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How does the daily regulation hydropower station reduce the hydrological regime impact? A case study in upper Yellow River

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ABSTRACT

Human activities, particularly the regulation of hydropower stations, have profoundly altered river flow patterns. While studies have extensively assessed the impact of large or multi-year regulated hydropower stations on hydrological regimes using indicators of hydrological alteration (IHA) and range of variability approach (RVA), the impact of daily regulation hydropower stations has received comparatively less attention. This study aims to evaluate the influence of daily regulation hydropower stations on hydrological regime changes, focusing on the upper Yellow River region in China. Using daily runoff data from 1954 to 2020 at the Guide station, the study compares the impacts of multi-year regulated (Longyangxia) and daily regulation (Laxiwa and Nina) hydropower stations. The Mann-Kendall test showed that 27 out of 32 Indicators of Hydrological Alteration (IHAs) had significant trends under Longyangxia operation, which reduced to 18 IHAs with the inclusion of daily regulation stations. The Range of Variability Approach (RVA) revealed that only 46.87% of IHAs exhibited high alteration from the natural regime when daily regulation was considered, down from 75.00% with Longyangxia alone. This suggests that daily regulation can mitigate the negative impacts of multi-year regulation, potentially enhancing the river's eco-hydrological health.

Key words: controlled hydroelectric power station, daily regulation hydropower station, hydrological regime, indicators of hydrologic alteration (IHA), Mann-Kendall test, range of variability approach (RVA)

HIGHLIGHTS

- This study contrasts the impacts from multiyear with daily regulation hydropower stations on hydrological regimes.
- The supplementary daily regulation tends to mitigate the alterations by multiyear hydropower station.
- The rate and frequency of runoff change increase with the additional daily operations.
- Nina and Laxiwa decrease hydrological regime change to 75.24% from 82.29% in the upper Yellow River region.

1. INTRODUCTION

The natural hydrological regime plays a crucial role in maintaining the ecological health and biodiversity of rivers (Radinger *et al.* 2018; Cui *et al.* 2020). However, human activities such as the operation of hydropower stations, irrigation, and land use changes have substantially impacted these regimes, contributing to significant alterations in approximately 24% of the world's largest rivers (Pfeiffer & Ionita 2017; Sarauskiene *et al.* 2021; Yang *et al.* 2022). Among these activities, the operation of hydropower stations stands as one of the most influential factors, leading to the disruption of ecological continuity in more than half of the world's large rivers, resulting in extensive river system fragmentation (Wang *et al.* 2018; Gierszewski *et al.* 2020; Knott *et al.* 2024). Given this scenario, it is imperative to thoroughly assess the impact of hydropower stations to support the ecological sustainability of river systems.

The analysis of hydrological regimes is primarily based on runoff data, with numerous studies highlighting the substantial influence of such changes on biodiversity and ecosystem integrity (Ma *et al.* 2014). Over 170 hydrological indicators have been proposed to characterize hydrological regimes, such as average flow conditions, variability in mean daily flow, skewness in flow and peak discharges, short-term estimates of flood frequency, seasonal distributions of monthly flows, flow and flood frequency duration curves, and time series of annual discharge (Olden & Poff 2003; Lu *et al.* 2018; Wang *et al.* 2018). However, due to correlations among some of these indicators, leading to redundant information, the indicators of hydrologic alteration (IHA) method, proposed by Richter *et al.* (1996) at the end of the 20th century, has facilitated the measurement of complex changes and the assessment of effects on hydrological ecosystems. The IHA method, which evaluates the differences between pre-impact and post-impact periods using 33 hydrological indicators, has significantly enhanced our comprehension of the interplay between flow regimes and river ecosystems (Zuo & Liang 2015; Wang *et al.* 2023). For instance, Monk *et al.* (2006) applied the IHA method to explore relationships with macroinvertebrate community metrics in 83 rivers in England and Wales, identifying the magnitude and duration of annual extreme water conditions as the 'best' predictors. Similarly, Mwedzi *et al.* (2016) utilized indicators of hydrological alterations (IHAs) to assess hydrological alterations caused by six dams in the Manyame catchment, Zimbabwe, revealing significant adverse effects on low flows, extreme low flows, and an increased number of zero-flow days. Across various regions, the application of IHA has unveiled diverse changes in hydrological regimes.

To quantify the overall extent of hydrological regime change using various indicators, several approaches have been proposed, such as the range of variability approach (RVA) (Richter *et al.* 1997), histogram matching approach (Shiau & Wu 2008), histogram comparison approach (Huang *et al.* 2017), among others. Notably, the RVA method stands out as one of the most widely adopted techniques, likely being the earliest method devised for assessing alterations in hydrological regimes (Huang *et al.* 2017). This method has proven instrumental in water resource and ecosystem management by effectively delineating optimal environmental flows that balance both ecosystem and human needs objectives (Shiau & Wu 2008). This method, based on the frequency of a hydrologic parameter falling within the target range and assigning equal weight for the parameter value within the target range, offers a simple calculation and low data requirements (Ge *et al.* 2018). For instance, Hu *et al.* (2008) utilized the RVA method to assess hydrologic alterations, demonstrating the profound influence of dams on eco-hydrological conditions in the Huaihe River basin (China), particularly highlighting substantial impacts on the timing, magnitude, and frequency of flow, especially during dry seasons. Similarly, by applying the RVA method based on IHAs, Li *et al.* (2014) analyzed four large-scale controlled hydropower stations in the mainstream of the Yellow River in China, revealing marked differences in hydrological regimes, resulting in an overall hydrological change of 87%. Furthermore, Pfeiffer & Ionita (2017) employed the RVA method to investigate the effects of climate change on the hydrological regimes of the Elbe and Rhine rivers in Germany, revealing significant changes in several hydrological indicators, particularly in the number of runoff reversals. In the RVA method, calendar years are utilized instead of the hydrological year, a modification that has been recently compared and refined (Ramesh & Thampi 2023; Zhou *et al.* 2023). Ge *et al.* (2018) enhanced the traditional RVA by incorporating the inherent characteristics of hydrological years, revealing that the conventional RVA method underestimated the alterations in hydrological regimes. Furthermore, the RVA method, when considering the hydrologic year, can more accurately depict changes in IHAs for monthly runoff and extreme runoff. Widely adopted and validated in numerous studies, the RVA method has significantly advanced the assessment of hydrological regime alterations (Pirnia *et al.* 2019). However, whether the RVA method effectively captures the impact of daily regulation hydropower stations remains uncertain, as previous studies have predominantly focused on the effects of controlled regulation hydropower stations operating on a yearly or multiyear scale.

In addition to the RVA method, various statistical hypothesis tests are commonly applied in hydrological regime alteration studies, including the Mann–Kendall (M-K) test, Spearman rank correlation test, and Pettitt test. The M-K test, a nonparametric statistical test recommended by the WMO (World Meteorological Organization), has found widespread use in hydrology research due to its low data requirement and high accuracy (Serrano *et al.* 1999; Tian *et al.* 2019; Guo *et al.* 2022a). For instance, Pirnia *et al.* (2019) utilized the M-K test to analyze the Tajan River in Iran, discovering significant decreases in runoff in the rainy season and increases in the dry season following the construction of dams. Fang *et al.* (2023) applied the M-K test to 77 indicator parameters, including IHAs, finding significant changes in 61 hydrological indicators after the construction of the Liujiaping hydropower station in China.

Given the widespread distribution of daily regulation hydropower stations in China and their cumulative impact on downstream hydrological regimes (Fang *et al.* 2023), it is crucial to prioritize an in-depth analysis of the effects of daily regulation hydropower stations. Therefore, this study seeks to employ the RVA and M-K methods to quantify the effects of daily regulation hydropower stations on changes in hydrological regimes based on IHAs. The upper Yellow River is chosen as the study area due to the presence of two daily regulation hydropower stations (Nina and Laxiwa), alongside a multiyear regulation hydropower station (Longyangxia). The downstream hydrological station at Guide station provides the necessary flow data to elucidate the impact of daily regulation hydropower station operations on runoff, thus enabling river ecologists to better comprehend and predict the effects of daily regulation hydropower stations on river hydrology.

2. STUDY AREA AND DATA

The Yellow River is the fifth longest river in the world, and its upper reaches contribute approximately 57% of the annual runoff for the entire Yellow River basin. The region has witnessed significant developments in the construction and regulation of cascade hydropower stations in China. In this article, the basin controlled by the Guide hydrological station in the upper reaches of the Yellow River is taken as the study area (Figure 1(a)). The annual average water volume is 202.6×10^8 m^3, and the inflow in flood season is 105.5×10^8 m^3, accounting for 52% of the annual total (Yang *et al.* 2010). Three prominent hydropower stations are operative in the study area (Table 1). Longyangxia hydropower station, built in 1986, is the closest hydropower station to the source area of the Yellow River with multiyear regulation capacity. The total storage capacity is about 274×10^8 m^3, controlling about 65% of the water in the upper reaches of the Yellow River. Nina hydropower station was built in 2004 as a daily regulation hydropower station, with a total storage capacity of 0.262×10^8 m^3. Laxiwa hydropower station is 8.6 km away from the downstream Nina hydropower station, and is the second largest cascade hydropower station in the upper reaches of the Yellow River, with a total storage capacity of 10.79×10^8 m^3. The annual power generation of 102.23×10^8 kW·h is about five times that of the Longyangxia hydropower station (Wang *et al.* 2021).

The study utilizes the observed daily runoff data collected from the Guide hydrological station, spanning from 1954 to 2020, encompassing information obtained from the 'Hydrologic Data Yearbook' published by the Yellow River Conservancy Commission (YRCC). Even though the daily operations of hydropower stations do indeed alter the intraday runoff distribution and regimes, this study utilizes daily data instead of hourly data for analysis. This choice is informed by the understanding that ecological impacts are the result of long-term, cumulative changes in runoff (Shu *et al.* 2010; Binh *et al.* 2020). In addition, conducting our analysis on a daily basis offers greater practicality for both ecological and water resource management purposes. The controlled basin area spans approximately 1.33×10^5 km^2, characterized by an average elevation exceeding 3,000 m a.m.s.l. (Figure 1(a)). This region exhibits a plateau continental climate, with an average annual precipitation of

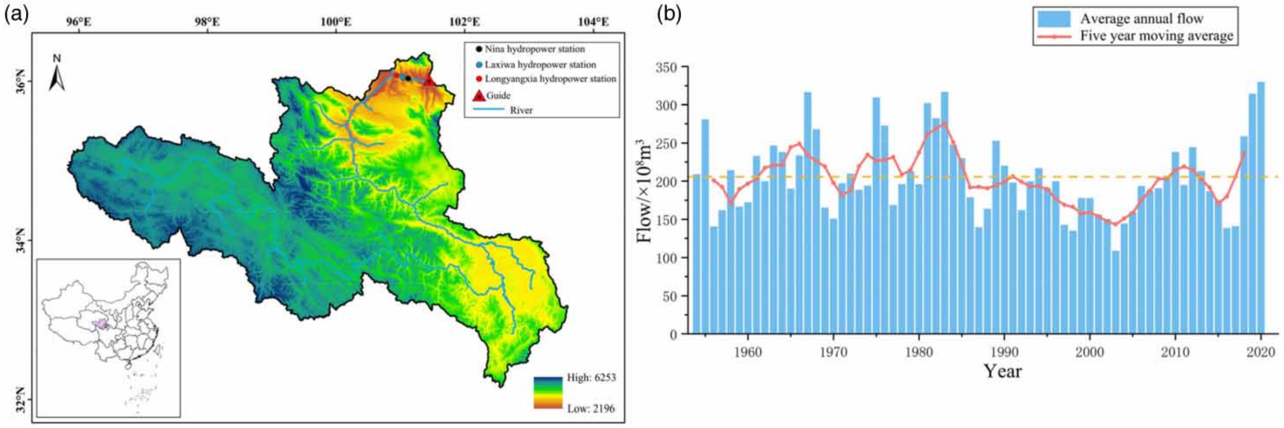

Figure 1 | The location and flow information in the study area.

Table 1 | Characteristic parameters of hydropower stations in river basins

Name	Construction time	Total storage (10^8 m^3)	Installed capacity (MW)	Annual power generation (10^8 KW·h)
Longyangxia	1986	274.4	1280	23.6
Nina	2004	0.262	160	7.63
Laxiwa	2010	10.79	4200	102.23

288 mm and an annual average temperature of 7.2 °C. Notably, over 70% of the precipitation occurs between May and September, with temperature ranges spanning from −23.8 to 34 °C (Yang *et al.* 2010).

The regulation of hydropower stations has substantially altered the hydrological and topographic characteristics of the upper Yellow River region (Wang *et al.* 2007; Jin *et al.* 2020). Figure 1(b) presents the annual runoff over the past 70 years, indicating an average runoff of 205.54 m^3/s. Notably, prior to 1986 when no hydropower stations were present, the annual runoff demonstrated significant fluctuations, with the maximum difference between annual runoff reaching up to 175.97 m^3/s. After that, the difference between annual runoff decreases visibly, the 5-year sliding average flow shows a sudden drop around 1985 and a continued decline for some time thereafter. Nina hydropower station operated around 2004, and the flow showed an upward trend.

3. METHODOLOGY

In this study, the impact of hydropower stations on the hydrological regime within the upper reaches of the Yellow River is assessed using IHA, the M-K trend test, and the M-K mutation test to characterize the significance of the change in indicators. In addition, the overall influence of hydropower stations on the hydrological regime is evaluated using the RVA method.

3.1. Indicators of hydrological alteration

Assessment of natural flow regime change is essential for understanding river ecosystems (Zeilhofer & de Moura 2009; Zhao *et al.* 2012). This study utilizes IHAs to evaluate the impact of hydropower stations on hydrological conditions in the upper Yellow River. The IHA method, as proposed by Richter *et al.* (1997), is employed to characterize inter-annual runoff variability. The IHA method comprises 33 hydrological indicators that encompass five types of hydrological characteristics within the basin. These indicators are used to analyze changes in hydrological conditions by comparing historical flow regimes of river systems across pre- and post-impact periods (Park *et al.* 2020). The 33 hydrological indicators are categorized into five groups: (1) magnitude of monthly water conditions, (2) magnitude and duration of annual extreme water conditions, (3) timing of extreme flow occurrences, (4) frequency and duration of high and low pulses, and (5) flow change rate and frequency (Table 2).

As all observed daily flows within our study area during the research periods were greater than zero, the IHAs 'number of zero-flow days' is not considered in this study. Instead of using the traditional IHA based on the calendar year, we applied an improved IHA method (Ge *et al.* 2018). This method is based on the hydrological year, which more accurately captures the fluctuations of hydrological indicators through a full rainy and dry cycle (Ramesh & Thampi 2023). In addition, the minimum 1-day flow in this region typically occurs during the transition between calendar years, which can lead to misleading results if the traditional calendar-based approach is used. For instance, a shift in the timing of such an event from December 31 to

Table 2 | The indicators of five groups in the IHA

Group	Types	Statistics	Symbol records
Group 1	Magnitude of monthly water conditions	Mean monthly flow from Jan to Dec	IHA1–IHA12
Group 2	Magnitude and duration of annual extreme water conditions	Annual 1-, 3-, 7-, 30-, 90-day maximum flow	IHA13–IHA17
		Annual 1-, 3-, 7-, 30-, 90-day minimum flow	IHA18–IHA22
		Number of zero-flow days	–
		Base flow index①	IHA23
Group 3	Time of extreme flow occurring	Date of 1-day maximum flow	IHA24
		Date of 1-day minimum flow	IHA25
Group 4	Frequency and duration of high and low pulses②	High (low) pulse count	IHA26–IHA27
		High (low) pulse duration	IHA28–IHA29
Group 5	Flow change rate and frequency	Number of flow reversals	IHA30
		Fall rate and rise rate③	IHA31–IHA32

Note: (1) Base flow index refers to the ratio of annual minimum 7-day average flow to daily average flow. (2) The hydrological change indicator method stipulates that the daily flow with a frequency greater than 75% before the reservoir is affected is a high flow, and the daily flow with a frequency less than 25% is a low flow. (3) The increase rate and the decrease rate of the average flow rate for 2 consecutive days compared with the mean value.

January 1 could falsely indicate a significant change. In line with the hydrological patterns of this area, the hydrological year begins on April 1 and concludes on March 31 of the following year.

The IHA method analyzes changes by comparing flow regimes in pre- and post-impact periods, which is normally determined as the influencing time of hydropower stations. In the current study, the period 1954–1986 is defined as the 'natural period' and referred to as the P1 period, since there are no hydropower stations or reservoirs. The period 1990–2010 is referred as the P2 period to evaluate the influence from Longyangxia reservoir or hydropower station. Since the construction of Nina and Laxiwa hydropower stations was completed in relatively close in time, and both stations regulate on a daily scale, their influences are considered together here and the period 2011–2020 is referred as the P3 period.

3.2. Trend and mutation analysis method

To ascertain the significance of changes in hydrological indicators, IHAs from different periods are compared using the M-K trend test and the M-K mutation test to evaluate the impact of additional regulation from daily hydropower stations on these indicators. Detailed information regarding the M-K test can be found in various studies (Lin *et al.* 2017; de Oliveira *et al.* 2021).

3.3. Range of variability approach

The RVA method, proposed by Richter *et al.* (1998), is employed to quantify alterations in the hydrological regime. The method involves dividing the runoff series into 'pre-impact' and 'post-impact' subsequences. The 75th and 25th quantiles of the 'pre-impact' indicators are used as thresholds, with the degree of indicator change calculated based on the proportion of 'post-impact' indicators falling within these thresholds. But it is worth noting that Duan *et al.* (2016) suggested expanding the range to 80% for studies with short datasets. Since our study has 10 years of data in the P3 period, we updated this and used the 90th and 10th percentiles as our cutoffs. The calculation formula of indicator change degree is as follows:

$$D_i = \left|\frac{N_i - N_e}{N_e}\right| \times 100 \tag{1}$$

$$N_e = rN_T \tag{2}$$

where D_i is the hydrological change degree of the ith runoff indicator; N_i is the actual number of years that the ith runoff indicator remains within the RVA threshold range after being affected; N_e is the number of years that the ith runoff indicator is expected to be within the threshold range after being affected; r is the proportion of the ith runoff indicator that was within the threshold range before being affected; N_T is the total number of years after the indicator is affected. According to the calculated D_i, the change degree is categorized into three levels: $0 \leq |D_i| < 33\%$ is low alteration, $33\% \leq |D_i| < 67\%$ is moderate alteration, and $67\% \leq |D_i| \leq 100\%$ is high alteration.

Shiau & Wu (2004) proposed the overall hydrological regime change degree 'D' based on the change degree of a single indicator. D is calculated as follows:

$$D = \sqrt{\frac{1}{N}\sum_{i=1}^{N} D_i^2} \tag{3}$$

where N is the number of hydrological indicators used. The final categorized change level is determined in the same way as Richter *et al.* (1998).

4. RESULTS AND DISCUSSION

This study aims to investigate the impact of daily regulation by hydropower stations on downstream hydrological regimes, which have been affected by multiyear reservoirs, in conjunction with observed runoff data in Guide station, and three subperiods (P1, P2, and P3) are applied in following results and analysis.

4.1. IHA assessment

Figure 2 presents the normalized IHAs in the three periods, ranging from 0 to 1, to facilitate a comparison of hydrological regime changes with the operation of hydropower stations. Each row in the figure represents an IHA indicator, with the columns corresponding to the P1, P2, and P3 periods. Darker colors indicate higher values. Comparing the variations of IHAs

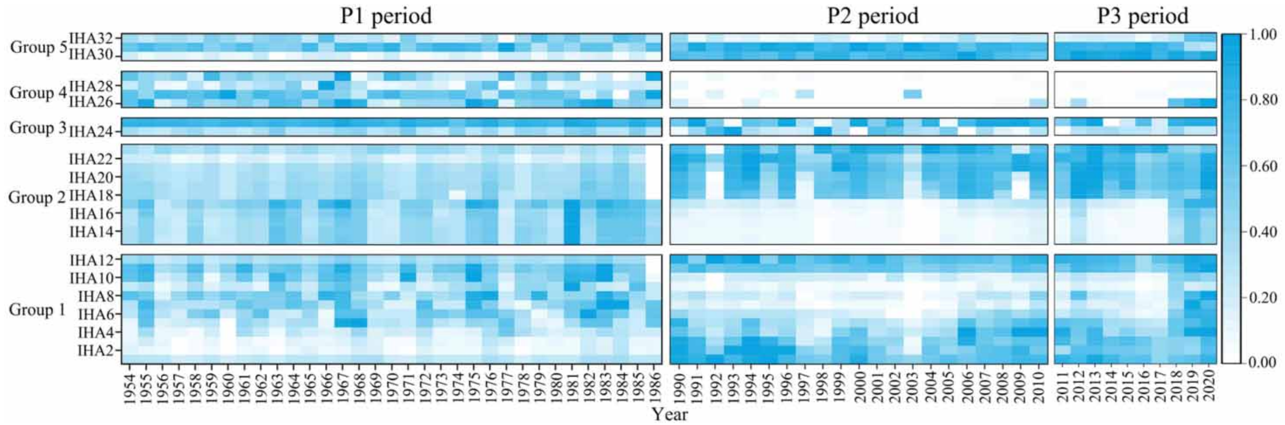

Figure 2 | The annual change of normalized IHAs in groups and periods.

across different periods, larger variances are observed for IHAs during the P1 period, signifying a substantial reduction in inter-annual variation due to the operation of hydropower stations. This finding aligns with previous studies, such as the work by Yan *et al.* (2021a), who observed a flatter flow sequence following the construction of the Liujiaping small hydropower station.

Beyond the overall change, distinct differences are detected among IHAs across different groups. Analysis of IHAs within Group 1 shows that the averaged IHAs 6–10 during the P1 period are larger compared to the other two periods, indicating a disruption of the natural seasonal hydrological regime, where the river flow increases in the dry season and decreases in the flood season (Yang *et al.* 2020; Mezger *et al.* 2021). Moving to the IHAs in Group 2, the colors between minimum and maximum IHAs present visible differences during the P2 and P3 periods besides the period 2018–2020, because the extreme magnitudes are polished by the hydropower station (Vicente-Serrano *et al.* 2017). For the occurrence time of hydrological extremes (IHAs in Group 3), the inter-annual difference in the P1 period seems much smaller than the period with hydropower stations' operation. The averaged IHAs in Group 4 are close to 0 in the P2 and P3 periods, differing substantially from the P1 period, suggesting significant impacts on hydrological extremes due to hydropower station operation (Wang *et al.* 2022; Zhang *et al.* 2023). Moreover, IHAs within Group 5 show smaller differences between years during the P2 and P3 periods compared to the P1 period, indicating a transition toward more stable general flow conditions. Overall, the operation of hydropower stations has led to significant alterations in hydrological regimes, and the noticeable differences between the P2 and P3 periods indicate that we could not ignore the influences of the daily regulation hydropower stations.

4.1.1. Monthly average flow

Figure 3 illustrates the impact of hydropower station regulation on the monthly streamflow. The lines represent the average monthly flow for the three periods, while the bars indicate the difference from the P2 and P3 periods to the baseline P1

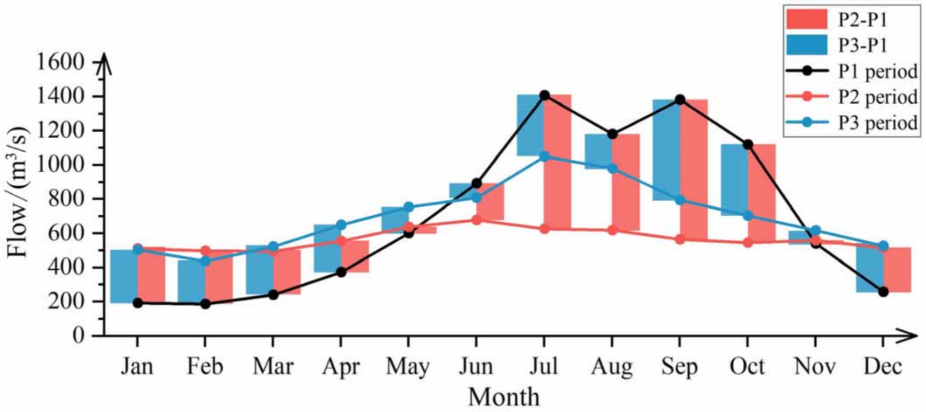

Figure 3 | The monthly mean runoff in different periods and their differences.

period. The monthly average flow in the P1 period appears as obvious seasonal variation, and the difference between the maximum and the minimum flow within the year is 1,218.72 m^3/s (July and February). Comparatively, the flow seasonality decreases markedly in the P2 period, which is affected by the regulation of the Longyangxia hydropower station, and the proportion of the flow in the flood season (July–October) decreases to 34.6% from 60.1% in the P1 period. The change aligns with the findings by Sun *et al.* (2008) and additionally proves the significant impact on the downstream flow regime by running the multiyear regulation and the controlled hydropower station (Poff *et al.* 2007; Zhang *et al.* 2015). The loss of runoff variation directly affects the behavior and life processes of aquatic organisms, leading to potential habitat degradation, especially in summer, when reduced water volume accelerates the breakdown of organic matter and diminishes food supply to organisms (Cui *et al.* 2018; Zheng *et al.* 2021). Comparing the P2 with P3 periods, there is almost the same for months from November to March, meaning the additional daily regulation hydropower stations have no influence. However, flows are obviously higher in other months during the P3 period than in the P2 period, and they align more closely with those during the P1 period. According to the bar plot, the monthly flow regime change decreases when taking the Laxiwa and Nina hydropower stations together with regulating Longyangxia, and the blue bars are generally shorter than the red ones. This result proves that additional inclusion of daily regulation hydropower station does not produce larger change in the monthly flow, which reminds us that we should pay more attention to analyzing different regulation effects on the hydrological regimes.

4.1.2. Annual extreme flows

Annual extreme flow plays a pivotal role in maintaining the equilibrium of competition among organisms and in shaping river ecosystems. Table 3 illustrates the mean values of extreme flow in three distinct periods, highlighting a decrease in maximum statistics and an increase in minimum statistics for the P2 period. This pattern reflects the primary impact of hydropower stations, which regulate based on reservoirs specifically designed to alter the hydrological regime in this manner (Brunner 2021; Lazin *et al.* 2023). Nevertheless, the extent of these changes varies significantly across different statistics and periods. Notably, when the statistics are analyzed within a weekly timeframe, the maximum statistics decrease by over 60% from the P1 to the P2 period. Similarly, Sarauskiene *et al.* (2021) examined hydrological alterations in Lithuanian rivers and observed a substantial impact of hydropower generation on the maximum discharge of 1-, 3-, and 7-day periods. Such substantial changes can heavily disrupt the distribution of plant and animal populations in floodplains (Junk & Bayley 2008). When incorporating the operation of daily regulation at hydropower stations, the maximum flow notably increases, while the variation is reduced by approximately 40% compared to the results observed between the P1 and P3 periods. The occurrence of high-flow events enhances the connectivity between the floodplain and the main channel, playing a crucial role in delivering nutrients to wetlands and providing fish and other mobile organisms with increased opportunities to move through rivers into floodplains for breeding or into shallower habitats (Xie 2003; Arthington *et al.* 2010; Guo *et al.* 2024). As for the minimum flow statistics, a positive relationship is evident between the extent of change and the timescale, consistent for both the P2 and P3 periods. For instance, from the P1 to the P2 period, the minimum 1-day flow increases by 32.16% and further rises to 66.47 and 126.71% for the minimum 7- and 90-day periods. This phenomenon is reasonable and expected, since raising the minimum daily flow is one of the functions of hydropower station-based reservoirs, which aims to meet the downstream domestic and ecological water needs. This difference and impacts are cumulated to be larger with the increased time, as well as more hydropower stations. Contrasting the extent of change between the P2 and P3 periods from the baseline P1 period, a larger average change is apparent in the P3 period. This change could not only enhance water purification but also increase the contact time between air and water, thereby effectively ensuring the safety and stability of the hydrological ecology in the basin (Cheng *et al.* 2018).

Table 3 | Magnitude and duration of extreme flows at different periods

Period	Max1d	Max3d	Max7d	Max30d	Max90d	Min1d	Min3d	Min7d	Min30d	Min90d	Base flow indicators
P1	2494.24	2432.02	2316.54	1852.04	1398.51	151.04	159.89	164.27	174.00	202.76	0.24
P2	960.71	911.62	874.33	790.50	693.38	199.63	233.74	273.46	369.12	459.67	0.48
P3	1544.10	1473.50	1403.01	1228.71	1017.97	249.40	311.83	344.66	395.03	467.00	0.52

Figure 4 depicts the maximum and minimum 1-day flows for each year during the three periods, showcasing clear differences from both the average and range perspectives. According to Figure 4(a), the P2 period exhibits lower maximum 1-day flow values, and they fluctuate within a smaller range. This pattern aligns with anticipated outcomes, as the water retention practices of hydropower stations significantly stabilize the downstream river flow, thereby profoundly affecting the natural runoff dynamics (Zhou *et al.* 2024). The interesting phenomenon is that the additional operation of daily hydropower stations (P3 period) has led to a rise in the average and variability of maximum 1-day flow, bringing them closer to the levels observed in the P1 period. Figure 4(b) displays the annual minimum 1-day flow across various periods, with a notable increase in the average values from 151.04 m^3/s in the P1 period to 249.40 m^3/s in the P3 period. The commencement of daily hydropower operations has significantly raised the minimum 1-day flow, from a low of 5.24 m^3/s in the P2 period to 169 m^3/s in the P3 period. Given the vital role extreme flows play in shaping channels, this enhancement in the flow is perceived to be beneficial for the river's ecological health and supports the finding that hydropower stations play a significant role in downstream channel morphology (Ma *et al.* 2012; Liu *et al.* 2021).

4.1.3. Occurrence time of annual extreme flows

The occurrence time change of the extreme flow could seriously affect the habitat environment of downstream organisms (Zheng *et al.* 2021). The left panel of Figure 5 presents the proportion of the time that the extreme flow occurs in each month for the three periods concerning the maximum 1-day flow, indicating a shift in the occurrence time of these extreme flows. In the P1 period, the maximum 1-day flow occurred predominantly from June to October, with the majority (93.93%)

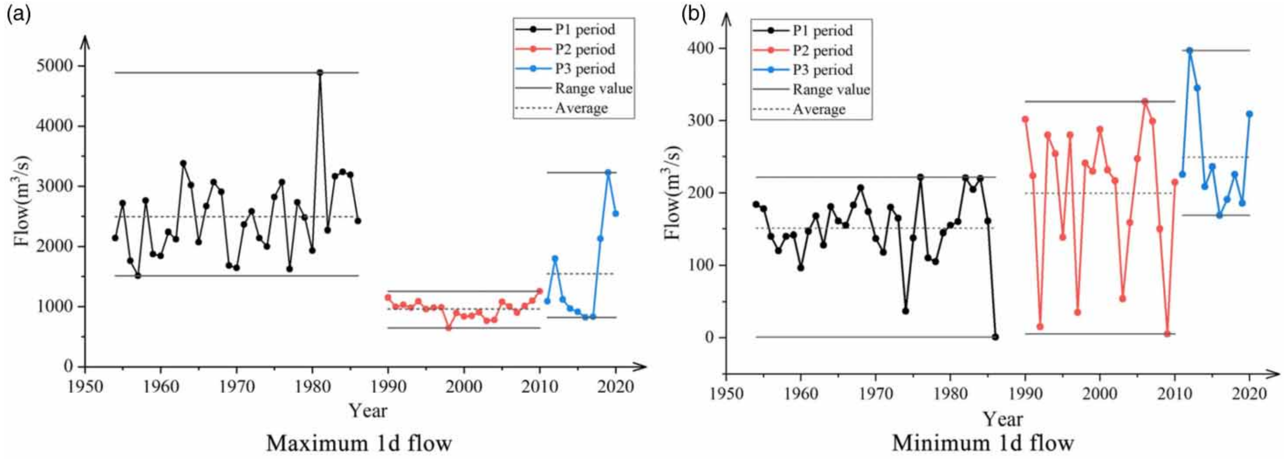

Figure 4 | Variation of annual maximum and minimum 1d flows in different periods.

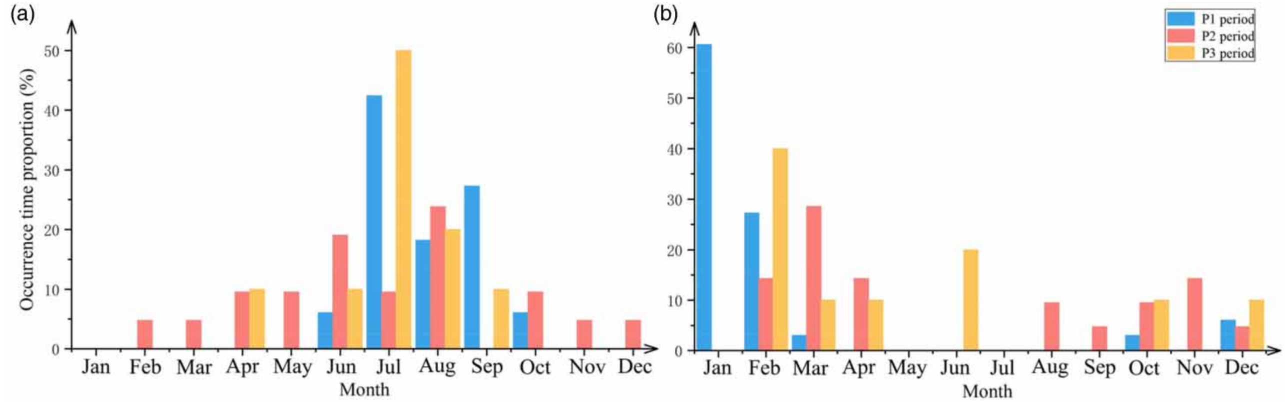

Figure 5 | Monthly distribution of occurrence time for (a) maximum and (b) minimum 1d flow in different periods.

occurring during the flood season. With the operation of the Longyangxia hydropower station, the occurrence time of the maximum 1-day flow in the P2 period varied across months, and the proportion from November to May reached 38.1%, which is 0 in the P1 period. The addition of daily regulation by hydropower stations resulted in a more concentrated distribution, whose proportion of occurrence in flood season is 80%, aligning it closer to the P1 period. What is more, the month with the highest probability of occurrence is July in P1 and P3 periods, while the largest probability of occurrence in the P2 period was August, indicating a favorable shift toward a more natural flow regime. The right panel of Figure 5 presents the minimum case; the occurrence time of minimum 1-day flow also exhibited substantial changes across the three periods. In the P1 period, the minimum 1-day flow occurred mainly in January and February, whose total proportion reaches 87.88%, which decreases to about 15% for the P2 period and 40% for the P3 period. Besides that, the occurrence time of minimum 1-day flow is found in only 5 and 6 months of the year for P1 and P3 periods, respectively; however, it increases to 8 months of the year for the P2 period. This result gives more support to the notion from Magilligan & Nislow (2005), who found that the operation of hydropower stations significantly affects the release time and greatly destroys the expected flow time of natural flow. Summarizing both plots over three periods, the differences between P1 and P2 are much larger those between P1 and P3 periods, meaning that the additional regulation of daily hydropower makes the hydrological regimes close to the natural station. Guo *et al.* (2022b) and Singh & Jain (2021) believe that the occurrence time of extreme flow may affect the life cycle and death pressure of various aquatic species under flood and drought conditions, so the additional regulation of daily hydropower stations will be favorable for fish breeding and habitat recognition.

4.1.4. The count and duration of high- and low-flow pulse

Table 4 illustrates the variation in the count and duration of high- and low-flow pulses, and the operation of Longyangxia hydropower station has greatly reduced the count and duration of both high and low flows. The count of pulses has decreased to less than 10 occurrences, with duration of less than 2 days and a change rate exceeding 90%. High flows are primarily a result of heavy rainfall and snowmelt, and the substantial reduction in pulse count and duration indicates a reduction in downstream flooding, ultimately leading to a more stable channel (Gao *et al.* 2012; Yang *et al.* 2020). However, Yang *et al.* (2020) and Guo *et al.* (2022a) pointed out that the reduction of high and low counts diminishes hydrological connectivity, hindering the exchange of nutrients and organic matter, and fish need high flows to stimulate reproduction. When comparing the P2 period, the average count of high-flow pulses increased from 7.05 in the P2 period to 47.70 in the P3 period, with the average duration extending to 2.42 days, indicating a more favorable environment for the ecosystem. He (2012) argues that an appropriate increase in the high-flow pulse can mitigate impacts such as the increased water temperature or low oxygen conditions caused by the low flow and provide nutritional supplementation. Moreover, it can also avoid excessive high-flow pulse resulting in various pollutants being washed into the river, causing water pollution. It merits attention that there is a notable reduction in the count and duration of low-flow pulses from the P2 to P3 period. This trend is plausible, given that the daily hydropower station should both meet the power generation demand and ensure ecological water use. In summary, with the inclusion of daily hydropower stations, contrast alteration trend between high and low flow is obtained, suggesting a reduction in low-flow occurrences, as noted by Kuriqi *et al.* (2021) and Wang *et al.* (2023). This change becomes more different from natural conditions, but might not be a bad phenomenon. As Rolls *et al.* (2012) have highlighted, the disappearance of low flow could prevent severe blooms and promote diversity of biological association.

4.1.5. Flow change rate and frequency

Figure 6 illustrates the rate and frequency of runoff changes, with frequency measured as the number of reversals, shown on the secondary *y*-axis. Following the operation of the Longyangxia hydropower station, there has been a significant increase in

Table 4 | The count and duration statistics of high- and low-flow pulse in different periods

Flow frequency and duration	P1 period	P2 period	P3 period
High-flow pulse count	91.03	7.05	47.70
Low-flow pulse count	90.79	8.81	2.30
High-flow pulse duration	30.14	1.33	2.42
Low-flow pulse duration	32.45	1.28	0.71

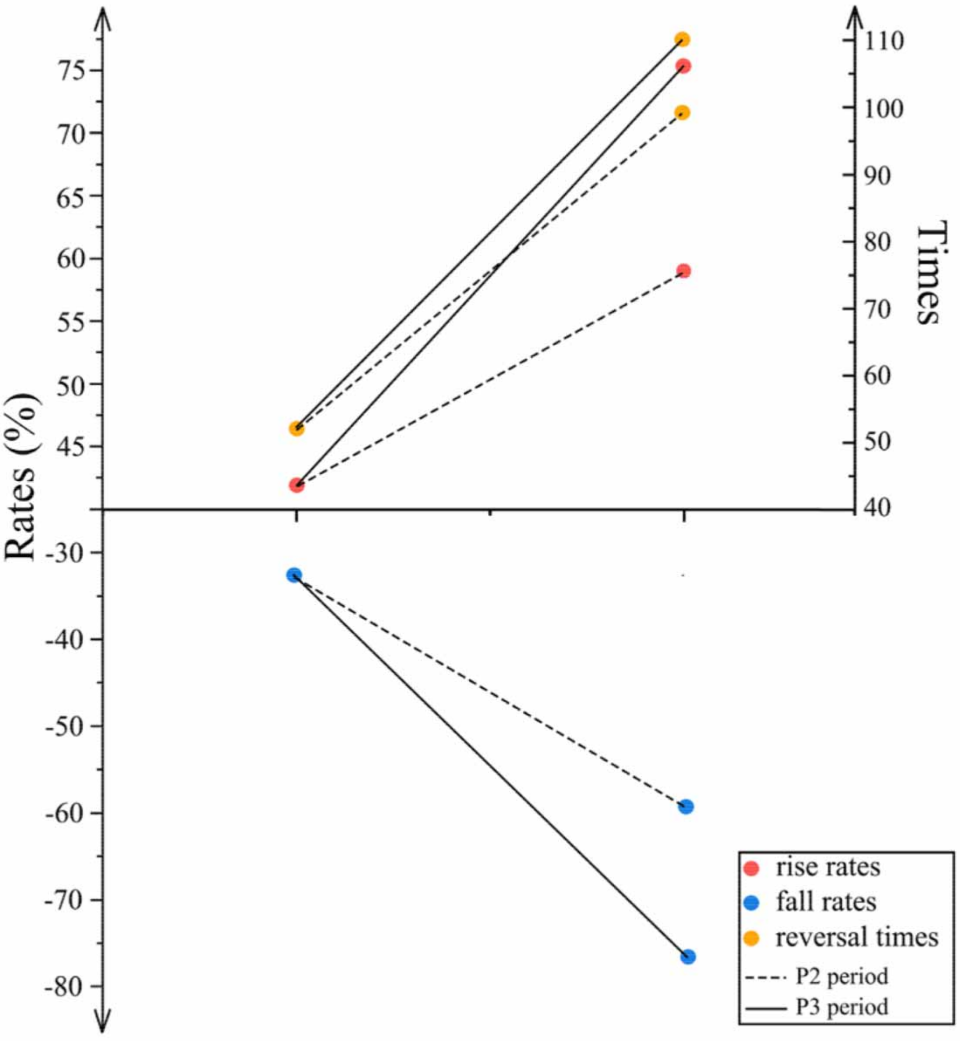

Figure 6 | Flow change rate and frequency in different periods.

the number of reversals, rising from 51.39 times in the P1 period to 99.29 times in the P2 period. This effect is further exacerbated with the addition of daily regulation at hydropower stations, possibly because this particular IHA is regarded as the most affected by hydropower operations (Sarauskiene *et al.* 2021). The rate of flow rise and fall in the P2 period has notably increased, consistent with the impact observed by Song *et al.* (2020) on the Guide Basin resulting from the operation of the Longyangxia hydropower station. Similar to the number of reversals, the degree of change rate further increases with the additional operation of daily regulation at hydropower stations, signifying that downstream runoff varies to a greater extent and at a more frequent pace. The larger and more frequent fluctuations in flow have more severe destabilizing effects on flora and fauna, hindering organisms in dive areas from laying roe and providing them with less time to seek shelter (Yan *et al.* 2021b; Zheng *et al.* 2021). Although the additional change extent might be smaller in other regions than here, as the Nina and Laxiwa hydropower stations are in close proximity to the hydrology observing station, amplifying the impact of small amplitude and short-duration changes (Zhou *et al.* 2012). The comparison reveals consistency among IHAs in Group 5, indicating that the deviation from the natural state becomes more pronounced with the added operation of daily regulated hydropower stations.

4.2. Significance test for IHAs

The preceding results demonstrate the temporal variation of IHAs, revealing noticeable changes. To ascertain the significance of these variations, the M-K test method is applied for all IHAs. The P3 period exhibits compounded impacts from both

Longyamngxia and the daily regulation hydropower stations, and when delineating the specific impacts attributable to the daily operation of hydropower stations, it is essential to exclude the impact from Longyangxia Station. For this purpose, refined datasets are employed following the approach from Fang *et al.* (2023).

Figure 7 presents the outcomes of the M-K trend test with a 95% confidence interval, with black circles indicating those IHAs whose trends shifted from significant to insignificant. When combining the P1 and P2 periods as a series, 27 indicators exhibit significant trends, signifying that almost 85% of IHAs have been significantly affected by the operation of the Longyangxia hydropower station. However, when combining the P1 and P3 periods, the number of IHAs experiencing significant trends reduces to 18, marking a decrease of over 30%. This substantial difference can be attributed to the additional regulation implemented by daily hydropower stations. Furthermore, the inclusion of the P3 period results in 10 IHAs' trends changing from significant to insignificant, which includes the monthly average flow during the flood season and extreme flow IHAs. Consequently, it is reasonable to posit that the inclusion of daily regulation hydropower stations has a positive impact on the long-term hydro-ecological sustainability, suggesting it as a potential means to mitigate future damages.

Figure 8 shows the M-K mutation test results for IHAs. Eighteen IHAs exhibit significant mutation due to the operation of daily regulation hydropower stations, accounting for 56.25% of all IHAs. Therefore, the impact of daily regulation hydropower stations should not be overlooked in future considerations. Upon examination of IHAs within each group, all IHAs in Group 3 show mutation, decreasing to eight IHAs (constituting over 70%) in Group 2 and 50% of IHAs in Group 1. These disparities between groups may stem from regional sensitivity. Further exploration is necessary to determine whether the changing characteristics of IHAs exhibit regional or consistent patterns within particular types of cases.

4.3. Evaluation of hydrological regime alteration

Clear disparities are evident when comparing IHAs across different periods, signifying shifts in hydrological regimes. To elucidate the degree of change for each indicator and the overall impact of hydropower stations, the RVA method is employed and the findings are presented in the following subsections.

4.3.1. Evaluation from each IHA's aspect

Figure 9(a) illustrates the degree of change for each indicator assessed using the RVA method, with high, moderate, and low alteration categories depicted from the center to the outermost. During the P2 period, 24 IHAs are situated in the high alteration zone, among which 7 IHAs exhibit a 100% change from the P1 period, indicating a comprehensive impact from the multiyear hydropower station on the hydrological regime. In contrast, the number of IHAs situated in the high alteration zone visibly decreases for the P3 period, such as maximum flow and occurrence time of extreme flow, suggesting that the

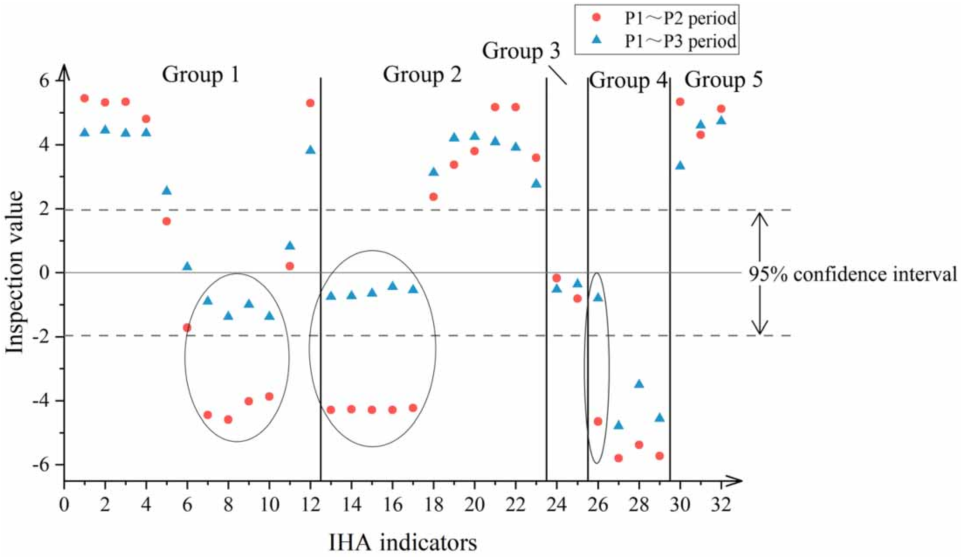

Figure 7 | The result of M-K trend test for IHAs in different periods (black circles indicate IHAs whose trends shifting from significant in P2 period to non-significant in P3 period).

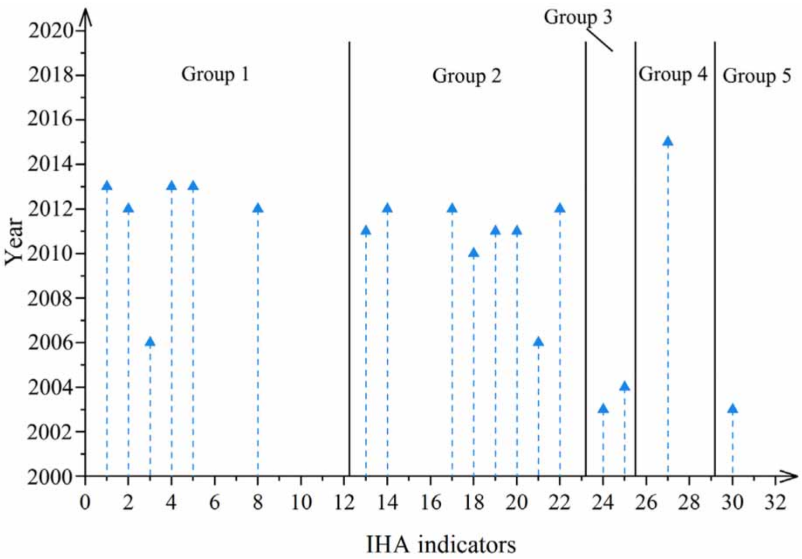

Figure 8 | The significantly changed IHAs and the changing point by M-K mutation test.

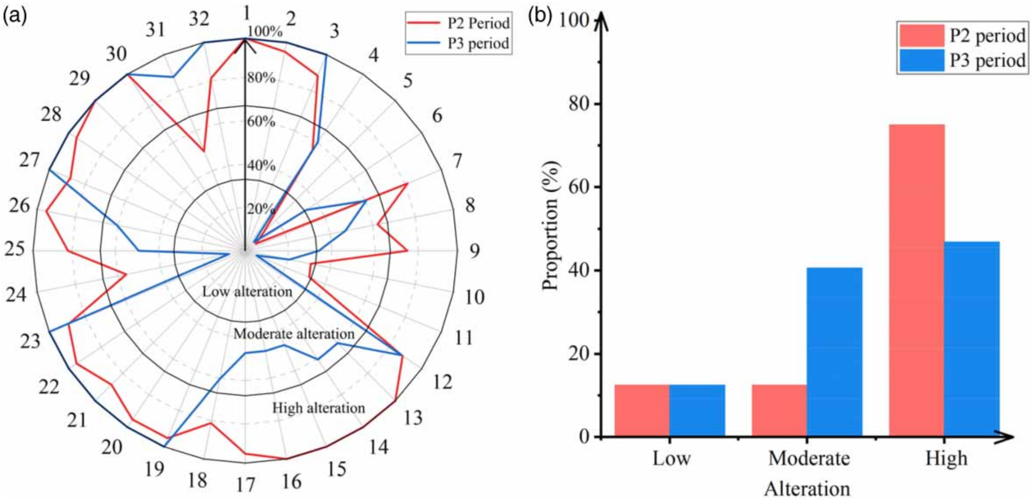

Figure 9 | Change diagram of 32 hydrological indicators in two periods. *Note:* Mean monthly flow from Jan to Dec (1–12): Annual 1-, 3-, 7-, 30-, 90-days maximum yearly flow and minimum flow (13–22); Base flow index (23); Date of 1-day maximum and minimum flow (24–25); Count and duration of high and low pulses per year (26–29); Average daily flow rise rates, fall rates, and number of flow reversals (30–32).

additional regulation with the daily hydropower station aligns the hydrological regimes more closely with those of the P1 period. However, it is noteworthy that IHAs in Group 4 and Group 5 (IHA26 – IHA32) remain in the high alteration category for both P2 and P3 periods, indicating their sensitivity to the impact from hydropower stations regardless of the regulation modes. This finding is partially consistent with Ely *et al.* (2020), who studied a watershed in Paraguay with numerous small hydropower stations and found the greatest impact on the Group 4 and Group 5 indicators.

Figure 9(b) presents the distribution of IHAs across change categories. At first glance, the proportion of IHAs in the low and moderate groups is minimal for the P2 period, with a similar distribution appearing between the moderate and high alteration groups for the P3 period. The significant 28.13% decrease in the high alteration category from the P2 to P3 period indicates that the combined operation of daily regulation hydropower stations effectively reduces the substantial impact from controlled hydropower stations.

Table 5 | Each group and overall hydrological alteration in P2 and P3 periods

Period	Hydrologic change degree (%)					Overall hydrologic change degree (%)
	Group 1	Group 2	Group 3	Group 4	Group 5	
P2	67.96	93.99	70.14	93.82	79.70	82.29
P3	64.46	78.41	35.22	91.72	95.80	75.24

4.3.2. Evaluation from groups and overall aspect

Table 5 outlines the degree of change for IHAs during the P2 and P3 periods in groups, calculated using Equation (3). Examining the results from the P2 period, IHAs in Group 1 exhibit the lowest degree of change, but still reaches a high alteration, with an overall hydrological change of 82.29% falling into the high alteration category. With the additional regulation from daily hydropower stations, the degree of change in Groups 2 and 3 significantly decreases, with Group 3 experiencing a 34.92% reduction from the P2 period. However, an opposite trend is observed in Group 5, with the change degree notably increasing to 95.8%, suggesting additional damage to hydrological regimes from the supplementary daily regulation of hydropower stations. Although the overall hydrological change degree decreases to 75.24%, indicating that the general hydrological regimes align more closely with natural conditions due to the inclusion of daily regulation hydropower stations, the additional impact observed in Group 5 warrants attention in future applications.

5. CONCLUSION

The burgeoning regulation of hydropower stations has sparked substantial debate surrounding the alteration of hydrological and ecological regimes in contemporary hydrological research. This study conducted an analysis in the upper Yellow River, where the hydrological regimes are impacted by three hydropower stations, employing the M-K test and RVA method with the IHAs to assess the influences of these hydropower stations. Through the comparison of impacts from multiyear and daily regulation hydropower stations, the following conclusions have emerged from this study:

(1) The impact of daily regulation hydropower stations on runoff dynamics is of significant consequence. Upon the integration of facilities for daily regulation with the Longyangxia, which is characterized by multiyear regulation capabilities, several observations have been made regarding the runoff patterns. Namely, the runoff patterns exhibited seasonal variability, and the annual extreme flow values have undergone changes, with their timing now more closely aligning with the natural period. The implementation of daily regulation hydropower stations has, in the majority of instances, led to the imitation of natural hydrological attributes in IHAs.

(2) The supplementary operation of daily regulation hydropower stations has the potential to mitigate the changes or impacts induced by multiyear hydropower stations on hydro-ecological environments, although not universally. The change degree decreased for 16 IHAs with the additional regulation of daily hydropower stations. According to the M-K test, the total number of IHAs exhibiting a significant trend decreased from 27 to 18 with the inclusion of daily regulation hydropower stations alongside the multiyear regulated hydropower station, and the operation of daily regulation hydropower stations caused mutations in 18 IHAs in the P2 period.

(3) With the operation of daily regulation hydropower stations (Nina and Laxiwa), the overall degree of change in the hydrological regime in the upper Yellow River decreased to 75.24% from 82.29% when solely operating the multiyear hydropower station, Longyangxia. Nevertheless, the change in IHAs within Group 5 increased by approximately 16.10%.

The findings underscore the complex interplay of multiyear and daily regulation hydropower stations on hydrological and ecological dynamics, emphasizing the need for continued investigation and monitoring to comprehensively understand and mitigate their impacts.

AUTHOR CONTRIBUTION STATEMENT

Xue Yang and Fengnian Li: conceptualization, methodology, funding acquisition, writing – original draft. Shi Li and Xiaohua Fu: data curation and analysis, methodology, investigation, writing – review and editing. Jungang Luo and Ganggang Zuo: data curation, funding acquisition and analysis – review and editing. Chong-Yu Xu: review and editing.

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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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