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Quantifying the impact of climate change and human activities on the eco-hydrological regimes of the Weihe River Basin, Northwest China

Shanhu Jiang[a,b,*], Yating Liu[b], Menghao Wang[b], Yongwei Zhu[b], Hao Cui[b], Shuping Du[b] and Chong-Yu Xu[c]

[a] State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, China
[b] College of Hydrology and Water Resources, Hohai University, Nanjing 210098, China
[c] Department of Geosciences, University of Oslo, Oslo, Norway
*Corresponding author. E-mail: hik0216@hhu.edu.cn

ABSTRACT

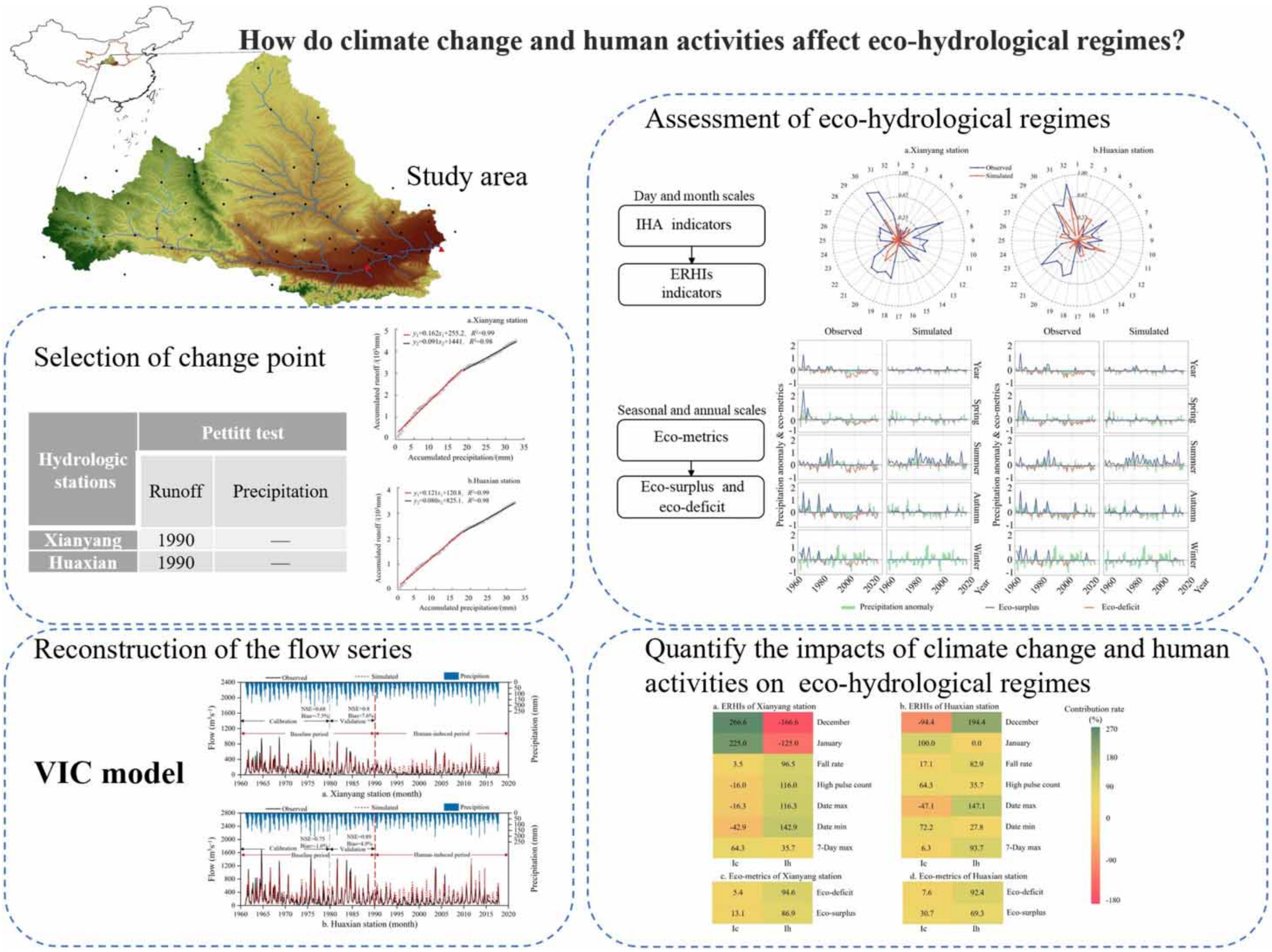
Climate change and anthropogenic interventions have obviously altered the eco-hydrological regimes. A quantitative evaluation and attribution of the eco-hydrological alterations are urgently required. In this study, we evaluated the various attributions of eco-hydrological regimes in the Weihe River Basin (WRB). Firstly, the trends and change-point analysis of hydrological elements were examined, and the natural streamflow was reproduced based on the variable infiltration capacity model. Then, the most ecologically relevant hydrological indicators (ERHIs) were selected and combined with the eco-deficit and eco-surplus indicators to assess the degree of eco-hydrological regime alterations. Finally, the relative contributions to eco-hydrological alterations were quantified using the 'simulated–observed comparison' method. The results showed that (1) the streamflow of the WRB exhibited significant decreasing trends ($p < 0.01$), and a significant change point ($p < 0.01$) of the streamflow series was identified in 1990. (2) Seven representative indicators of hydrological alteration were selected as ERHIs. (3) During the human-induced period (1991–2017), human activities were the dominant factors in the eco-hydrological alterations as well as the variations of the ERHI indexes and the eco-deficit and eco-surplus metrics. Overall, the proposed framework may improve the understanding of the driving forces of eco-hydrological regime alterations under a changing environment.

Key words: changing environment, eco-deficit, eco-hydrological regime, eco-surplus, Weihe River Basin

HIGHLIGHTS

- The principal component analysis was used to remove redundancy and correlation among the indicators of hydrological alterations and determine the ecologically relevant hydrological indicators.
- A combination of ERHIs and eco-metrics to assess the eco-hydrological regime alterations at different time scales is used.
- The effects of climate change and anthropogenic activities on the eco-hydrological regime alterations were quantitatively distinguished.

GRAPHICAL ABSTRACT



1. INTRODUCTION

River streamflow and flow regimes determine many fundamental ecological processes in river ecosystems, which in turn affect river ecosystem health (Poff & Zimmerman 2010). With the development of the social economy and population increase, human interventions have caused a massive change in the hydrological cycle of basins and consequently altered the eco-hydrological regimes of rivers to varying degrees, adversely affecting the health of river ecosystems over the past several decades (Zhu *et al.* 2021; Cui *et al.* 2022; Jiang *et al.* 2022; Wang *et al.* 2022b). River atrophy, sediment deposition, water pollution, and biological diversity are persistent problems (Nienhuis *et al.* 2020; Zhang *et al.* 2020; Luo *et al.* 2021; Wang & Sun 2021). Analysing the degree of change in river eco-hydrological regimes and quantitatively differentiating the impacts of climate change and human activities on the evolution of eco-hydrological regimes are of great scientific importance for river health management with environmental change adaptation.

In recent years, an increasing number of experts have focused on quantifying the evolution of eco-hydrological regimes. The indicators of hydrological alterations (IHAs) with 32 parameters developed by Richter *et al.* (1996) can be used to quantitatively evaluate the variable characteristics of hydrological regimes and serve as an important foundation for further investigation of hydrological processes. Richter *et al.* (2003) proposed the range of variation approach (RVA) based on IHA indexes to evaluate the degree of hydrological change and quantitatively set the range of environmental flow change in a natural state. Yang *et al.* (2012) analysed the hydrological index characteristics of the main channel of the Yellow River in accordance with the RVA method and evaluated the ecological benefits of the river. Lian *et al.* (2012) used IHA indexes to analyse the impact of human activities such as the construction of locks and dams in the Illinois River, a tributary of the Mississippi River. However, the 33 IHA indexes were too numerous to be easily calculated and analysed, making it challenging to operate and manage water resources in practice. In addition, there is an issue with autocorrelation among the IHAs. Yang *et al.* (2008) used principal component analysis (PCA) and other techniques to select six indicators as ecologically relevant hydrological indicators (ERHIs) of the Illinois River to simplify the IHA indexes. In addition, Vogel *et al.* (2007) examined the relationship between dam construction and eco-hydrological regimes by combining flow duration curves (FDCs) with eco-deficit and eco-surplus indicators, a technique that was recently implemented in the Yangtze and Yellow Rivers (Zhang *et al.* 2016, 2018; Gao *et al.* 2018). By using the eco-deficit and eco-surplus indicators, the changes in the eco-hydrological regimes of a basin can be observed more intuitively.

In addition, previous research shows that global warming has become an indisputable fact (Ji *et al.* 2014). With the rapid development of the social economy, it has become impossible to ignore the increasing anthropogenic influence (Jiang *et al.* 2019). Examples of global environmental problems include river cut-offs (Belletti *et al.* 2020), ecosystem degradation (Palmer & Ruhi 2019), and a severe shortage of water in meeting ecological water demand (Yan *et al.* 2022). Under the combined influence of climate change and anthropogenic activities, the characteristics of the water cycle in basins have changed dramatically, especially regarding the evolution of eco-hydrological regimes (Jiang *et al.* 2021). Therefore, a suitable approach is required to distinguish between the contributions of climate change and anthropogenic activities to eco-hydrological regimes. The simulated-observed comparison method is widely used to quantify the impact of environmental changes on runoff evolution by comparing runoff characteristics under natural and human-influenced conditions (Jiang *et al.* 2011, 2019). This method requires minimal data and can be used to reconstruct the natural streamflow process with a suitable hydrological model.

The Weihe River, which flows through the arid and semi-arid areas of Northwest China, is the largest tributary of the Yellow River. There is a clear contradiction between the development of water resources and the ecological environment. The ecological water demand is frequently displaced by the national economic water demand (Liu *et al.* 2022), resulting in a series of environmental problems (Ma *et al.* 2022). However, most studies on hydrological alterations in the Weihe River basin (WRB) have not used an in-depth approach to improve the redundant IHA indexes, nor have they evaluated the relationship between hydrological changes and ecosystems.

In this study, the effects of climate change and anthropogenic activities on the eco-hydrological regime alterations of rivers (the ERHIs, eco-surplus, and eco-deficit metrics) were quantitatively distinguished using the simulated-observed comparison method to provide a scientific foundation for river health management with adaptation to an environmental change.

2. STUDY AREA AND DATA

2.1. Study area

The Weihe River (Figure 1), which originates at the Niaoshu Mountain in Gansu Province and flows 818 km through the Gansu and Shannxi Provinces, is the largest tributary of the Yellow River. The WRB is located between 33°–38°N and 104°–110°E. The drainage area is 10.6×10^4 km^2 and encompasses three provinces (Gansu, Ningxia, and Shaanxi). This basin primarily consists of the Loess Plateau and the Guanzhong Plain. The WRB is situated in the transition zone between semi-humid and semi-arid areas and is characterised by a temperate continental monsoon climate. Winters are dry and cold, whereas summers are wet and hot. Based on the observed hydro-meteorological records from 1961 to 2017, the mean annual precipitation is 564.5 mm. The annual average natural runoff is 6.331 billion m^3, which corresponds to a runoff depth of 59.7 mm, and the annual average runoff coefficient is 0.11.

2.2. Data

Meteorological and hydrological stations are established in the WRB (Figure 1). All meteorological stations possess the daily precipitation, maximum, mean, and minimum air temperatures, and wind speed data from 1 January 1961 to 31 December 2017. These datasets were acquired from the China Meteorological Data Service Centre (http://data.cma.cn/en). Two hydrological stations, Xianyang and Huaxian, with drainage areas of 4.68×10^4 and 10.6×10^4 km^2, respectively, were selected as the control sites. Both sites had complete daily streamflow records from 1 January 1961 to 31 December 2017. The Yellow River Conservancy Commission supplied the data from hydrological stations. Moreover, three GIS data layers were utilised for variable infiltration capacity (VIC) modelling: the global 3-s Shuttle Radar Topography Mission digital elevation model (DEM) data provided by the U.S. Geological Survey (USGS) (https://lta.cr.usgs.gov/SRTM); the 30-arcsec global DEM

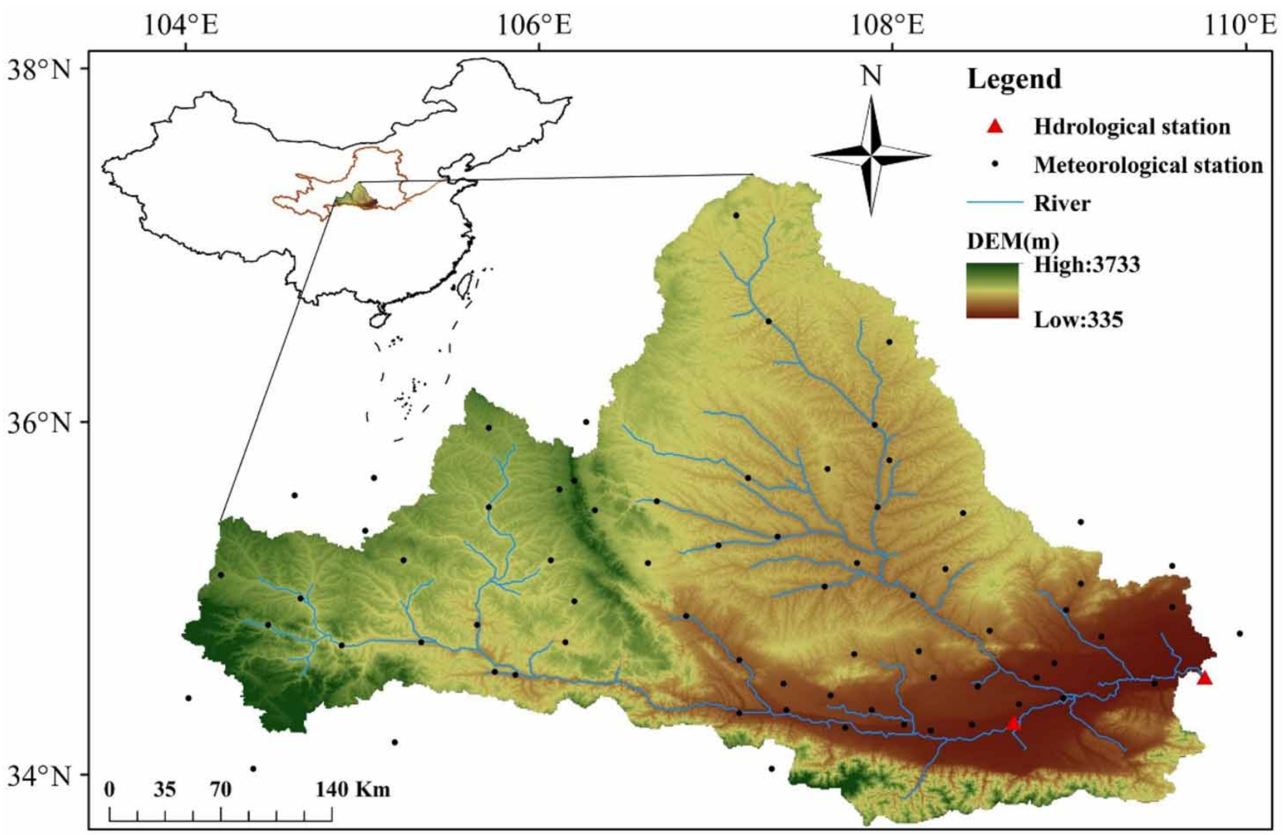


Figure 1 | Location of the WRB and distributions of hydro-meteorological stations.

data from the USGS website (https://www.usgs.gov/); and the global 1-km land cover classification product developed by the University of Maryland (UMD) (Hansen *et al.* 2010).

3. METHODS

Figure 2 depicts the steps and methods of the study. They are described in detail below.

3.1. Variation analysis method

The Mann–Kendall trend test, the Pettitt test, and the double mass curve were applied to the annual runoff data of the WRB from 1961 to 2017 to demonstrate the hydrological process variability. Based on the outcomes of transition point selection, the study period can be divided into the baseline (i.e., less disturbed by human activities) and the human-induced (i.e., more affected by human activities) periods.

3.2. Description of the VIC model

The VIC model was used to reconstruct natural runoff in the WRB. VIC is a macroscale distributed hydrological model that aims to balance water and surface energy budgets within the grid-cell (Jiang *et al.* 2021). It simulates terrestrial surface–atmosphere fluxes of moisture and energy such as evapotranspiration, surface runoff, baseflow, radiative fluxes, turbulent transport fluxes, and sensible heat within the grid-cell. The surface runoff and baseflow components of the gridded runoff are subsequently routed to the basin outlet. The model parameters can be divided into two categories. The first category of parameters is left unadjusted once calculated from the Harmonized World Soil Database and comprises soil porosity θ_s ($m^3\,m^{-3}$), saturated soil potential ψ_s (m), saturated hydraulic conductivity k_{sat} (ms^{-1}), and exponent B for unsaturated flow, as well as the UMD global land cover classifications (root depth and root fraction). The second category includes user-calibrated parameters (variable infiltration curve parameter b and thickness of different soil layers d) based on the agreement between the simulated and observed hydrographs at the basin outlet (Liang *et al.* 1994; Wang *et al.* 2020).

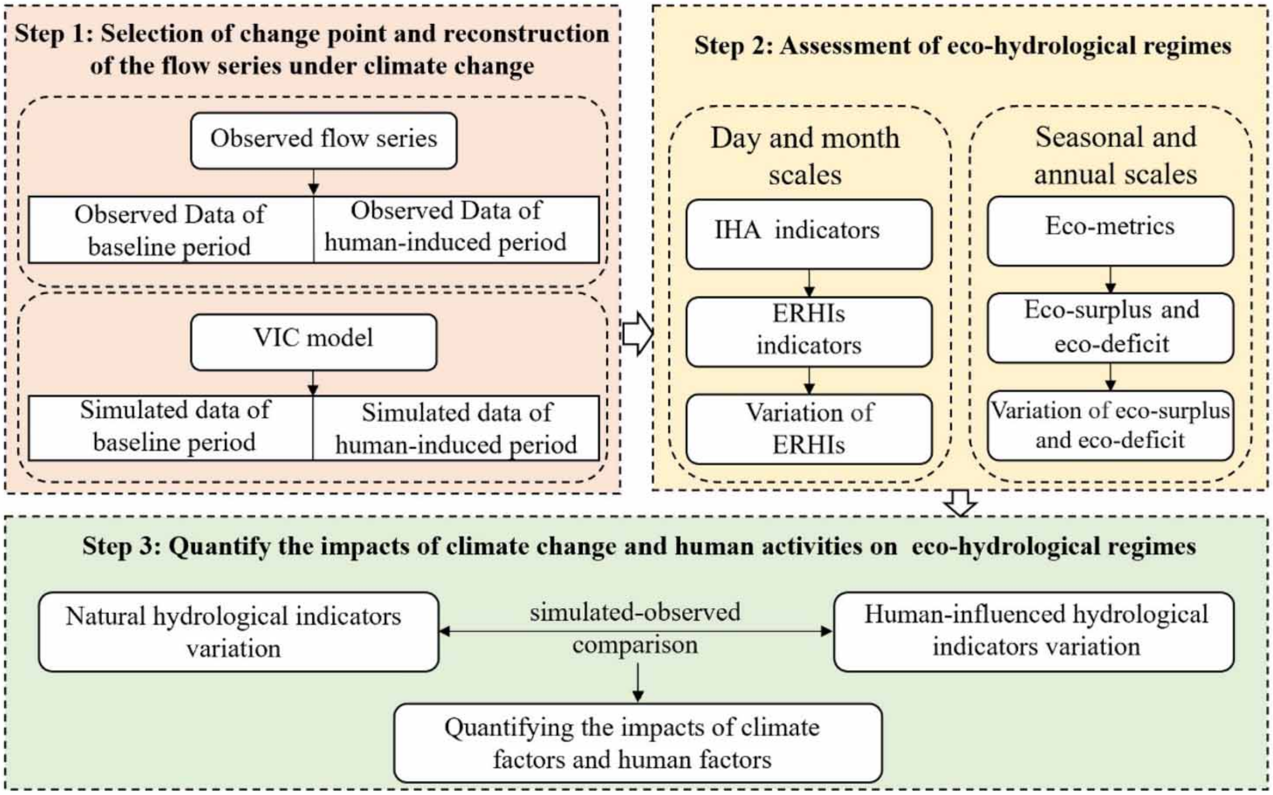


Figure 2 | An observation-based strategy for comparing natural and human-impacted catchments to distinguish the effects of climate change and human activities on eco-hydrological regime alterations.

To estimate the relative contributions of climate change and human-induced activities to streamflow changes, the authors assumed that climate change and human activities were the two primary drivers that independently caused streamflow changes in the WRB (Wang *et al.* 2008). This assumption permits a linear and additive relationship between the relative contributions of climate change and human activities. Based on the change detection, the study period can be divided into baseline and human-induced periods. The VIC model was then used to simulate natural runoff processes in the human-induced period using parameters calibrated in the base period and meteorological forcing variables in the human-induced period. It was assumed that the reconstructed streamflow was free of human disturbances.

3.3. Selection of ERHIs and hydrological alteration analysis

In the current study, we employed PCA to remove redundancy and correlation among IHAs, thus improving the RVA method. The PCA method adopts the concept of dimension reduction, and based on the premise that the essence of original data is retained with no or minimal loss of information, the large number of originally related and redundant variables are transformed into a small number of new relevant variables. Each principal component is generated from the linear combination of the original variables and is made up of the new comprehensive variables. The PCA method is described in detail by Cheng *et al.* (2018).

Richter *et al.* (1998) proposed the RVA method, which was based on the IHA index system and can quantitatively define the degree of change in a single hydrological index after it has been affected, compare hydrological data before and after alteration and evaluate the degree of change within the hydrological index. For non-parametric statistics, 75 and 25% of the occurrence frequency of indicators are used as the upper and lower limits, respectively (i.e., the RVA threshold), to meet the ecological demand of rivers (Wang *et al.* 2022a). The IHA index of the year following the transition point was estimated, and the degree of change to the hydrological index was estimated to determine the extent to which hydrological series were affected.

Several ERHIs were selected to replace the original 32 IHAs using the PCA method. The degree of change (D_i) in a single hydrological indicator was calculated as follows:

$$D_i = \left|\frac{N_{oi} - N_f}{N_f}\right| \times 100\%. \quad (1)$$

where D_i was the degree of change in the ith hydrological index (values less than 33rd percentile belonged to the lowest category; values between the 33rd and 67th percentiles belonged to the middle category; and values larger than 67th percentile belonged to the highest category). N_{oi} was the number of years that the ith index was within the RVA threshold range following the transition point. N_f was the expected number of years that the indicator would have been within the RVA threshold following the transition point.

3.4. Eco-surplus and eco-deficit

Vogel *et al.* (2007) derived dimensionless eco-metrics (eco-surplus and eco-deficit) based on FDCs to quantify seasonal and annual ecological runoff changes. An FDC was estimated using daily streamflow data during a time interval of interest; it was used to obtain a measure of the time (in percentage) during which streamflow equals or exceeds a certain value, which can indicate the relationship between runoff and its frequency in a simple and intuitive manner.

During a given time interval, daily streamflow (Q_i) was ranked in a descending order, and its exceeding probability was computed (Vogel *et al.* 2007):

$$p_i = i/(n+1) \quad (2)$$

where i was the rank and n was the sample size of the observed daily streamflow (Q_i).

Considering that human activities primarily affect the seasonal ecological runoff by altering the annual runoff distribution, the eco-surplus and eco-deficit changes were analysed at annual and seasonal time scales. The annual and seasonal FDCs for each year were calculated using the observed daily flow data of each hydrological station. The streamflow series before the transition point was defined as the natural state, and the annual and seasonal FDCs created using the daily streamflow data before the transition point were set as the 25th and 75th percentile threshold values. If the FDC exceeded 75% of the values for any year and season, the ratio of the area enclosed by the given FDC and 75th percentile FDC to the long-term average annual or seasonal flow was defined as the eco-surplus. This indicated that the hydrological factor exceeded the demand value of the river ecosystem for this factor. If the FDC was lower than 25th percentile, the ratio of the area enclosed by the given FDC and 25th percentile FDC to the long-term average annual or seasonal flow was defined as the eco-deficit. This indicated that the hydrological factor was lower than the demand value of the river ecosystem for this factor (Gao *et al.* 2012). The eco-surplus and eco-deficit indicators were defined as eco-metrics.

3.5. Quantifying the impacts of climate change and human activities on eco-hydrological regimes

To analyse the impact of human activities and climate factors on eco-hydrological regimes in the Weihe River, their contribution rates were quantitatively distinguished using a simulated-observed comparison analysis method (Jiang *et al.* 2019, 2021; Wang *et al.* 2021). The degrees of changes in the observed (D_{obs}) and simulated series (D_{sim}) of each index throughout the baseline and human-induced periods were calculated. Assuming that the effects of climate change and human activities on the evolution of eco-hydrological regimes are independent, the total change based on the observed flow could be expressed as follows:

$$D_{obs} = D_c + D_h. \quad (3)$$

As the structure and parameters of the VIC model were consistent with the baseline period, the reconstructed runoff reflected only the scenario of climate change influence; hence, the comprehensive degree of change based on the simulated flow could be expressed as follows:

$$D_{sim} = D_c \quad (4)$$

The difference in the comprehensive degrees of changes between observed and simulated flows can be expressed as follows:

$$\Delta D = D_{\text{obs}} - D_{\text{sim}} = D_{\text{h}} \tag{5}$$

The contribution rates of climate change and human activities to eco-hydrological regimes were calculated using the following equations:

$$I_{\text{c}} = \frac{D_{\text{sim}}}{D_{\text{obs}}} \times 100\% \tag{6}$$

$$I_{\text{h}} = \frac{D_{\text{obs}} - D_{\text{sim}}}{D_{\text{obs}}} \times 100\% \tag{7}$$

where D_{c} and D_{h} were the respective changes in eco-hydrological regime indicators produced by climate change and human activities. I_{c} and I_{h} represented the rates of contributions of climate change and human activities, respectively.

4. RESULTS

4.1. Changes in the hydrological series and reconstruction of natural runoff

Table 1 shows the results of the Mann–Kendall trend and Pettitt's transition point analyses for the annual runoff and precipitation series of the WRB from 1961 to 2017. The annual runoff and precipitation of both the stations showed a declining trend. The Mann–Kendall test statistic Z-values of the runoff for the Xianyang and Huaxian stations were −4.1 and −3.4, respectively. Pettitt's transition point detection test showed that an abrupt change in the runoff series occurred in 1990. Figure 3 depicts double mass curves of cumulative precipitation–runoff depth that validate this result. As can be observed, the relationship between cumulative precipitation and runoff depth collapsed around 1990. The slopes of these curves during the post-transition period (1991–2017) became smaller than those during the pre-transition period (1961–1990), indicating a decrease in the runoff coefficient (i.e., runoff depth/precipitation) in the post-transition period. Consequently, the study period from 1961 to 2014 was divided into two distinct periods: 1961–1990 as the baseline period and 1991–2017 as the human-induced period.

The baseline period (1961–1990) was further divided into the model calibration (1961–1980) and validation (1981–1990) periods (Figure 4). The VIC model performed effectively for the data from both the Xianyang and Huaxian stations, with NSE >0.67 and absolute relative error >7.7%. This demonstrated that the VIC model could reconstruct the historical hydrological process of the WRB in an objective manner. The model parameters derived during the baseline period were used to simulate the monthly average runoff of the basin. The comparison of the VIC-simulated (baseline period), reconstructed (human-induced period), and *in situ* observed monthly hydrographs is shown in Figure 4.

4.2. ERHIs and their trends

Figure 5 depicts the degrees of changes of the 32 IHA indexes in Xianyang and Huaxian calculated by Equation (1) using measured and simulated data. There were numerous IHAs, and there was little variation between IHA variables within the same group. For example, variables 30–32 were part of a group that represented the rate and frequency of changes in water conditions, and the degree of change in the measured sequence was substantial. To avoid redundancy and correlation

Table 1 | Results of the Mann–Kendall (MK) trend and Pettitt's transition point analyses of hydrological parameters for selected basins during 1961–2017

	MK trend test		Pettitt's test	
Hydrological stations	Runoff Z	Precipitation Z	Runoff	Precipitation
Xianyang	−4.1*	−1.8	1990	–
Huaxian	−3.4*	−1.7	1990	–

*Represents the significance level $p = 0.01$; – represents a sequence without a mutation.

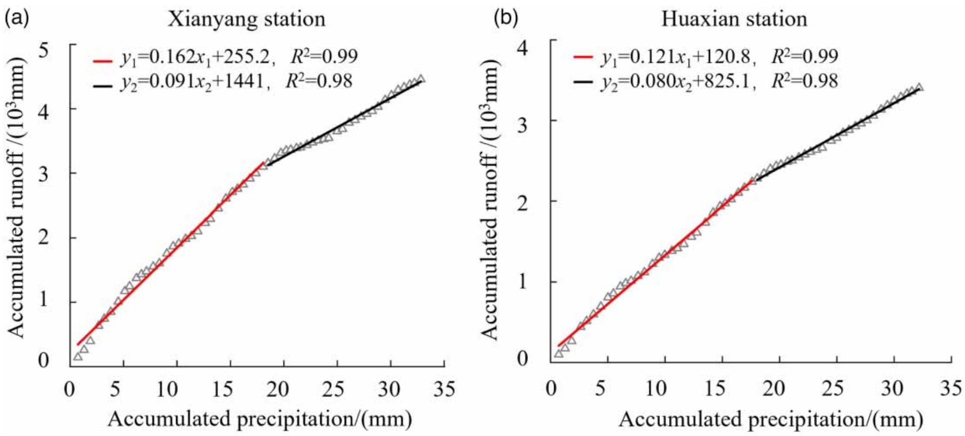


Figure 3 | Double mass curve of cumulative precipitation and runoff in the WRB.

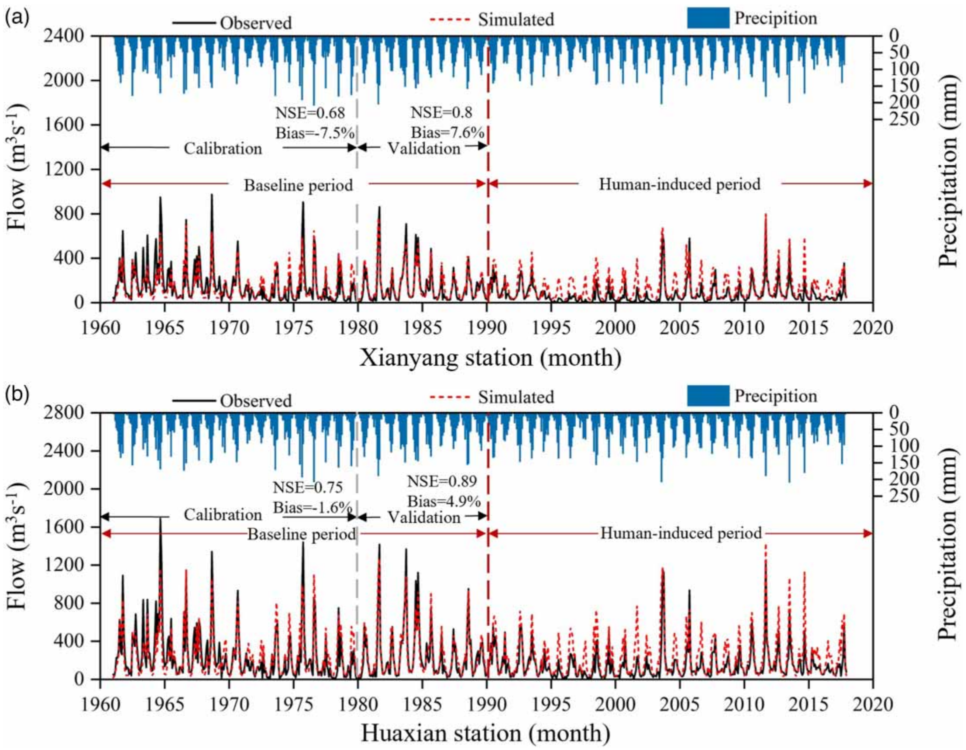


Figure 4 | Comparison of the VIC-simulated (baseline period), reconstructed (human-induced period), and *in situ* observed monthly hydrographs for the period from 1961 to 2017 at the (a) Xianyang and (b) Huaxian stations.

across IHAs, seven of the 32 IHA indexes, namely fall rate, 7-day max, date min, date max, January, December, and high pulse count, were selected as ERHIs for the WRB via PCA.

Figures 6 and 7 depict the temporal variation characteristics of the seven ERHIs in the WRB. The red line represents the linear trend, whereas the light red-shaded area represents the 95% confidence interval. The average flow in January and December and the 7-day max of the Xianyang station decreased significantly at an annual rate of 0.66 $m^3 s^{-1}$, 1 $m^3 s^{-1}$, and 12 $m^3 s^{-1}$, respectively. The high pulse count showed a gradual decline. The fall rate gradually increased. The date min and date max flows did not change significantly. The average flow in December and the 7-day max of the Huaxian station decreased significantly at an annual rate of 1 $m^3 s^{-1}$ and 19 $m^3 s^{-1}$, respectively. The trend of other indexes, except the

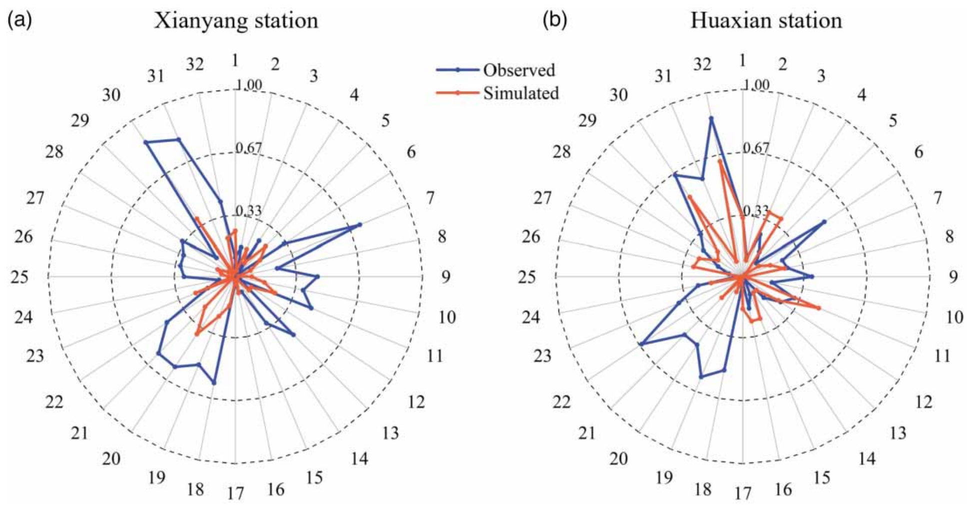


Figure 5 | Degree of hydrological change (D_i) of the 33 variables of IHAs.

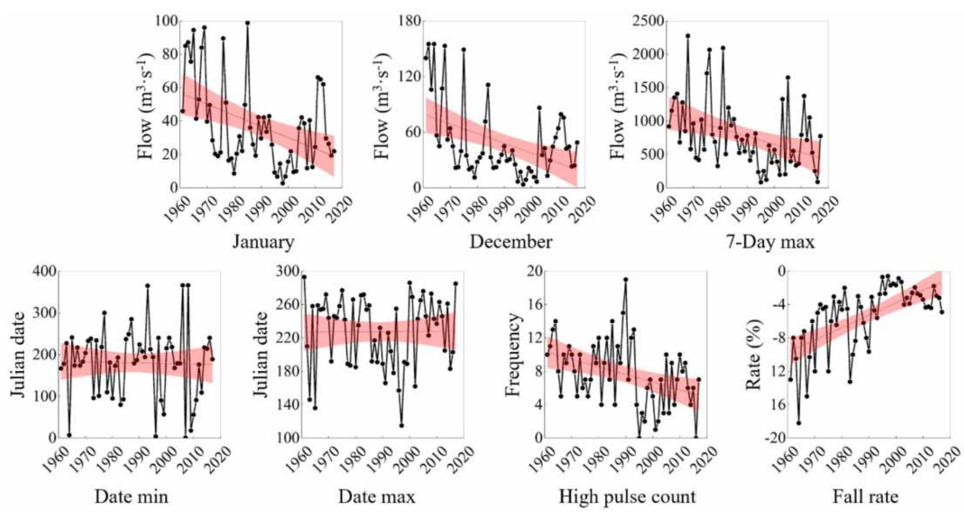


Figure 6 | Temporal variations of ERHIs in the Xianyang station (1961–2017). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/nh.2022.194.

average flow in January, was consistent with that of the Xianyang station; however, the average flow in January did not exhibit a clear decreasing trend. These trends showed that the flood peak discharge and total runoff of the WRB decreased.

4.3. Variability in eco-deficit and eco-surplus indicators

Annual and seasonal eco-metrics (eco-surplus and eco-deficit) were used to analyse the change in annual and seasonal runoffs as ecological response indexes to further explore the degree of change in the total runoff and its impact on the ecology of the WRB. The scatter plots of annual and seasonal FDCs for measured and simulated runoff at the two stations are depicted in Figure 8. According to the plotted FDC, the occurrence ranges of high and low flows prior to and following the alteration of eco-hydrological regimes were markedly different, particularly during spring and winter. The magnitude and frequency of high flow in spring and winter after the transition were significantly reduced compared to those before the transition point, and the area under the first quartile of FDC increased, indicating that the observed eco-deficit indicator of the river in spring and winter increased significantly.

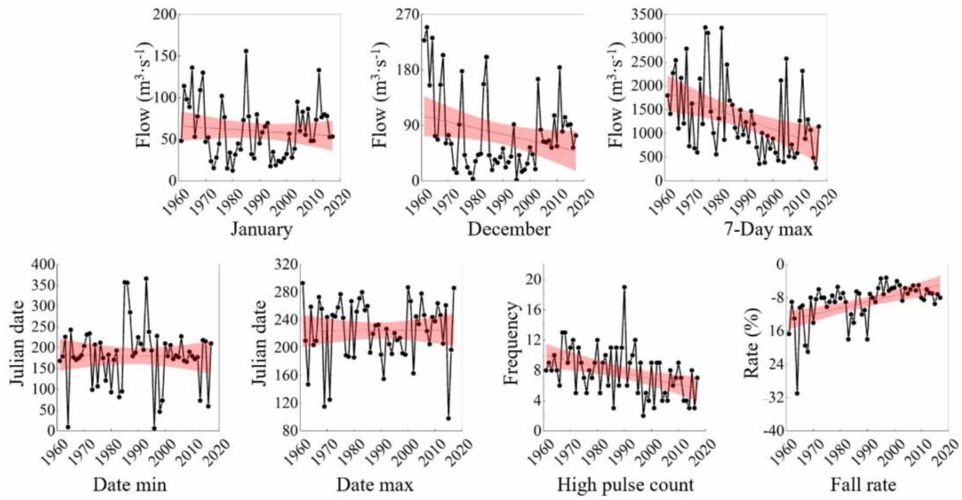


Figure 7 | Temporal changes of ERHIs at the Huaxian station (1961–2017). Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/nh.2022.194.

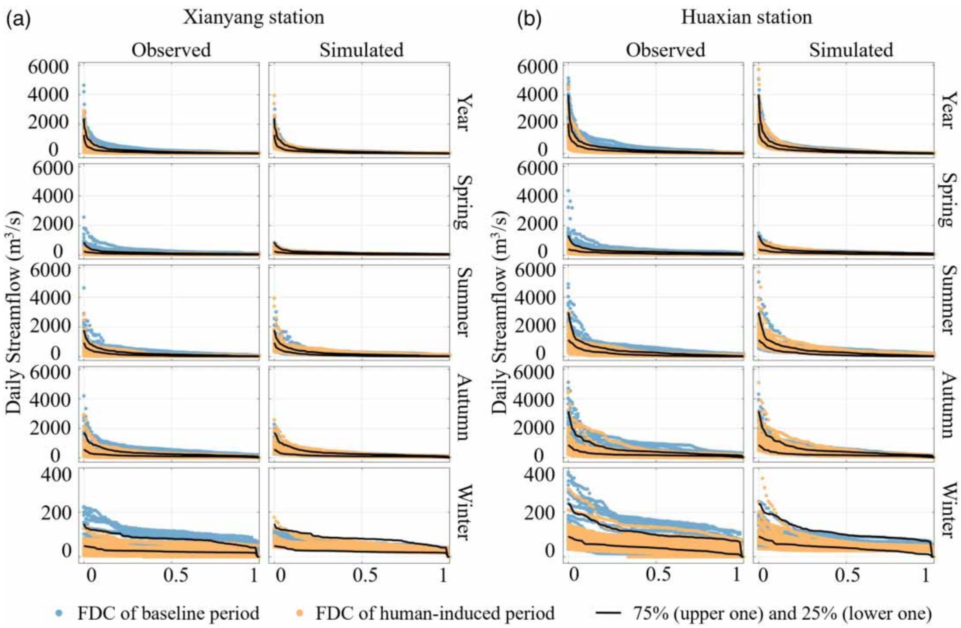


Figure 8 | FDCs before and after the transition point.

Comparing the FDCs of simulated runoff to that of measured runoff revealed that the observed high flow was lower than that of the simulated data after the transition point in summer. This indicated that, relative to the natural flow regime, the actual flow was significantly reduced in summer. This led to a decrease in the summer eco-surplus, which may be attributed to the construction of numerous water conservation projects based on the Weihe River in recent decades. Changes in FDCs between the two scenarios can be used to estimate the preliminary characteristic differences in annual and seasonal ecological flows, and the change in ecological indicators cannot be alienated from the impact of precipitation. Given the correlation between precipitation anomalies and eco-metrics, this can provide a preliminary foundation for the analysis of eco-metrics caused by climate change.

Figure 9 shows the annual and seasonal eco-metrics (eco-surplus and eco-deficit) and the time variation characteristics of the annual and seasonal precipitation anomalies at each hydrological station, as determined from the annual and seasonal FDCs. Based on the measured index of the annual scale, the temporal variations of eco-metrics at the two stations were

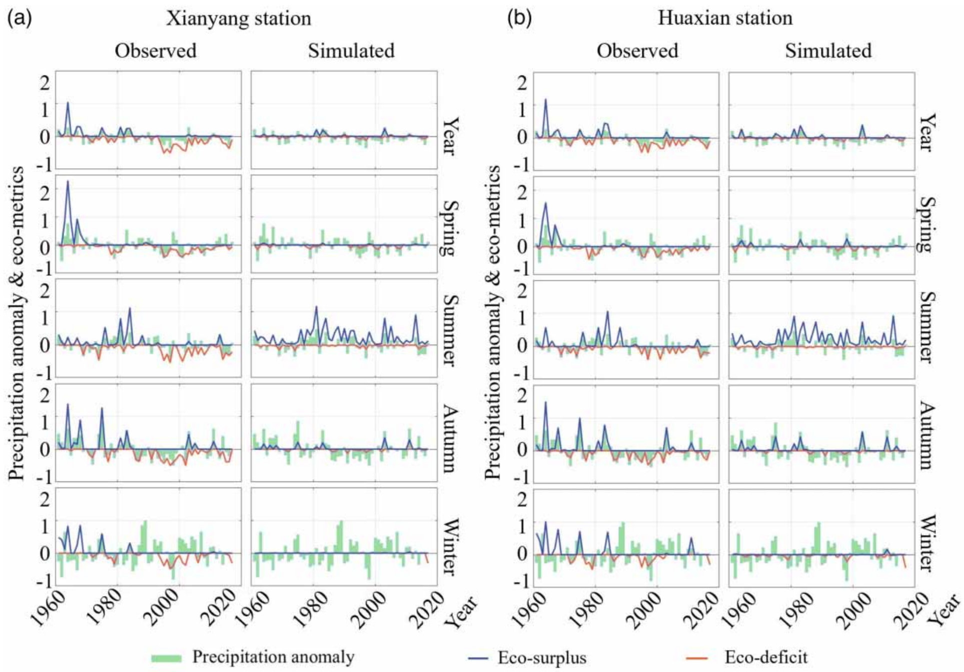


Figure 9 | Yearly variations of precipitation anomaly and eco-metrics.

consistent with the precipitation anomalies, indicating a positive correlation between the two variables. The peaks of eco-surplus and eco-deficit did not occur simultaneously; rather, alternately. In addition, the peak values of the eco-surplus were considerably greater than those of the eco-deficit. The eco-deficit increased and the eco-surplus decreased significantly in the human-induced period compared with those of the baseline period. From the seasonal change perspective, the fluctuations of eco-hydrological regime indexes in winter were minimal, and their contrast with the precipitation anomalies was evident. There was a significant correlation between the temporal variations of eco-metrics and precipitation anomalies. At the annual and seasonal scales, the eco-surplus of the two hydrological stations was primarily observed before the transition point, whereas the eco-deficit was observed following it. The results indicated that the ecological water demand of the river in the WRB was inadequate during the human-induced period.

Analysing the simulated eco-metrics at each time scale, it was found that the eco-surplus was dominant in summer, and the eco-deficit was considerably smaller than the eco-surplus. The eco-deficit and eco-surplus of other seasons and at the annual scales were stable and remained within a relatively narrow range near zero. There was no discernible temporal variation, indicating that the effects of climate change did not have a significant impact on the eco-metrics in the WRB.

4.4. Quantification of the impacts of climate change and human activities on eco-hydrological regimes

The rates of contribution of climate change and human activities to the evolution of the Weihe River eco-hydrological regimes were quantitatively separated using the 'observation–simulation' comparison approach. Figure 10 shows the degree of change in ERHIs and eco-metrics for the Xianyang and Huaxian stations using measured and simulated runoff data as inputs. The contribution rates of human activities to most ERHIs at the two locations were greater than those of climate change. For some indicators (e.g., high pulse count, date max, and date min in Xianyang and December and date max in Huaxian), the contribution rate of human activities was higher than 100%. The fall rate based on measured runoff changed considerably at the Xianyang and Huaxian stations; however, the degree of change in this index was greatly reduced during calculation based on simulated runoff. This indicates that human activities play a predominant role in the evolution of the eco-hydrological regimes in the WRB, and their impact is evident from the reduction in river discharge. As can be seen from Figure 10(c) and 10(d), the contribution of human activities to the change in eco-metrics was substantially higher than that of climate change. In other words, human activities played a crucial role in the escalation of eco-deficit and diminution of eco-surplus

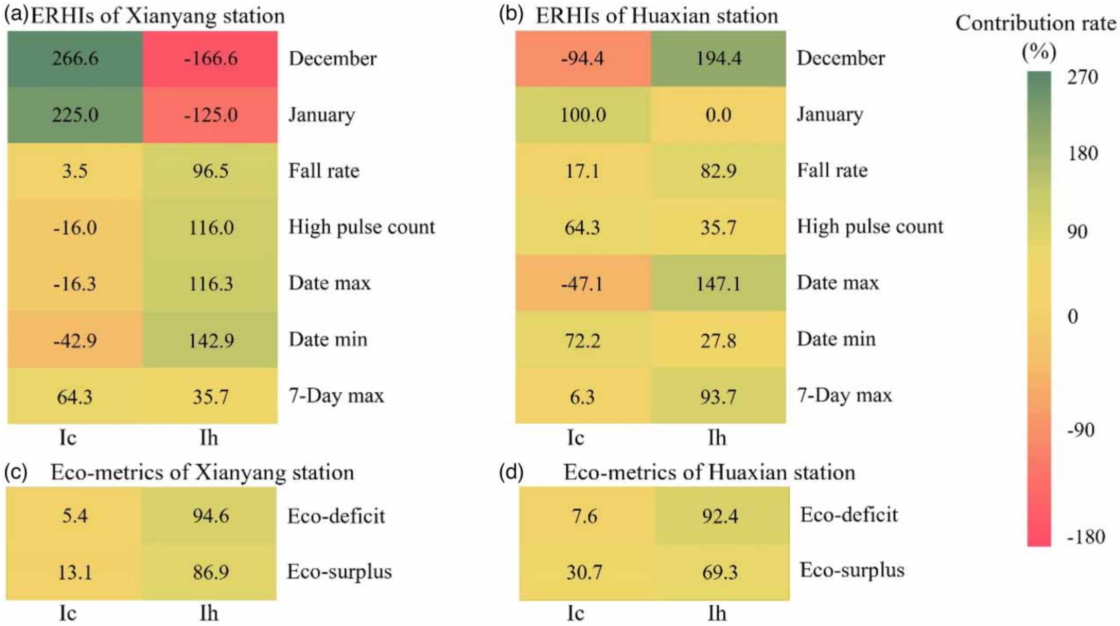


Figure 10 | Contribution rates of climate change and human activities to eco-hydrological regimes. The variation is the change in ERHIs and eco-metrics between the baseline and human-induced periods.

throughout the transition period. Considering ERHIs (daily and monthly scales) and eco-metrics (seasonal and annual scales), the contribution rate of human activities was greater than that of climate change.

5. DISCUSSION

5.1. Impact of climate change on eco-hydrological regimes

Numerous studies have attempted to determine the reasons for runoff fluctuations in the WRB. Liu *et al.* (2022) showed that climate change exerted specific impacts on runoff reduction in the WRB, but that this impact was minimal. While analysing the impact of climate change on runoff in the WRB, precipitation is often regarded as the driving factor directly related to runoff, as well as the primary source of runoff recharge in the WRB. The annual average precipitation decreased from 563.5 mm during the baseline period to 514.9 mm during the human-induced period; however, the trend analysis revealed no significant decreasing trend for precipitation. Both Guo *et al.* (2017) and Liu *et al.* (2022) discovered that precipitation in the WRB did not decrease significantly. Climate change is a slower process than the intense human activity in recent decades. In this study, we used ERHIs and eco-metrics to analyse the changes in eco-hydrological regimes to explore the attributes of river ecology as opposed to runoff only. Similar to the runoff change attribution, the effect of climate change on the alteration of eco-hydrological regimes was limited.

Contrary to the human activities of the past few decades, climate change is a slow-growing process with temporal scales spanning from a hundred to a thousand years (Parmesan & Yohe 2003), thus making it difficult to accurately understand this change using short-term data records. Different results may be obtained when analysing the hydrological response to climate change, depending on the selection of the baseline and study periods.

5.2. Impact of human activities on eco-hydrological regimes

The attribution analysis revealed that human activities contributed more to the decline of eco-hydrological regimes in the WRB than climate change (Figure 10). Anthropogenic interventions such as land-use changes, water resource consumption, and large-scale water-control projects could all have impacts on regional water resources.

The land in the WRB is mainly cropland and grassland, while cropland acreage continuously diminishes during the human-induced period. A major factor was the Grain-for-Green (GFG, Chen *et al.* 2007) project that is established by the Chinese government in 1999 which aimed to reduce soil erosion and increase vegetation area by converting sloped cropland into vegetativefriendly land. The substantial increase in vegetation coverage caused by the GFG project could decrease surface runoff, enhance evaporation from soil moisture, and intensify plant transpiration (Li *et al.* 2016). The expanded vegetation canopy would intercept more precipitation, the majority of which would eventually evaporate into the atmosphere. On the other hand, the continuous advancement of urbanisation could not only increase the impervious area but also weaken the infiltration, resulting in the increase of interception and direct runoff. As a further matter, a portion of the intercepted water will be consumed through evaporation, while the majority of the surface runoff will contribute to urban water circulation by the 'Rainfall Collection' (RC) project implemented in 1996 (Gao *et al.* 2013). According to the statistics, two million cellars have been constructed in recent decades to collect rainfall with an annual water storage capacity of approximately 6.0×10^6 m^3 for drinking water supply and irrigation during the dry season. As a result, the water flowing into the river dropped significantly (Gao *et al.* 2013).

Moreover, vigorous socio-economic development accelerates the consumption of water. The mid-downstream region of the WRB (i.e., the Guanzhong Plain) faced the most rapid economic growth. In recent decades, agricultural irrigation, industrial development, and domestic use have been the primary drivers of rising water demand. In the 1960s, the average annual water consumption was 7.3×10^8 m^3, which increased to 19.7×10^8 m^3 by the 1990s, representing 46% of the observed streamflow at the Huaxian station (Gao *et al.* 2013). Ren *et al.* (2016) reported that irrigation accounted for 71% of total water consumption in the WRB with an average annual amount of 16.7×10^8 m^3 and an annual increase ratio of 0.4×10^8 m^3 yr^{-1} during the period from 1991 to 2013. It was evident that agricultural irrigation was one of the most significant water use sectors in the WRB.

In conclusion, human activities impacted the regional eco-hydrological regimes of the WRB in a complex manner. Changes in land-use types could alter eco-hydrological regimes in different ways. For example, afforestation can reduce surface runoff by increasing interception and evapotranspiration, whereas urbanisation can increase surface runoff and weaken infiltration by increasing impervious areas. Moreover, water-control projects, such as reservoirs, could exert a considerable impact on flow convergence by regulating floods and redistributing streamflow. This could subsequently cause seasonal variations in streamflow patterns. In the meantime, agricultural hyper-irrigation consumed substantial volumes of water, and this is also one of the reasons for the reduction of runoff in the WRB.

5.3. Uncertainty in quantifying the impact on eco-hydrological regimes

This study focused on detecting and attributing eco-hydrological regime changes in the WRB based on the VIC modelling framework. However, there were no exact values for the contributions of climate change and human activities to eco-hydrological regime changes. One should keep in mind that this method is limited to fully and objectively describing eco-hydrological regimes in a changing environment because of the complex nature of eco-hydrological regimes and the high non-linearity in the interaction between human society and nature systems. Therefore, it is necessary to evaluate uncertainties in the modelling findings. Uncertainties in this study are considered from three aspects: basic assumptions and associated simplifications, selected hydrological model, and model parameter calibration.

The attribution framework presumed that climate change and human activities can independently affect eco-hydrological regimes in the WRB (Dey & Mishra 2017). Without this basic assumption, one cannot separate the contribution of these two components, because this assumption neglects the inter-correlation among the climate system, hydrological cycle, and land surface. For example, afforestation could indirectly increase evapotranspiration by enlarging canopy interception and enhancing soil and water conservation, thus affecting regional climate conditions. Therefore, this assumption is a simplification needed to solve scientific questions, which inevitably introduces uncertainty.

Hydrological models are an approximation of natural processes. Different models have different structures and thus different regional applicability. Previous studies have shown that the VIC model has good applicability in the northern semi-arid region of China and thus can reduce the uncertainty of hydrological evolution attribution (Ren *et al.* 2016; Jiang *et al.* 2019, 2022). However, the VIC model requires multi-source datasets for both model input and *a priori* parameter estimation, thereby potentially introducing uncertainties arising from these data.

Parameter calibration is another significant source of uncertainty for the VIC model. There are two key main sources of uncertainty in the VIC model calibration. One source of uncertainty is the calibration strategy. Although the manual calibration employed is efficient with the insights of a modeller's priori experience, it is still unclear whether one eventually obtains the global optimum or not (Tolson & Shoemaker 2007). Another source of uncertainty in the VIC is from the conflict among spatially varied parameterisation, simulation accuracy, and computational burden. Considering the computational burden, a regionally uniform calibration strategy was conducted in the WRB.

6. CONCLUSIONS

This study proposed a comprehensive assessment framework to distinguish the relative contributions of climate change and human activities on the eco-hydrological regimes at the daily, monthly, seasonal, and annual timescales. Firstly, the variation trends and abrupt changes of hydrological variables in the WRB between 1961 and 2017 were analysed. Then, seven representative IHAs were selected as ERHIs and used in combination with the eco-deficit and eco-surplus metrics to assess the eco-hydrological regime changes. Finally, the relative contributions of climate change and human activities on eco-hydrological regime changes were explored by using the simulated–observed comparison method. The principal findings of this study can be summarised as follows.

1. Hydrological variation analysis revealed that the annual precipitation in the WRB did not decrease significantly between 1961 and 2017, whereas the annual streamflow at the Xianyang and Huaxian stations showed a significant decreasing trend. Moreover, abrupt transition points were identified in the streamflow series in 1990, thereby dividing the study period into the baseline (1961–1990) and human-induced (1991–2017) periods. Calibration and validation of the VIC model showed good performance during the baseline period, indicating that this model was appropriately benchmarked.
2. Seven out of 32 IHA indexes were selected using the PCA method: fall rate, 7-day max, date min, date max, January, December, and high pulse count. These were regarded as ERHIs of the WRB. The trends of these indexes indicated that the flood peak discharge and total runoff were decreasing. Furthermore, the eco-surplus of the two hydrological stations was primarily observable before the transition point, whereas the eco-deficit was observable after it. The eco-deficit at annual and seasonal scales increased, whereas the eco-surplus tended to decrease. This indicated that the river ecological water demand in the WRB was insufficient during the human-induced period.
3. The attribution analysis revealed that human activities were responsible for more than 80% of the ERHI changes at the Xianyang and Huaxian stations and for more than 60% of the eco-deficit and eco-surplus of these stations. Overall, human activities were the major factors leading to the decline and shifts in the eco-hydrological regime of the WRB.

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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.

REFERENCES

Belletti, B., Garcia De Leaniz, C., Jones, J., Bizzi, S., Börger, L., Segura, G., Castelletti, A., van de Bund, W., Aarestrup, K., Barry, J., Belka, K., Berkhuysen, A., Birnie-Gauvin, K., Bussettini, M., Carolli, M., Consuegra, S., Dopico, E., Feierfeil, T., Fernández, S., Fernandez Garrido, P., Garcia-Vazquez, E., Garrido, S., Giannico, G., Gough, P., Jepsen, N., Jones, P. E., Kemp, P., Kerr, J., King, J., Łapińska, M., Lázaro, G., Lucas, M. C., Marcello, L., Martin, P., McGinnity, P., O Hanley, J., Olivo Del Amo, R., Parasiewicz, P., Pusch, M., Rincon, G., Rodriguez, C., Royte, J., Schneider, C. T., Tummers, J. S., Vallesi, S., Vowles, A., Verspoor, E., Wanningen, H., Wantzen, K. M., Wildman, L. & Zalewski, M. 2020 More than one million barriers fragment Europe's rivers. *Nature* **588**, 436–441.

Chen, L., Wei, W., Fu, B. & Lü, Y. 2007 Soil and water conservation on the Loess Plateau in China: review and perspective. *Progress in Physical Geography: Earth and Environment* **31**, 389–403.

Cheng, J., Xu, L., Wang, X., Jiang, J. & You, H. 2018 Assessment of hydrologic alteration induced by the Three Gorges Dam in Dongting Lake, China. *River Research and Applications* **34**, 686–696.

Cui, H., Jiang, S., Ren, L., Xiao, W., Yuan, F., Wang, M. & Wei, L. 2022 Dynamics and potential synchronization of regional precipitation concentration and drought-flood abrupt alternation under the influence of reservoir climate. *Journal of Hydrology: Regional Studies* **42**, 101147.

Dey, P. & Mishra, A. 2017 Separating the impacts of climate change and human activities on streamflow: a review of methodologies and critical assumptions. *Journal of Hydrology* **548**, 278–290.

Gao, B., Yang, D., Zhao, T. & Yang, H. 2012 Changes in the eco-flow metrics of the Upper Yangtze River from 1961 to 2008. *Journal of Hydrology* **448–449**, 30–38.

Gao, P., Geissen, V., Ritsema, C. J., Mu, X. M. & Wang, F. 2013 Impact of climate change and anthropogenic activities on stream flow and sediment discharge in the Wei River basin, China. *Hydrology and Earth System Sciences* **17**, 961–972.

Gao, B., Li, J. & Wang, X. 2018 Analyzing changes in the flow regime of the Yangtze river using the eco-flow metrics and IHA metrics. *Water* **10**, 1552.

Guo, A., Chang, J. & Liu, D. 2017 Variations in the precipitation-runoff relationship of the Weihe River Basin. *Hydrology Research* **48**, 295–310.

Hansen, M. C., Defries, R. S., Townshend, J. R. G. & Sohlberg, R. 2010 Global land cover classification at 1km spatial resolution using a classification tree approach. *International Journal of Remote Sensing* **21**, 1331–1364.

Ji, F., Wu, Z., Huang, J. & Chassignet, E. P. 2014 Evolution of land surface air temperature trend. *Nature Climate Change* **4**, 462–466.

Jiang, S., Ren, L., Yong, B., Singh, V. P., Yang, X. & Yuan, F. 2011 Quantifying the effects of climate variability and human activities on runoff from the Laohahe basin in northern China using three different methods. *Hydrological Processes* **25**, 2492–2505.

Jiang, S., Wang, M., Ren, L., Xu, C. Y., Yuan, F., Liu, Y., Lu, Y. & Shen, H. 2019 A framework for quantifying the impacts of climate change and human activities on hydrological drought in a semiarid basin of Northern China. *Hydrological Processes* **33**, 1075–1088.

Jiang, S., Zhou, L., Ren, L. L., Wang, M. H., Xu, C. Y., Yuan, F., Liu, Y., Yang, X. L. & Ding, Y. 2021 Development of a comprehensive framework for quantifying the impacts of climate change and human activities on river hydrological health variation. *Journal of Hydrology* **600**, 126566.

Jiang, S., Wang, M., Ren, L., Liu, Y., Zhou, L., Cui, H. & Xu, C. 2022 An integrated approach for identification and quantification of ecological drought in rivers from an ecological streamflow perspective. *Ecological Indicators* **143**, 109410.

Li, S., Liang, W., Fu, B., Lü, Y., Fu, S., Wang, S. & Su, H. 2016 Vegetation changes in recent large-scale ecological restoration projects and subsequent impact on water resources in China's Loess Plateau. *Science of The Total Environment* **569–570**, 1032–1039.

Lian, Y., You, J., Sparks, R. & Demissie, M. 2012 Impact of human activities to hydrologic alterations on the Illinois river. *Journal of Hydrologic Engineering* **17**, 537–546.

Liang, X., Lettenmaier, D. P., Wood, E. F. & Burges, S. J. 1994 A simple hydrologically based model of land surface water and energy fluxes for general circulation models. *Journal of Geophysical Research* **99**, 14415.

Liu, Q., Li, S., Zhou, G., Feng, Z., Wang, G. & Qiu, Q. 2022 Attribution of nonstationary changes in the annual runoff of the Weihe River using the de-nonstationarity method. *Hydrology Research* **53**, 407–418.

Luo, Z., Shao, Q. & Liu, H. 2021 Comparative evaluation of river water quality and ecological changes at upstream and downstream sites of dams/sluices in different regulation scenarios. *Journal of Hydrology* **597**, 126290.

Ma, L., Huang, Q., Huang, S., Liu, D., Leng, G., Wang, L. & Li, P. 2022 Propagation dynamics and causes of hydrological drought in response to meteorological drought at seasonal timescales. *Hydrology Research* **53**, 193–205.

Nienhuis, J. H., Ashton, A. D., Edmonds, D. A., Hoitink, A. J. F., Kettner, A. J., Rowland, J. C. & Törnqvist, T. E. 2020 Global-scale human impact on delta morphology has led to net land area gain. *Nature* **577**, 514–518.

Palmer, M. & Ruhi, A. 2019 Linkages between flow regime, biota, and ecosystem processes: implications for river restoration. *Science* **365**, 6459.

Parmesan, C. & Yohe, G. 2003 A globally coherent fingerprint of climate change impacts across natural systems. *Nature* **421**, 37–42.

Poff, N. L. & Zimmerman, J. K. H. 2010 Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. *Freshwater Biology* **55**, 194–205.

Ren, L., Shen, H., Yuan, F., Zhao, C., Yang, X. & Zheng, P. 2016 Hydrological drought characteristics in the Weihe catchment in a changing environment (in Chinese). *Advances in Water Science* **27** (4), 492–500.

Richter, B. D., Baumgartner, J. V., Powell, J. & Braun, D. P. 1996 A method for assessing hydrologic alteration within ecosystems. *Conservation Biology* **10**, 1163–1174.

Richter, B. D., Baumgartner, J. V., Braun, D. P. & Powell, J. 1998 A spatial assessment of hydrologic alteration within a river network. *Regulated Rivers: Research & Management* **14**, 329–340.

Richter, B. D., Baumgartner, J. V., Wigington, R. & Braun, D. 2003 How much water does a river need? *Freshwater Biology* **37**, 231–249.

Tolson, B. A. & Shoemaker, C. A. 2007 Dynamically dimensioned search algorithm for computationally efficient watershed model calibration. *Water Resources Research* **43**, 1.

Vogel, R. M., Sieber, J., Archfield, S. A., Smith, M. P., Apse, C. D. & Huber-Lee, A. 2007 Relations among storage, yield, and instream flow. *Water Resources Research* **43**, 5.

Wang, H. & Sun, F. 2021 Variability of annual sediment load and runoff in the Yellow River for the last 100 years (1919–2018). *Science of the Total Environment* **758**, 143715.

Wang, G., Zhang, J., He, R., Jiang, N. & Jing, X. 2008 Runoff reduction due to environmental changes in the Sanchuanhe river basin. *International Journal of Sediment Research* **23**, 174–180.

Wang, M., Jiang, S., Ren, L., Xu, C., Yuan, F., Liu, Y. & Yang, X. 2020 An approach for identification and quantification of hydrological drought termination characteristics of natural and human-influenced series. *Journal of Hydrology* **590**, 125384.

Wang, M., Jiang, S., Ren, L., Xu, C., Menzel, L., Yuan, F., Xu, Q., Liu, Y. & Yang, X. 2021 Separating the effects of climate change and human activities on drought propagation via a natural and human-impacted catchment comparison method. *Journal of Hydrology* **603**, 126913.

Wang, H., Huang, L., Guo, W., Zhu, Y., Yang, H., Jiao, X. & Zhou, H. 2022a Evaluation of ecohydrological regime and its driving forces in the Dongting Lake. *China. Journal of Hydrology: Regional Studies* **41**, 101067.

Wang, M., Jiang, S., Ren, L., Xu, C., Wei, L., Cui, H., Yuan, F., Liu, Y. & Yang, X. 2022b The development of a nonstationary standardised streamflow index using climate and reservoir indices as covariates. *Water Resources Management* **36**, 1377–1392.

Yan, S., Wang, Z., Wu, L. & Huang, W. 2022 An ecological interval two-stage fuzzy shadow price model for environmental flow allocation in the Shaying River Basin. *Hydrology Research* **53**, 279–296.

Yang, Y. E., Cai, X. & Herricks, E. E. 2008 Identification of hydrologic indicators related to fish diversity and abundance: a data mining approach for fish community analysis. *Water Resources Research* **44**, 4.

Yang, Z., Yan, Y. & Liu, Q. 2012 Assessment of the flow regime alterations in the Lower Yellow River, China. *Ecological Informatics* **10**, 56–64.

Zhang, H., Singh, V. P., Zhang, Q., Gu, L. & Sun, W. 2016 Variation in ecological flow regimes and their response to dams in the upper Yellow River basin. *Environmental Earth Sciences* **75**, 11.

Zhang, Q., Zhang, Z., Shi, P., Singh, V. P. & Gu, X. 2018 Evaluation of ecological instream flow considering hydrological alterations in the Yellow River basin, China. *Global and Planetary Change* **160**, 61–74.

Zhang, H., Jarić, I., Roberts, D. L., He, Y., Du, H., Wu, J., Wang, C. & Wei, Q. 2020 Extinction of one of the world's largest freshwater fishes: lessons for conserving the endangered Yangtze fauna. *Science of the Total Environment* **710**, 136242.

Zhu, Y., Wang, H. & Guo, W. 2021 The impacts of water level fluctuations of East Dongting Lake on habitat suitability of migratory birds. *Ecological Indicators* **132**, 108277.

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