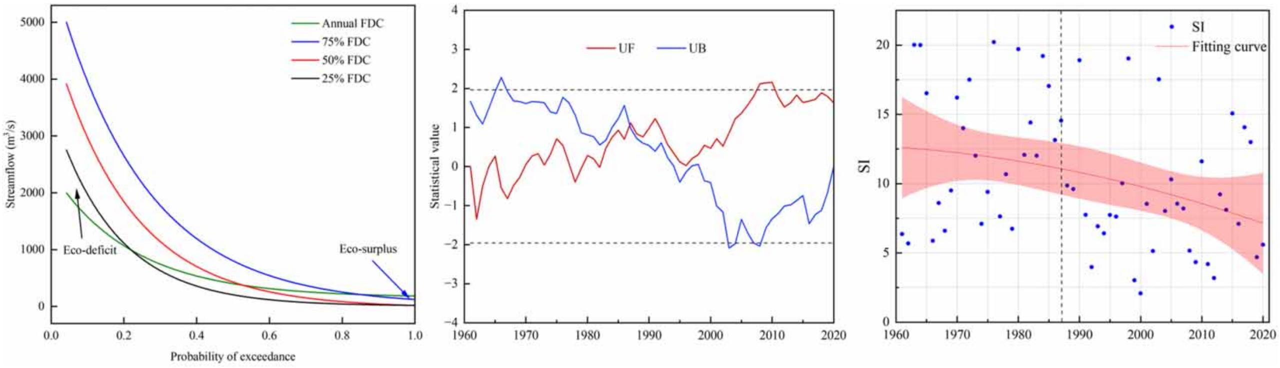
Natural flow regime (instream ecological flow) is a vital element of ecological hydrology, serving a crucial role in the fundamental functions of river ecosystems. Intense human activities, especially reservoir operation, have unavoidably altered the flow regime of the Upper Huai River, leading to further impacts on river ecosystems. It is essential to quantify hydrological alterations in flow regimes and their associated impacts on river ecosystems for effective river water management. Ecological flow indicators, namely ecological deficit and surplus, were analyzed to assess instream ecological flow. The overall degree of alteration (D_o) and the Dundee Hydrological Regime Alteration Method (DHRAM) were utilized to evaluate the degree of hydrological alteration. Additionally, the Shannon Index (SI) was employed to estimate the impact of hydrological alterations on ecological diversity in this study. The results reveal that the streamflow series underwent mutation in 1987, leading to a decrease in ecological surplus and an increase in ecological deficit. The overall alteration degree is 32%, with a DHRAM level of 3, signifying low hydrological alteration and moderate ecological risk in the region. Furthermore, the biodiversity of the river has markedly declined due to human activities following the alteration.

Key words: ecological deficit, ecological surplus, human activities, hydrological alteration, instream ecological flow, Upper Huai River

HIGHLIGHTS

- Ecological deficit and surplus indicators were studied.
- Degree of hydrological alteration was measured.
- The impact of hydrological alterations on ecological diversity was studied.
- Conservation of riverine ecological systems was studied.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Rivers are important pathways in the earth's water cycle, influencing the global transfer and transport of materials and energy (Gao *et al.* 2016). Likewise, river ecosystems constitute the foundation for human survival, social development, and are intricately connected to every facet of the natural environment (Luo *et al.* 2018; Meulenbroek *et al.* 2019; Sofi *et al.* 2020). The sustained health of river ecosystems has long been acknowledged to hinge on the natural flow regime, also known as instream ecological flow, within a river (Ge *et al.* 2018; Prakasam & Saravanan 2021). Studies indicate that more than 70% of rivers and their associated aquatic habitats face significant threats from human activities in China (Yang *et al.* 2022). The biodiversity of river ecosystems is declining, underscoring the escalating conflict between human social development and ecological protection (Doi *et al.* 2013; Sabater *et al.* 2023). Coordinated conservation and development necessitate an understanding of the flow regime, underscoring the essential need for evaluating instream ecological flows.

Climate change and human activities serve as the primary drivers for alterations in the flow regime (Frederick & Major 2017; Cavalcante *et al.* 2019). The full extent of the impact of human activities on the flow regime and ecology remains uncovered, particularly with the escalating industrial, agricultural, and domestic water use, as well as reservoir construction (Wang *et al.* 2020; Guan *et al.* 2023). During the natural period, characterized by minimal or no human activity, the flow regime was predominantly influenced by climatic factors like precipitation and evaporation (Patterson *et al.* 2013; de Freitas 2020). Nevertheless, heightened human activities, including reservoir storage and increased water use for economic and social development, have led to alterations in the river flow regime (Lin *et al.* 2017; Maskey *et al.* 2022; Yang *et al.* 2022). Despite numerous studies identifying the effects of climate change and human activities on river flows, there has been limited discussion regarding their impact on river ecosystems (Gao *et al.* 2010; Wei *et al.* 2013; Cheng *et al.* 2019; Yang *et al.* 2022). These studies have predominantly concentrated on annual-scale changes in precipitation forecasts, and their practical implementation in the basin remains unknown (Yang *et al.* 2022).

Indicator analysis approaches are commonly utilized to assess the flow regime in rivers (Poff & Zimmerman 2010). Richter *et al.* (1996) introduced the indicators of hydrological alteration (IHA), which is based on the consideration of the normal functioning of river ecosystems and the dynamics of streamflow throughout a year. The range of variability approach (RVA), derived from the IHA, compares the flow regime under natural conditions with that after hydrological alteration and gives a threshold value for each indicator (Richter *et al.* 1997). Vogel *et al.* (2007) introduced ecological surplus and ecological deficit indicators to evaluate instream ecological flow in a river, based on the flow duration curve (FDC). Subsequently, ecological surplus and ecological deficit were refined to use the 25th and 75th percentiles of the FDC as thresholds, meeting the practical needs of river management. In addition, the overall degree of alteration (D_o) and the Dundee Hydrological Regime Alteration Method (DHRAM) have been developed to assess integrated hydrological alterations (Black *et al.* 2005; Shiau & Wu 2007). However, relying on a single ecological flow indicator assessment method may overlook specific hydrological features (Zhang *et al.* 2015). Despite numerous studies assessing instream ecological flow and hydrological alteration in rivers, the corresponding ecological effects have not been thoroughly examined and clearly elucidated (Zhang *et al.* 2018; Li *et al.* 2020). Therefore, an approach of evaluating flow regime from the perspective of protecting the river ecosystems is essential.

To quantitatively assess instream ecological flow and its impact on river ecosystems, we employed a multi-indicator assessment framework in this study. The study area selected for this research is the Upper Huai River, characterized by multiple large reservoirs and a dense population. The study aims to (1) analyze instream ecological flow surplus and deficit, (2) assess the degree of hydrological alteration in rivers using IHA and DHRAM, and (3) evaluate the impact of flow alteration on river ecosystems, as indicated by river biodiversity.

2. MATERIALS AND METHODS

2.1. Study area and data sources

The Upper Huai River, situated in eastern China, refers to the region upstream of the Wangjiaba station and encompasses a basin area of 30,075 km^2 (Figure 1). The western mountainous regions of the basin exhibit higher elevations, generally exceeding 1,000 m above sea level, whereas the central and eastern areas comprise extensive plains with a more gradual topography. The basin experiences an average annual precipitation exceeding 800 mm, with a rainfall distribution favoring the northern and mountainous regions over the southern and plain areas, and a disparity between seasons, with less precipitation in spring and winter and more in summer and autumn. The construction of numerous large reservoirs in the basin for flood storage,

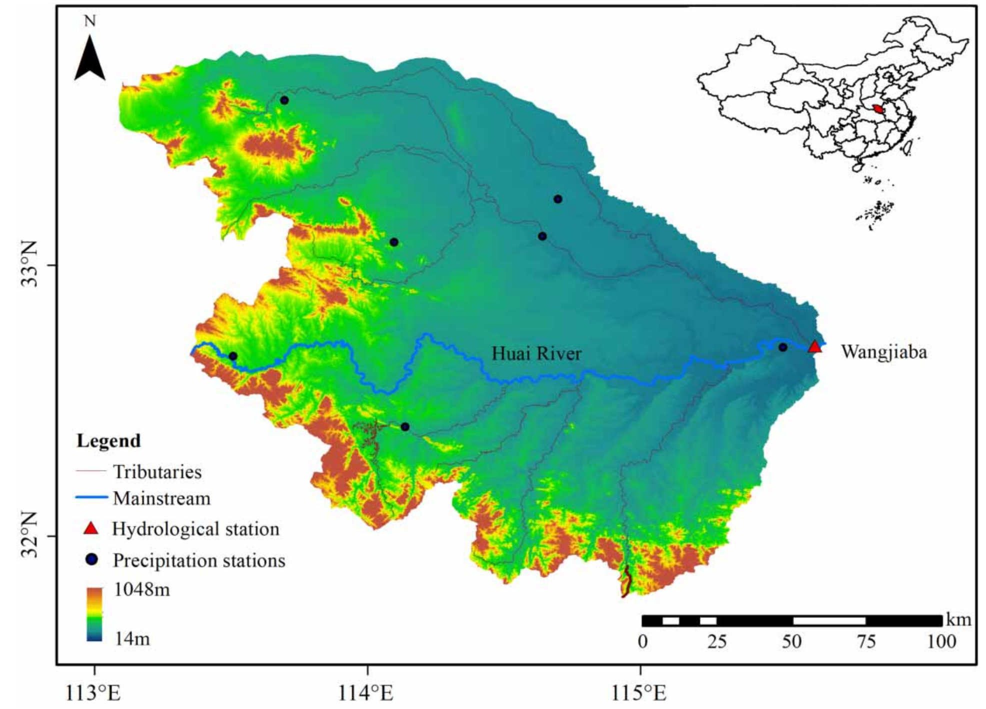


Figure 1 | River system and hydro-precipitation stations of the Upper Huai River.

irrigation, and power generation has induced alterations in streamflow dynamics to some extent, posing various challenges to the stability of the ecosystem. In addition, the basin has witnessed a rapid surge in population and urbanization, leading to a significant transformation in the land use/cover conditions of the Upper Huai River.

The daily streamflow time series during 1961–2020 at the Wangjiaba station were obtained from *The Huaihe River Commission of the Ministry of Water Resources P.R.C.* Precipitation data of the 7 precipitation stations during 1961–2020 were obtained from *China Meteorological Data Service Centre* (http://cdc.cma.gov.cn/).

2.2. Methodology

2.2.1. Ecological deficit and ecological surplus

This study employs the Mann–Kendall test to identify the change point in the streamflow time series at the Wangjiaba station spanning 1961–2020. Subsequently, the streamflow time series is segmented into two distinct periods: pre-alteration (i.e., natural period, characterized by minimal or no human activity) and post-alteration.

Ecological deficit and ecological surplus, as proposed by Vogel *et al.* (2007), represent the overall loss or gain in instream ecological flow. These indicators are derived from the FDC, constructed using daily flow data over a specific period. The FDC illustrates the percentage of time when daily flow equals or surpasses a given threshold (Singh *et al.* 2014). Typically, the 25 and 75% FDCs are considered the lower and upper thresholds for river protection, with the intervening range deemed suitable for maintaining a healthy riverine ecosystem (Zhang *et al.* 2015; Zhang *et al.* 2018). Illustrated in Figure 2, when the annual FDC falls below the 25% threshold, the region enclosed by the two FDCs is identified as an ecological deficit, while the circumscribed area above the 75% FDC is labeled as ecological surplus (Gao *et al.* 2012). Both ecological deficit and surplus serve as ecological flow indicators. By ranking daily flows in descending order, the exceedance probability can be determined:

$$p_i = i/(n+1) \tag{1}$$

where p_i is the exceedance probability; i and n are the rank and the sample size of daily flow (Q_i), respectively. The values of ecological deficit and ecological surplus were then divided by the area merely enclosed by the 50% FDC to quantify the

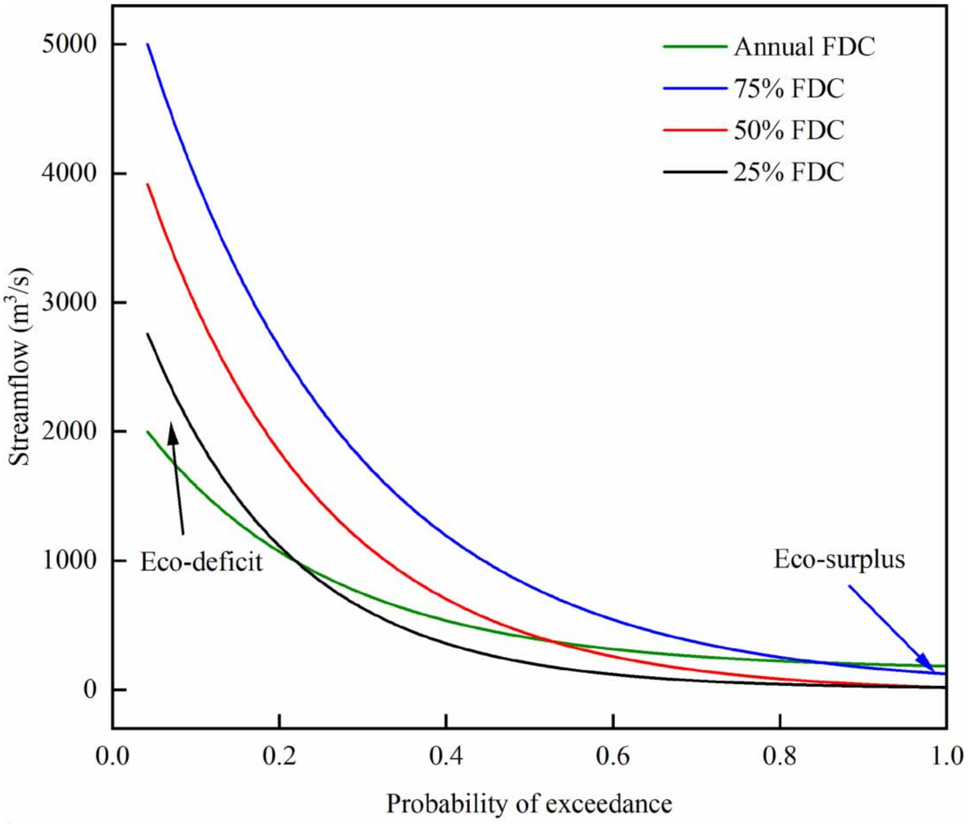


Figure 2 | Schema of ecological deficit and ecological surplus.

fractions of corresponding eco-flow indicators:

$$ED(ES) = \frac{A_{25(75)}}{A_{50}} \tag{2}$$

Here, $ED(ES)$ represents the ecological deficit and surplus, A_{25} (A_{75}) denotes the area encircled by a specific FDC and the corresponding 25% (75%) FDC; A_{50} signifies the area enclosed by a specific FDC and the 50% FDC.

2.2.2. Hydrological alteration

The Indicators of Hydrological Alterations (IHA) were used to evaluate the hydrological alteration. IHA includes 33 indicators in five groups (Supplementary material, Table S1). The degree of hydrological alteration for each indicator was calculated as:

$$D_i = \frac{N_{o,i} - N_e}{N_e} \times 100\% \tag{3}$$

where D_i is the degree of hydrological alteration of the ith indicator; $N_{o,i}$ denotes the number of post-alteration years when the IHA values fall between 25th percentile and 75th percentile (low and high boundaries of RVA); N_e denotes the expected number of years when the IHA values fall between 25th percentile and 75th percentile ($N_e = P \times N_T$, $P = 50\%$, N_T is the number of years for the post-alteration period). The overall degree of alteration (D_o) can be expressed as:

$$D_o = \left(\frac{1}{n}\sum_{i=1}^{n} D_i^2\right)^{1/2} \tag{4}$$

where n is the number of IHA parameters. The value of $|D_i|$ and $|D_o|$ in the range of 0–0.33 indicates low alteration; 0.34–0.66 indicates moderate alteration; 0.67–1 indicates high alteration (Shiau & Wu 2007).

The Dundee Hydrological Regime Assessment Method (DHRAM), another hydrological alteration approach, was proposed by Black *et al.* (2005). The DHRAM classifies the absolute changes of the mean and coefficient of variation (CV) of the IHA parameters into three impact categories, namely, category 1 representing the lowest degree of change, category 2 representing the medium degree of change, and category 3 representing the highest degree of change. The classification results are shown in Supplementary material (Table S2). For the mean in group 1, if the change in the IHA parameters was less than 19.9%, then the point was recorded as 0; if the change in the IHA parameters ranged from 19.9 to 43.7%, then the point was recorded as 1; if the change in the IHA parameters ranged from 43.7 to 67.5%, then the point was recorded as 2; if the change in the IHA was more than 67.5%, then the point was recorded as 3. The same approach was applied to other groups as well.

Considering the sum of the points of the mean and CV for each group, total point was obtained. The total point allows conversion to a final DHRAM classification of impact severity on a 1–5 class scale (Supplementary material, Table S3). The point value is associated with the integrated degree of hydrological alteration and can help in evaluating the extent of potential damage to aquatic ecosystems. Higher points lead to greater alterations in the flow regime, indicating higher vulnerability of the river ecosystem to damage.

2.2.3. Evaluation of fluvial biodiversity

The Shannon Index (SI) is widely used to assess fluvial biodiversity, and a smaller SI indicates poorer biodiversity. Yang *et al.* (2008) established a relationship between SI and the IHA parameters, which allows a rough estimate of the biodiversity of a river ecosystem. The relationship between SI and the IHA parameters was widely employed to evaluate the fluvial biodiversity in China (Zhang *et al.* 2015). Expressed as follow:

$$\mathrm{SI} = \frac{D_{\mathrm{min}}/\mathrm{Min}_7 + D_{\mathrm{min}}}{Q_3 + Q_5 + \mathrm{Min}_3 + 2 \times \mathrm{Max}_3} + R_{\mathrm{rate}} \tag{5}$$

where D_{min} is the Julian date of minimum flow; Min_3 (Min_7) is the annual minimum 3-day (7-day) flow; Q_3 (Q_5) is the monthly mean flow of March (May); Max_3 is the annual maximum 3-day flow; R_{rate} is the rise rate in group 5.

3. RESULTS AND DISCUSSIONS

3.1. Changes in the instream ecological flow

The test results of the Mann–Kendall method revealed a significant change point in 1987 at a 0.05 significant level (Figure 3). Consequently, the annual runoff series is divided into the pre-alteration period (1961–1987) and the post-alteration period (1988–2020). In the 1980s, amid the initial phases of China's reform and opening-up, the Huai River Basin witnessed unparalleled development in agriculture and industry, accompanied by enhancements in water facilities. Concurrently, heightened efforts in soil and water conservation in the region resulted in changes in land use/cover and, to some extent, the streamflow status.

Scatter plots illustrating annual flow duration curves (FDCs) for the pre- and post-alteration periods, along with the 25th percentile FDC and 75th percentile FDC, are presented in Figure 4. Flow components between 25th percentile FDC and 75th percentile FDC remain consistent before and after the hydrological alteration. However, high-flow components exceeding the 75th percentile FDC generally decrease below this threshold following alteration, resulting in a diminished occurrence of ecological surplus. Simultaneously, some flow components within the suitable ecological flow range tend to drop below the 25% FDC, contributing to an increased occurrence of ecological deficit. These phenomena can be attributed to the operations of reservoirs upstream of the Huai River, which curtail water discharge during the flood season. While this diminishes the frequency of flooding to some extent, it poses a potential ecological risk to river ecosystems.

Given that river streamflow in the Huai River basin is mainly influenced by precipitation (Zhang *et al.* 2013; Gao & Ruan 2018), we analyzed annual precipitation anomalies. These anomalies were computed as the difference between annual precipitation and the average annual precipitation (1961–2020), divided by the average annual precipitation. The annual precipitation anomalies are calculated and presented in Figure 5, along with ecological surplus and deficit computed using

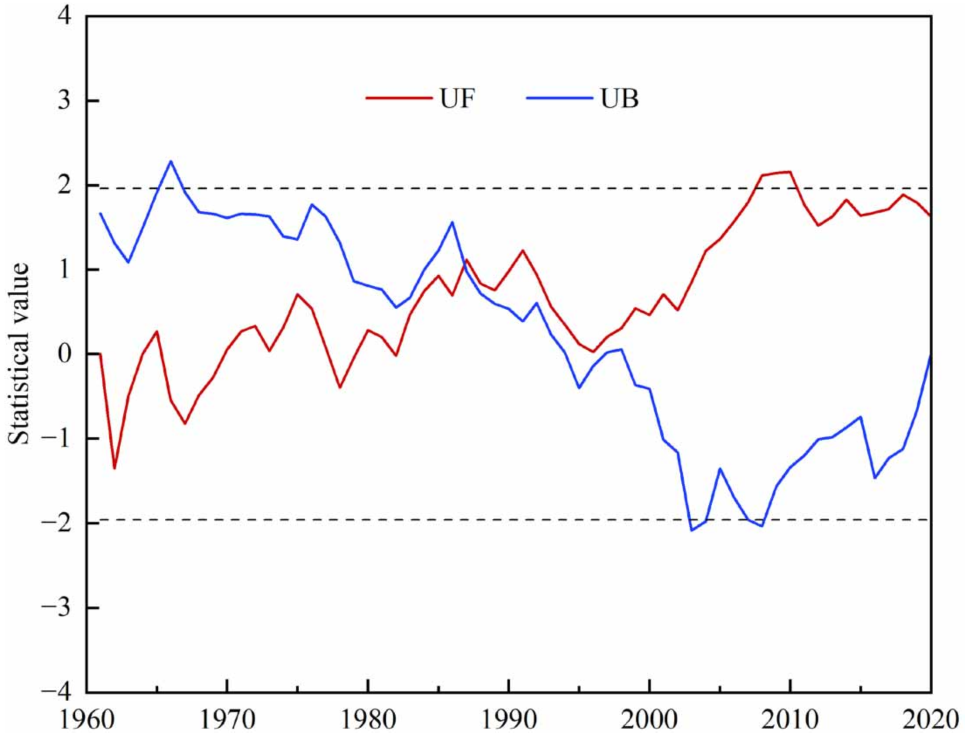


Figure 3 | Change point of the annual runoff series using the Mann–Kendall method at Wangjiaba (the dotted lines represent the significance level of $\alpha = 0.05$).

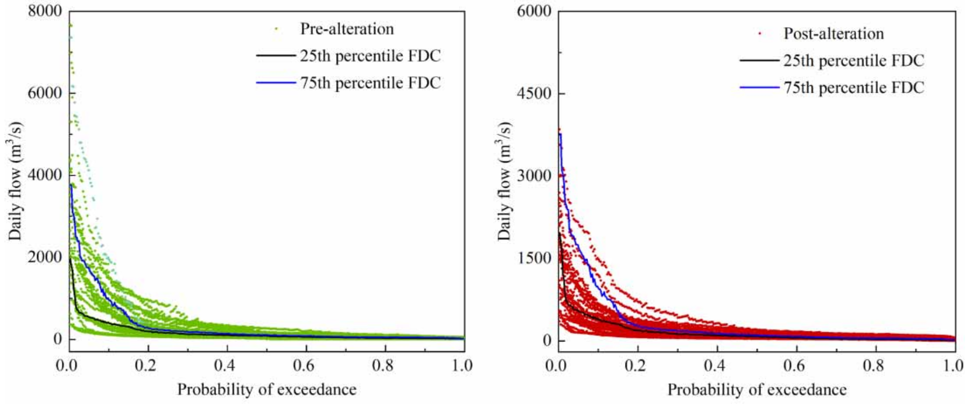


Figure 4 | Scatter plots of annual FDCs for pre- and post-alteration at Wangjiaba.

Equation (2). Overall, the trend of ecological flow indicators closely mirrors that of annual precipitation anomalies. Specifically, an increase in precipitation leads to a high-flow regime and an augmented ecological surplus, while a decrease in precipitation results in a low-flow regime and an elevated ecological deficit. Notable instances of high ecological surpluses occurred in 1963, 1964, and 1970, with the values of 0.56, 0.45, and 0.39, respectively. Conversely, significant ecological deficits were observed in 1988, 1999, and 2001, with values of −0.34, −0.32, and −0.50, respectively. Furthermore, the disparity between ecological flow indicators and precipitation anomalies has grown since 1987. This can be attributed to the escalating impact of human activities on ecological flows, coupled with the effects of climate change, disrupting ecological flow regimes. Consequently, during the pre-alteration period (1961–1987), precipitation predominantly governed ecological flow dynamics.

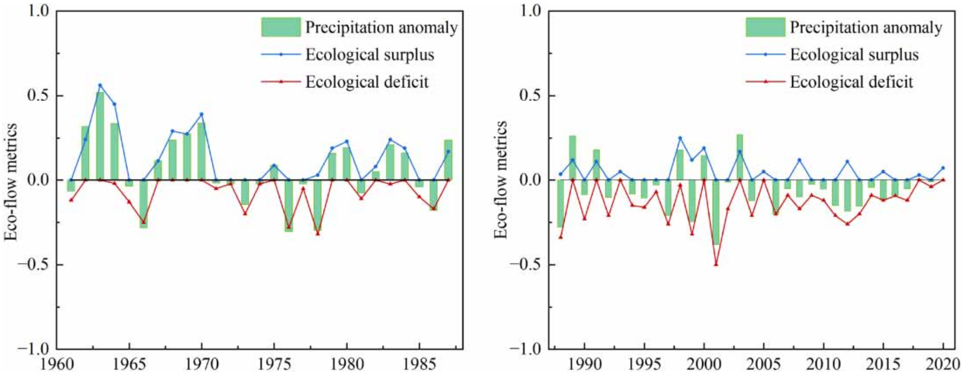


Figure 5 | Annual precipitation anomalies and ecological flow indicators during the pre- and post-alteration periods at Wangjiaba.

However, during the post-alteration period (1988–2020), human activities, especially with reservoir operation and land use/cover change in this region, have emerged as key factors shaping ecological flow regimes.

3.2. Evaluation of hydrological alteration

The calculation of hydrological alteration at the Wangjiaba station reveals that most IHA parameters indicate low alteration (Table 1). March and May flow, 90-day minimum, 7-day maximum, date of maximum, low-pulse duration, and high-pulse count show moderate alteration; high-pulse duration indicates high alteration. The alteration process of the four typical parameters during 1961–2020 is illustrated in Figure 6, including March flow, 7-day maximum flow, date of maximum flow, and high pulse duration. These four parameters underwent the most significant changes among the groups and all exhibited moderate or high alteration.

In terms of monthly flow, all parameters experienced low or moderate alterations, with March flow undergoing the greatest change. Compared to the pre-alteration period (1961–1987), the number of years that fall within the RVA threshold for March flow decreased significantly during the post-alteration period (1988–2020) (Figure 6(a)). For annual extreme flow, the 7-day maximum flow exhibits the most notable alteration. In 1968, the 7-day maximum flow well surpassed the high boundary of RVA, indicating extreme flooding. Although there have been no large flood processes exceeding 6,000 m^3/s since 1987, most years did not fall within the RVA threshold (Figure 6(b)). Regarding the timing of annual extreme flow, the date of the annual minimum flow shifted considerably earlier, from early June to mid-March (the dates for the pre- and post-alteration periods are 155.5 and 78, respectively, Table 1). The hydrological alteration degree of the date of the annual minimum flow is moderate, with a value of −35%, and this parameter rarely falls within the RVA threshold after alteration (Figure 6(c)). The parameter of high-flow duration is crucial to the health of riverine water ecosystems. Certain duration of high-flow processes can promote fish spawning and provide spawning sites and nutrients for fish (Guan *et al.* 2021). The number of times this parameter falls within the RVA threshold increased slightly after 1987 (Figure 6(d)). Moreover, most indicators have lower CV, indicating a more concentrated distribution of flows throughout the year. These results suggest that the hydrological processes of the river stabilize under the regulation of upstream reservoir operation, leading to a homogenization of streamflow.

The impact points and total points of DHRAM and D_o are illustrated in Table 2. The DHRAM level at the Wangjiaba station is 3, with a total of 7 points, signifying a moderate ecological risk. Furthermore, the overall alteration degree at the Wangjiaba station is 32%, indicating low hydrological alteration. The analysis shows that the region has experienced changes in its ecological hydrological regime and faces a moderate ecological risk. To mitigate adverse effects on river hydrology and ecological damage, implementing various ecological protection measures is essential to restore the natural eco-hydrological regime.

3.3. Impacts of instream ecological flow alteration on biodiversity

The SI was utilized to assess the impacts of instream ecological flow alteration on biodiversity. In the current study, the local weighted multiple repressive approach (Zhang *et al.* 2015) was employed to fit the alteration trend of SI. The alteration trend of SI and the corresponding 95% confidence interval are illustrated in Figure 7.

Table 1 | Statistics on IHA parameters pre- and post-alteration at the Wangjiaba station

IHA parameters	Pre-alteration		Post-alteration		RVA boundaries		Hydrologic Alteration (%)
	Mean values	CV	Mean values	CV	Low	High	
January	51.6	0.874	62.85	0.757	40.47	63.02	−10.6
February	53.63	1.287	58.9	0.9909	35.92	68.43	−2.5
March	54.65	1.551	87.15	1.532	45.51	79.72	−59.4
April	75.45	1.416	82.88	1.545	43.01	134.5	30.0
May	75.45	4.35	97.8	1.15	61.97	168.2	38.1
June	78.88	2.492	116.8	0.9314	41.52	138.6	30.0
July	392.5	1.784	309.5	1.577	245.8	651.8	5.6
August	203	2.016	268	1.173	141.7	365.6	−10.6
September	155.8	1.629	171.8	1.214	103.2	317.5	21.9
October	108	2.252	82.65	0.9628	82.56	220	−10.6
November	86.05	1.105	77.55	1.145	53.75	116.7	13.8
December	60.6	0.6543	75.45	0.8943	50.35	73.24	−18.8
1-day minimum	16.05	1.77	22.25	1.097	7.843	25.85	−10.6
3-day minimum	16.35	1.79	28.25	0.9409	8.28	27.14	−10.6
7-day minimum	17.73	1.833	30.97	0.8521	8.652	29.9	5.6
30-day minimum	28.14	1.401	43.48	0.8397	16.17	42.2	13.8
90-day minimum	50.31	0.6375	54.76	0.8528	34.99	53.18	−35.0
1-day maximum	3,290	0.6922	2,650	0.9443	2,159	4,055	−26.9
3-day maximum	2,980	0.6527	2,445	1.074	1,969	3,741	−26.9
7-day maximum	2,454	0.6751	1,812	1.205	1,527	2,882	−43.1
30-day maximum	1,156	1.082	907.2	1.316	738.3	1,760	−2.5
90-day maximum	626.5	1.347	501.8	1.355	385.2	982.5	21.9
Number of zero days	0	0	0	0	0	0	23.8
Base flow index	0.06472	1.54	0.1386	0.8748	0.02179	0.09465	−18.8
Date of minimum	155.5	0.4734	78	0.4331	100.6	187.4	−26.9
Date of maximum	199.5	0.1407	203	0.1878	190.7	207.2	−35.0
Low pulse count	4	1.625	3	2.25	2	8	−1.3
Low pulse duration	7	1.5	4.75	1.711	5.5	10.25	−54.9
High pulse count	6.5	0.3462	6	0.6667	5.91	7	−45.8
High pulse duration	7.5	1.183	7	0.8571	4.955	10.18	70.6
Rise rate	13.75	0.8618	8.05	0.6351	10.49	17.05	−25.6
Fall rate	−11.88	−0.9895	−7.45	−0.9396	−13.95	−7.201	−10.6
Number of reversals	67.5	0.3	68	0.6728	63.73	72.18	−26.9

The SI exhibits a closely aligned trend with the ecological surplus and an opposing trend to the ecological deficit, as depicted in Figures 5 and 7. SI peaked at 20 in 1963, underwent a gradual decline, experienced a slight increase in 1976, and saw a steep decline after 1987. Likewise, ecological flows exhibited a surplus in 1963 followed by multiple deficits after 1987. After 2004, river biodiversity exhibited poor conditions, with SI dropping below 10, and ecological flows consistently in deficit. The analyses uncovered a substantial influence of instream ecological flow alterations on SI, where excess ecological flow benefits river biodiversity, while deficient ecological flow has a detrimental effect. Notably, the decline in the fitting curve is markedly higher after 1987 than in the preceding period. River biodiversity has markedly decreased due to human activities in the region, as reported by Tang *et al.* (2021). The escalating urbanization in the region

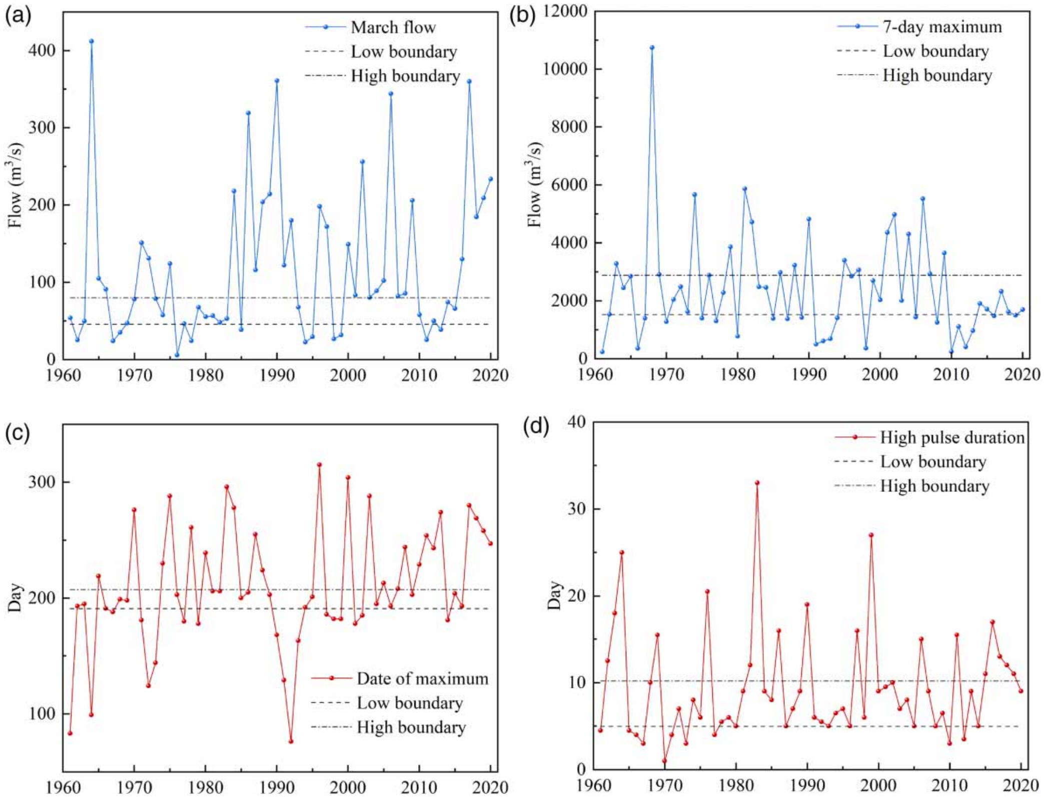


Figure 6 | The process of change in the four typical indicators during 1961–2020.

Table 2 | Hydrological alteration degree at the Wangjiaba station

	Change (%)		**Impact points**			
Group	**Mean values**	**CV values**	**Mean values**	**CV values**	**Overall alteration degree (%)**	**Total points**
1	25	30	1	1	32	7(3)
2	39	38	0	1		
3	26	21	2	0		
4	18	43	0	1		
5	26	52	0	1		

post-1980s led to the discharge of a substantial volume of pollutants into the river, negatively impacting river biodiversity, as highlighted by Shen *et al.* (2021).

Both climate change and human activities significantly impact river streamflow. Precipitation is the primary factor influencing the ecological flow of rivers in the Huai River basin, followed by human activities (Zhang *et al.* 2022). The correlation between precipitation and ecological flow indicators are evaluated and shown in Table 3. During 1961–1987, there is a strong correlation between precipitation and ecological surplus and deficit, with correlation coefficients of 0.75 and 0.73. Following the influence of human activities, the correlation between precipitation and ecological surplus and deficit decreases, reflected in correlation coefficients of 0.63 and 0.58. This implies a reduced impact of precipitation on ecological flow indicators, indicating the involvement of factors beyond precipitation. The study unveils a profound

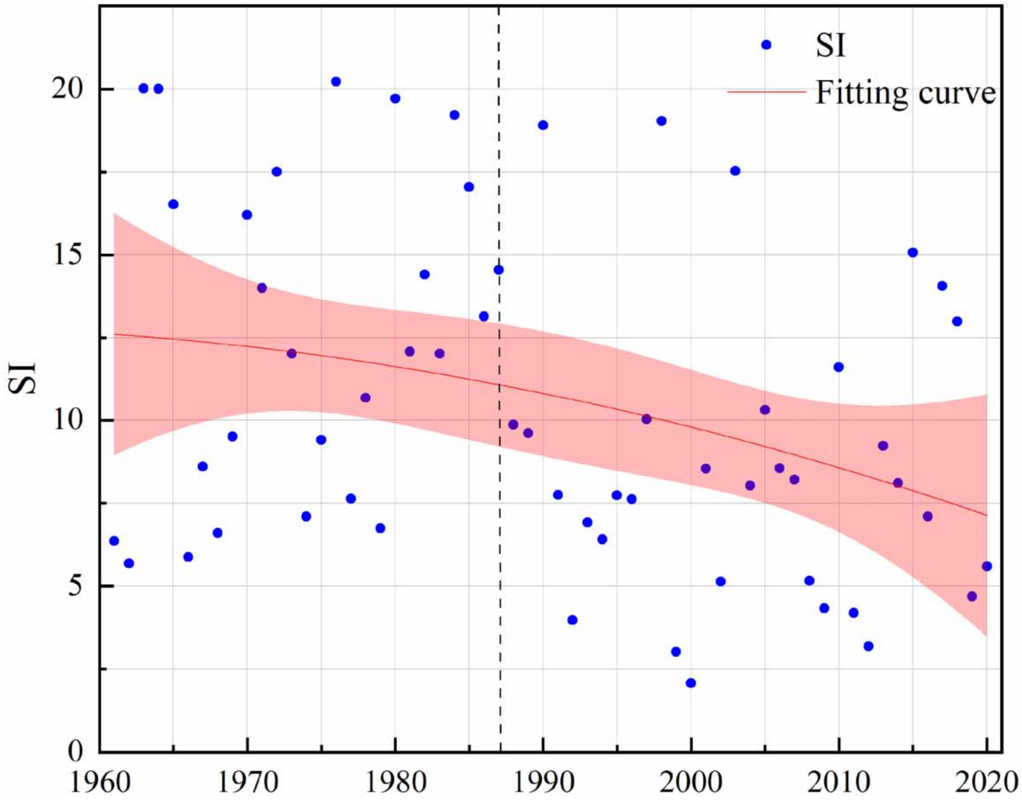


Figure 7 | Alteration trend of the SI. The gray shadowy regions represent 95% confidence intervals.

Table 3 | Correlation coefficient between precipitation and ecological flow indicators

Indicators	1961–1987	1988–2020
Ecological surplus	0.79	0.63
Ecological deficit	0.75	0.58

impact of human activities on the river environment, especially concerning fish species (Inogwabini & Lingopa 2013; Ko *et al.* 2017). The 2015 ecological survey of *The Huaihe River Commission of the Ministry of Water Resources P.R.C.* reveals a 40.8% decrease in the number of fish species in the upper Huai River compared to the 1980s, indicating a serious and irreversible decline in species diversity. Furthermore, accelerated urbanization and reservoir operations have led to significant reductions in the population size and species of some rare and endemic fish in the Upper Huai River, as documented by Ai *et al.* (2022).

4. CONCLUSION

This study utilizes multiple assessment indicators based on hydrological alteration for a quantitative evaluation of instream ecological flow in the Upper Huai River and their corresponding ecological impact. Based on the precipitation and streamflow time series from 1961 to 2020, several conclusions can be drawn:

(1) The annual streamflow time series experienced an alteration in 1987 at a significance level of 0.05. Subsequent to the alteration, there is a significant decrease in the occurrences of ecological surplus and a significant increase in the occurrences

of ecological deficit. In the period 1961–1987, precipitation primarily influences ecological flow, while from 1988 to 2020, human activity emerges as a key factor affecting ecological flow regimes. (2) In the period 1988–2020, several indicators no longer fell within the RVA threshold, potentially elucidating the decline in ecological surplus and the rise in ecological deficit in the basin. The overall alteration degree at the Wangjiaba station is 32%, and the DHRAM level is 3, indicating low hydrological alteration and moderate ecological risk in the region. (3) During 1988–2020, the correlation between precipitation and ecological surplus and deficit weakens, reflected in correlation coefficients of 0.63 and 0.58. The SI exhibits an almost identical trend to ecological surplus and an opposite trend to ecological deficit.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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