



Vegetation restoration and climate shifted hydrological regime from drying to wetting in China's Loess Plateau

Yingxi Zeng^{1, 2}, Cong Wang^{1, 5, 6}, Bojie Fu^{1, 2, 5, 6}, Guangyao Gao^{1, 2, 5, 6}, Vinícius B. P. Chagas⁷, Shuai Wang³, Yu Liu^{2, 4}, Yihe Lü^{1, 2, 5, 6}, Marcus Schaub⁹, James W. Kirchner^{8, 9}

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¹State Key Laboratory of Regional and Urban Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing 100085, China

²College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China

10 ³State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science, Beijing Normal University, Beijing 100875, China

⁴Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

⁵Shaanxi Yan'an Forest Ecosystem National Observation and Research Station, 100085 Beijing, China

15 ⁶National Observation and Research Station of Earth Critical Zone on the Loess Plateau in Shaanxi, 710061 Xi'an, China

⁷Department of Sanitary and Environmental Engineering, Federal University of Santa Catarina, Brazil

⁸Department of Environmental System Sciences, ETH Zurich, Zurich, Switzerland

⁹Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, Switzerland

20 *Corresponding to: Cong Wang (congwang@rcees.ac.cn)*

Abstract. Large-scale ecological restoration, climate variability, and human water management are jointly reshaping river flow regimes, yet their combined effects on low and high flows remain poorly understood. We examined flow-regime changes in 13 typical basins of China's Loess Plateau, where extensive ecological restoration has occurred across a strong hydroclimatic gradient. Annual 7-day minimum and 1-day maximum flows during 1990–2020 were analyzed, and their joint trends were related to vegetation cover (VC), climatic water availability, and human water use (WU). Both low and high flows generally declined during 1990–2005 but increased during 2005–2020, indicating a shift from drying to wetting, with more pronounced changes in northern basins. Panel regression models showed that low-flow changes were most strongly associated with VC, whose estimated contribution shifted from negative to positive between the two periods, mainly in northern basins. In contrast, high-flow changes were consistently positively associated with short-term water availability, represented by maximum 14-day P–ET (precipitation minus evapotranspiration). During 2005–2020, WU and VC showed negative modeled contributions to high flows, suggesting partial attenuation of high-flow responses. Thus, the

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post-2005 wetting phase was characterized by a reversal of the modeled VC–low-flow association, while
35 high-flow changes remained primarily associated with short-term water availability. Adaptive
revegetation and high-flow risk management are both needed to sustain water security under a more
variable hydroclimate.

1 Introduction

Climate change and human activities shape the patterns of changes in the hydrological cycle. Climate
40 change influences the spatial and temporal distribution of water resources by altering precipitation,
evapotranspiration, and runoff, while also modifying the frequency and intensity of extreme events such
as floods and droughts (Li et al., 2013). Human activities, on the other hand, directly or indirectly impact
the hydrological cycle through land use changes, hydraulic engineering, and groundwater extraction
(Song et al., 2013). Shifts in hydrological regime can profoundly affect ecosystem structure and
45 functioning at both regional and global scales (Poff and Zimmerman, 2010; Vörösmarty et al., 2010;
Perkin et al., 2017).

In recent years, global warming has intensified extreme hydrological events, leading to long-term impacts
on ecosystems (IPCC, 2023). For example, since the early 2000s, frequent droughts have led to a
significant loss of resilience in the Amazon rainforest, with profound implications for global carbon
50 storage, biodiversity, and the climate system (Boulton et al., 2022). In 2022, the super flood in Pakistan
caused widespread destruction of wildlife habitats and forest vegetation (Government of Pakistan, 2022).
Between 2022 and 2023, California, USA, experienced an extreme hydrological event characterized by
a rapid transition from drought to flood (DeFlorio et al., 2024). These extreme hydrological events may
have profound consequences for regional food security, ecosystems, and infrastructure (Lesk et al., 2016;
55 Ward et al., 2020; Zscheischler et al., 2020). Against the backdrop of increasing flood and drought risks
under climate change and intensified human activities, examining hydrological regime helps improve
our understanding of hydrological process responses and provides a scientific basis for guiding basin
management.

Current studies on hydrological regimes have two main limitations. First, many studies focus on
60 individual indicators or processes, which may result in an incomplete understanding of the overall
hydrological regime. For instance, studies on China's Loess Plateau, a key region for ecological



restoration research, have separately examined changes in mean annual streamflow and their climatic and land-use drivers (Zhang et al., 2008; Liang et al., 2015), soil moisture responses to afforestation and vegetation restoration (Jia et al., 2017), or long-term baseflow variation and its driving factors (Yan et al., 2023). Second, although some studies incorporate multiple indicators (T. Wang et al., 2022; Li et al., 2023), these studies generally focus on annual mean conditions and pay less attention to changes in annual extreme water conditions. Such conditions are particularly relevant to water-resource management because they characterize seasonal flood potential, dry-season water availability, and ecosystem water stress (Richter et al., 1996). Chagas et al. (2022) advanced the field by classifying hydrological regime shifts into four categories—drying, wetting, accelerating, and decelerating—by combining annual low flows and high flows, providing a novel framework for the comprehensive analysis of changes in the hydrological cycle.

As an ecologically fragile region in northern China, the Loess Plateau's hydrological processes have been profoundly influenced by climate change and human activities. Over the past 60 years, the region has experienced increasingly frequent droughts (Liu et al., 2023; Yang et al., 2025), while in recent years, extreme rainfall has also become more frequent (Zhang et al., 2020), leading to recurrent floods (Jin et al., 2024). Meanwhile, the Loess Plateau has undergone extensive vegetation restoration through national government programs aimed at soil and water conservation and revegetation (Liu et al., 2004; Wu et al., 2020), alongside rapid urbanization associated with national economic reforms and regional development policies (Bryan et al., 2018; Tang et al., 2023). Human activities have altered the Loess Plateau through changes in land use types and human water consumption. For example, agricultural irrigation water use, which constitutes the dominant component of water consumption in the Loess Plateau (50%-70% of the total), has gradually decreased, and non-irrigation water use like industrial and domestic water consumption has increased instead (Zhou et al., 2020). Climate change, particularly the increasing frequency of extreme events, coupled with intensifying human activities, has led to complex changes in the hydrological cycle.

In this study, we investigate trends in extreme hydrological events in the Loess Plateau between 1990 and 2020. We aim to identify the primary driving factors and to reveal the characteristics of the hydrological regime, providing scientific insights for basin management in the region. For this, we adopt the classification method of hydrological regimes proposed by Chagas et al. (2022). We first calculate



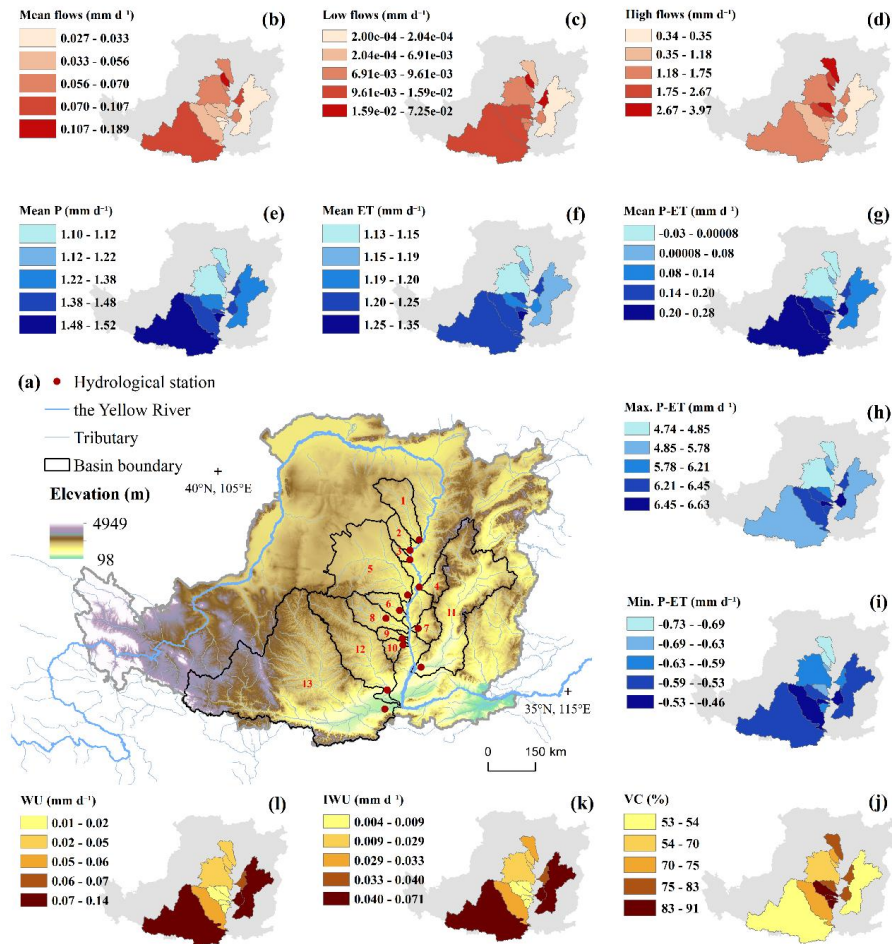
extreme flow indicators based on daily flow data from 13 typical basins in the Loess Plateau. Subsequently, we analyze the influence of climatic and human activity indicators on joint trends in extreme flows within each basin and the Loess Plateau as a whole, as well as the relative contributions of these factors. For this, we adopt panel regression models, the Theil-Sen test for trend and the Bai-
95 Perron test for change-point shifts.

2 Study area

The Loess Plateau, located in the upper and middle reaches of the Yellow River in northern China, covers approximately 530,000 km² and is one of the world's largest loess regions (Fu, 1989). The region has a continental monsoon climate, with mean annual precipitation increasing from approximately 200 mm in
100 the north to 750 mm in the southeast. Precipitation is highly seasonal, with most rainfall occurring between July and September (Sun et al., 2015).

This study focuses on 13 representative basins across the Loess Plateau (Fig. 1, Table 1), ranging in area from 1,121 to 106,498 km², and collectively covering approximately 44% of the plateau. The region has experienced severe soil erosion owing to its highly erodible soils and intensive agricultural activities (Shi
105 and Shao, 2000). Since the implementation of the Grain for Green Program in 1999, large-scale vegetation restoration has substantially reduced soil erosion and altered regional hydrological processes (Fu, 2022; Liu et al., 2025). In addition, the Fenhe and Weihe basins in the southern Loess Plateau are important irrigated agricultural regions that have undergone extensive high-standard farmland development (the State Council of China, 2013) and play an important role in China's food security.

110 In the past 30 years, precipitation and water availability (precipitation minus actual evapotranspiration) across the Loess Plateau have generally decreased from south to north, whereas high flows have often been greater in the northern basins than in the southern ones (Fig. 1). This mismatch highlights the substantial influence of human activities on hydrological regimes across the Loess Plateau.



115 Fig. 1. Study area and the long-term (1990-2020) averages of the climate and anthropogenic drivers of the 13
basins. (a) The Loess Plateau and the selected basins. (b) Long-term mean streamflow, (c) low flows (annual
120 minimum 7-day moving mean streamflow), (d) high flows (annual maximum daily streamflow), (e) mean
precipitation, (f) mean actual evapotranspiration, (g) Mean P-ET (annual mean daily precipitation minus
actual evapotranspiration), (h) Max. P-ET (annual maximum 14-day moving mean P-ET), (i) Min. P-ET
(annual minimum 90-day moving mean P-ET), (j) VC (vegetation cover), (k) IWU (annual irrigation water
use) and (l) WU (annual total water use).

Table 1. Description of the basins selected in this study.

Number	Basin	Code	Hydrologic station	Area (km ²)	Distance (km)	Region
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1	Kuyehe	KY	Wenjiachuan	8515	0	N
2	Tuweihe	TW	Gaojiachuan	3253	41.2	N
3	Jialuhe	JL	Shenjiawan	1121	70.7	N
4	Sanchuanhe	SC	Houdacheng	4102	189.3	N
5	Wudinghe	WD	Baijiachuan	29662	266.5	N
6	Qingjianhe	QJ	Yanchuan	3468	344.8	N
7	Xinshuihe	XS	Danling	3992	402.5	S
8	Yanhe	YH	Ganguyi	5891	414.5	S
9	Yunyanhe	YY	Xinshihe	1662	444.2	S
10	Shiwangchuan	SW	Dacun	2141	462.7	S
11	Fenhe	FH	Hejin	38650	560.9	S
12	Beiluohu	BL	Zhuangtou	25645	675.9	S
13	Weihe	WH	Huaxian	106498	683.9	S

Distance is measured along the Yellow River from the outlet of the northernmost basin, Kuyehe (KY), to the outlet of each basin, with the KY outlet assigned a distance of 0 km. **Region** refers to whether a basin is classified in the northern (N) or the southern (S) Loess Plateau based on the along-river distance from KY.

3 Materials and methods

3.1 Data sources

The daily flow data for each basin, corresponding to hydrological stations, are sourced from the 1990-2020 Yellow River Basin Hydrological Yearbook. VC for each basin was calculated based on the proportion of forest, shrubland, and grassland areas extracted from the China Annual Land Cover Dataset (CLCD) with a spatial resolution of 30 meters (Yang and Huang, 2021). Human water use data are sourced from the National Long-term Water Use Dataset of China (NLWUD) dataset (Zhou et al., 2020) and the annual water resource bulletins (WRB) of various provinces within the Yellow River Basin. The NLWUD dataset includes annual water use from 1990 to 2013 for Chinese prefecture-level cities, while



the water resource bulletins include total water use data from 2000 to 2020 for each province. A linear fit of the total water usage data for overlapping years (2000-2013) from the two datasets showed a significant linear relationship ($R^2=0.97$, $RMSE=1.43$, Fig. B1). Therefore, the water use data from the water resource bulletins for 2014-2020 can be used to estimate the prefecture-level city water usage from
140 1990 to 2020 and match the NLWUD dataset. Assuming uniform water use distribution across each prefecture-level city, the annual water use for each basin is calculated by computing the proportional area of each city within the basin and using area-weighted averaging.

The daily evapotranspiration data are from the global land evapotranspiration model, GLEAM v4.1a with a spatial resolution of 0.1° (Miralles et al., 2025), which has performed very well in arid and semi-arid
145 areas of China (Shi et al., 2024) and the Yellow River Basin (Wang et al., 2018). The daily rainfall data are obtained from the National Meteorological Information Center (Zhao and Zhu, 2015). This dataset utilizes high-quality daily precipitation data from meteorological stations and applies thin plate spline interpolation to spatially interpolate precipitation data, resulting in a $0.5^\circ \times 0.5^\circ$ grid of daily precipitation values. The daily rainfall data is first resampled to a 0.1° resolution using nearest-neighbor interpolation,
150 and then combined with the evapotranspiration data to calculate daily P-ET. Subsequently, daily average P-ET was computed for each basin based on spatial aggregation.

3.2 Indices

This study involves three categories of indicators: extreme flows, climate, and human activities. To normalize for differences in basin area, all indicators were standardized to units of $\text{mm} \cdot \text{d}^{-1}$, except for
155 vegetation cover, which is expressed as a percentage.

For the annual extreme flow indices, we adopt the hydrological regime classification method proposed by Chagas (2022). It uses annual minimum 7-day moving mean streamflow to represent annual low flows and annual maximum daily streamflow to represent annual high flows. For each basin, these indices are calculated as follows:

$$LF_{i,y} = \min_{d \in W_{y,7}} \left(\frac{1}{7} \sum_{j=0}^6 Q_{i,d-j} \right), \quad (1)$$

$$HF_{i,y} = \max_{d \in D_y} Q_{i,d}, \quad (2)$$



160 where i indexes basins, y denotes the year, and d denotes the date; $Q_{i,d}$ is daily streamflow expressed as runoff depth ($\text{mm}\cdot\text{d}^{-1}$); D_y is the set of dates in year y ; and $W_{y,7}$ is the set of valid k -day moving-window end dates assigned to year y . The moving window advances by one day.

The joint trends of low and high flows are used to characterize changes in the hydrological regime. If both low flows and high flows exhibit decreasing trends, the basin's hydrological regime is classified as a drying trend. If both low flows and high flows show increasing trends, the hydrological regime is
165 classified as a wetting trend. If low flows decrease while high flows increase, the hydrological regime is classified as an accelerating trend, with the opposite classified as a decelerating trend.

For the climatic indices, we use precipitation minus actual evapotranspiration ($P - ET$) to represent daily water availability. Mean $P - ET$ is defined as the annual mean of daily $P - ET$, Min. $P - ET$ as the
170 annual minimum of its 90-day moving mean, and Max. $P - ET$ as the annual maximum of its 14-day moving mean. Both moving windows advance by one day. These indices are calculated as follows :

$$(\text{Mean } P - ET)_{i,y} = \frac{1}{N_y} \sum_{d \in D_y} (P_{i,d} - ET_{i,d}), \quad (3)$$

$$(\text{Min. } P - ET)_{i,y} = \min_{d \in W_{y,90}} \left[\frac{1}{90} \sum_{j=0}^{89} (P_{i,d-j} - ET_{i,d-j}) \right], \quad (4)$$

$$(\text{Max. } P - ET)_{i,y} = \max_{d \in W_{y,14}} \left[\frac{1}{14} \sum_{j=0}^{13} (P_{i,d-j} - ET_{i,d-j}) \right], \quad (5)$$

where $P_{i,d}$ and $ET_{i,d}$ denote basin-averaged daily precipitation and actual evapotranspiration, respectively ($\text{mm}\cdot\text{d}^{-1}$); N_y is the number of days in year y . D is the set of dates in year y , and W is the set of valid moving-window end dates assigned to that year, with the window length indicated by 90
175 or 14. The annual minimum or maximum is selected after calculating the corresponding moving means. Mean $P-ET$, Min. $P-ET$, and Max. $P-ET$ represent the annual daily mean available water, the annual minimum 90-day available water, and the annual maximum 14-day available water, respectively (Chagas et al., 2022). These three climate indicators can be used to assess the long-term average water resource status of a basin, as well as water resource conditions under seasonal meteorological drought and extreme
180 rainfall events.

For the human activity indices, considering the implementation of ecological projects and economic policies since the late 1970s, we select vegetation cover (VC), total water use (WU) and irrigation water



use (IWU) as three human activity indicators that have a profound impact on the ecohydrological processes of the Loess Plateau. VC for each basin was calculated based on the proportion of forest, shrubland, and grassland areas. WU and IWU refer to total or irrigation water withdrawals from both surface water and ground water. No large reservoirs exist in the 13 study basins, so reservoir effects were assumed to be negligible.

3.3 Trend analysis

We divided the record into two equal periods, 1990–2005 and 2005–2020. The year 2005 was used as a process-informed temporal reference rather than an exact hydrological breakpoint. It approximately marks the transition from the initial implementation of major ecological restoration and regional development programs in the early 2000s to a subsequent stage emphasizing the consolidation of restoration outcomes and resource conservation (Zhao et al., 2017; Tang et al., 2023). As a sensitivity analysis, the Pettitt (Pettitt, 1979) and Bai–Perron tests (Bai and Perron, 1998) were also applied, both of which identified 2005 as a candidate breakpoint (Fig. A3); however, given the limitations associated with the short record length and serial correlation (Busuioc and Storch, 1996; Bai and Perron, 1998), these results were not used as the primary basis for defining the two periods. The formulations the change-point analyses are provided in Appendix A. The Theil-Sen slope analysis method (Sen, 1968) was then applied to analyze the slopes before and after 2005. Additionally, the Mann-Kendall test (Mann, 1945) was used to assess the significance of the slopes. For indicators reported as relative changes, the annual slope was normalized by a reference mean and converted to a decadal percentage change:

$$R_{10} = 100 \times \frac{10b_{TS}}{\bar{X}}, \quad (6)$$

where R_{10} is the relative change expressed as a percentage per decade, b_{TS} is the Theil-Sen slope, and $\bar{X}$ is mean of the annual indicator values within the corresponding subperiod (1990–2005 or 2005–2020).

Thus, the trend in each subperiod is normalized by the mean calculated over that same subperiod.



205 3.4 Trend attribution analysis

We use panel regression models to investigate the relationships between climate change, human activities, and extreme flow events of all 13 basins and of different regions. Panel regression allows the incorporation of time-series data from multiple individuals (basins) into a single regression equation, thus providing a more comprehensive analysis of the relationship between hydrological variability and its driving factors across both temporal and spatial scales. In panel regression models, fixed effects and random effects models can control for unobserved heterogeneity across individuals or time, thereby reducing estimation bias and improving explanatory accuracy. The fixed effects model treats individual differences as unobserved but constant parameters, whereas the random effects model assumes these differences are random variables uncorrelated with the explanatory variables (Bassiouni et al., 2016; Steinschneider et al., 2013; Chagas et al., 2022). Models were fitted separately for annual low flows and high flows in each subperiod. We use random-effects models as indicated by the Hausman specification test (Hausman, 1978), but also re-estimated all models using fixed-effects models for robustness; the results are provided in the Appendix A (Fig. A1, 2). We use the linear form as a simple approximation, informed by studies of climate–runoff relationships (Sankarasubramanian et al., 2001; Miao et al., 2020), vegetation effects on water balance (Zhang et al., 2001), and human water abstracting effects on streamflow (Zipper et al., 2019).

For the baseline models, the explanatory variables for low flows included VC, IWU, Min. P-ET, and Mean P-ET, while those for high flows included VC, WU, Max. P-ET, and Mean P-ET:

$$LF_{i,t} = \beta_1 \overline{P - ET}_{i,t} + \beta_2 \overline{P - ET}_{i,t,90}^{min} + \beta_3 IWU_{i,t} + \beta_4 VC_{i,t} + \gamma t_c + \alpha + u_i + \varepsilon_{i,t}, \quad (7)$$

$$HF_{i,t} = \beta_1 \overline{P - ET}_{i,t} + \beta_2 \overline{P - ET}_{i,t,14}^{max} + \beta_3 WU_{i,t} + \beta_4 VC_{i,t} + \gamma t_c + \alpha + u_i + \varepsilon_{i,t}, \quad (8)$$

where $LF_{i,t}$ and $HF_{i,t}$ are the low flows and the high flows of basin i at year t , respectively; $\overline{P - ET}_{i,t}$, $\overline{P - ET}_{i,t,90}^{min}$ and $\overline{P - ET}_{i,t,14}^{max}$ denote the annual mean (Mean P-ET), minimum 90-day moving average (Min. P-ET) and maximum 14-day moving average (Max. P-ET) of the daily difference between precipitation and actual evapotranspiration for basin i at year t , respectively; β_1 to β_4 are the coefficients of the explanatory variables; α , u_i and $\varepsilon_{i,t}$ represent the overall intercept of all basins, the random error for basin i and the idiosyncratic error, respectively. A linear time trend (γt_c) is also included to account for a common linear temporal trend (Wooldridge, 2012, pp. 366–368), where $t_c =$



$t - \bar{t}$ is the mean-centered time variable, thereby reducing the correlation between the estimated intercept (α) and time-trend coefficient (γ).

To identify the differences between the northern and southern basins while avoiding potential estimation bias caused by the reduced sample size in regional analyses, a dummy variable, North (1 for the northern and 0 for the southern basins), together with its interaction terms with other explanatory variables, was incorporated into the original model. Each interaction term was tested separately by adding it individually to the original model (Table A1), and only those with significant effects were retained in the final model:

$$\begin{aligned} \text{LF}_{i,t} = & \beta_1 \overline{\text{P}} - \overline{\text{ET}}_{i,t} + \beta_2 \overline{\text{P}} - \overline{\text{ET}}_{i,t,90}^{\text{min}} + \beta_3 \text{IWU}_{i,t} + \beta_4 \text{VC}_{i,t} + \beta_5 \text{North} \\ & + \beta'_3 (\text{IWU}_{i,t} \times \text{North}) + \beta'_4 (\text{VC}_{i,t} \times \text{North}) + \gamma t + \alpha + u_i + \varepsilon_{i,t}, \end{aligned} \quad (9)$$

$$\begin{aligned} \text{HF}_{i,t} = & \beta_1 \overline{\text{P}} - \overline{\text{ET}}_{i,t} + \beta_2 \overline{\text{P}} - \overline{\text{ET}}_{i,t,14}^{\text{max}} + \beta_3 \text{WU}_{i,t} + \beta_4 \text{VC}_{i,t} + \beta_5 \text{North} \\ & + \beta'_3 (\text{WU}_{i,t} \times \text{North}) + \beta'_4 (\text{VC}_{i,t} \times \text{North}) + \gamma t + \alpha + u_i + \varepsilon_{i,t}, \end{aligned} \quad (10)$$

where North is the dummy variable; $\text{VC}_{i,t} \times \text{North}$, $\text{IWU}_{i,t} \times \text{North}$ and $\text{WU}_{i,t} \times \text{North}$ are interaction terms constructed by multiplying North with $\text{VC}_{i,t}$, $\text{IWU}_{i,t}$, and $\text{WU}_{i,t}$, respectively; and β_5 , β'_3 and β'_4 are the coefficients of the dummy variable and interaction terms. In the model, β_3 and β_4 are the coefficients of the explanatory variables for the southern basins (North = 0), whereas the corresponding coefficients for the northern basins (North = 1) are obtained by summing the main-effect and interaction-term coefficients. The standard errors and significance levels of these combined coefficients were estimated using the Delta method and Wald tests, respectively, as implemented via the deltaMethod and linearHypothesis functions from the R package car (Oehlert, 1992; Fox et al., 2013).

The selection of water use and climate indicators differed slightly between the two models due to the pronounced seasonal variation and synchronicity of extreme flows, climate variables, and human water use on the Loess Plateau. Low flows mainly occur in late spring and early summer (Fig. B2b), when precipitation is scarce and evapotranspiration is intense. To ensure the regreening of winter wheat and the growth of spring-sown crops during this period, IWU becomes the dominant water use type, reaching its annual peak (J. Wang et al., 2022) and thus exerting a strong potential influence on low flows. The occurrence of Min. P-ET mainly spans March to June (Fig. B2b), closely overlapping with the timing of low flows. Therefore, IWU and Min. P-ET were selected as the explanatory variables for the low-flow model. High flows, however, mainly occur during the main rainy season in summer (Fig. B2a), when rainfall is abundant and WU reaches its annual maximum. Combined with high irrigation demand from



the preceding spring-summer transition, spring and summer are the dominant contributor to annual water use and exert considerable potential influence on high flows. Meanwhile, Max. P-ET mainly occurs between July and September (Fig. B2a), closely overlapping with the occurrence of high flows. Therefore, WU and Max. P-ET were selected as the explanatory variables for the high-flow model.

260 Panel regression analysis was conducted using the plm package in R (Croissant and Millo, 2008), with all variables standardized prior to modelling using scale function in R to facilitate comparison of regression coefficients:

$$x^* = \frac{x - \bar{x}}{s_x}, \quad (11)$$

where x^* is the standardized value of x , and $\bar{x}$ and s_x are the corresponding sample mean and sample standard deviation, respectively.

265 In addition, we adopted cluster-robust standard errors (Arellano, 1987) that allow for heteroskedasticity and serial correlation of arbitrary form, implemented via the vcovHC function in plm with clustering at the individual level. Based on the regression coefficients derived from the panel regression results of extreme flows and their driving factors, the contribution of each indicator to streamflow trends can be quantified. The sign of the regression coefficient indicates whether the influence of each driving factor
270 on streamflow variation is positive or negative. For example, a coefficient of 0.1 means a 0.1-standard-deviation change in streamflow for each one-standard-deviation change in the driver.

4. Results

4.1 Trends in annual extreme streamflow and the hydrological regime shift

Low and high flows decreased overall from 1990 to 2005 but increased from 2005 to 2020 (Fig. 2). This
275 marks a hydrological regime transition from drying trends to wetting trends. From 1990 to 2005, both low and high flows in the basins showed a general decreasing trend, with a median change rate of -76.0% per decade for low flows ($p < 0.05$) and -54.7% per decade for high flows ($p < 0.05$). In contrast, from 2005 to 2020, both low and high flows showed an overall increasing trend, with a median change rate of 61.6% per decade for low flows ($p < 0.01$) and 57.1% per decade for high flows ($p = 0.05$). Thus, the hydrological
280 regime has undergone the transition from drying (1990-2005) to wetting (2005-2020). Moreover, for most basins, the percentage change in low flows was larger than the percentage change in high flows from 2005 to 2020 (Fig. 3). From 1990 to 2020, the overall hydrological cycle on the Loess Plateau



indicated a decelerating trend (Fig. 3), with low flows increasing across the basins at a median change
rate of 36.4% per decade ($p < 0.01$), and high flows decreasing at a median rate of -23.1% per decade
285 ($p < 0.05$). Extreme streamflow trends are more pronounced in the north (Fig. 4a, e, Fig. 5a, b).
Specifically, the northern basins exhibited a stronger drying trend in 1990-2005 and a stronger wetting
trend in 2005-2020.

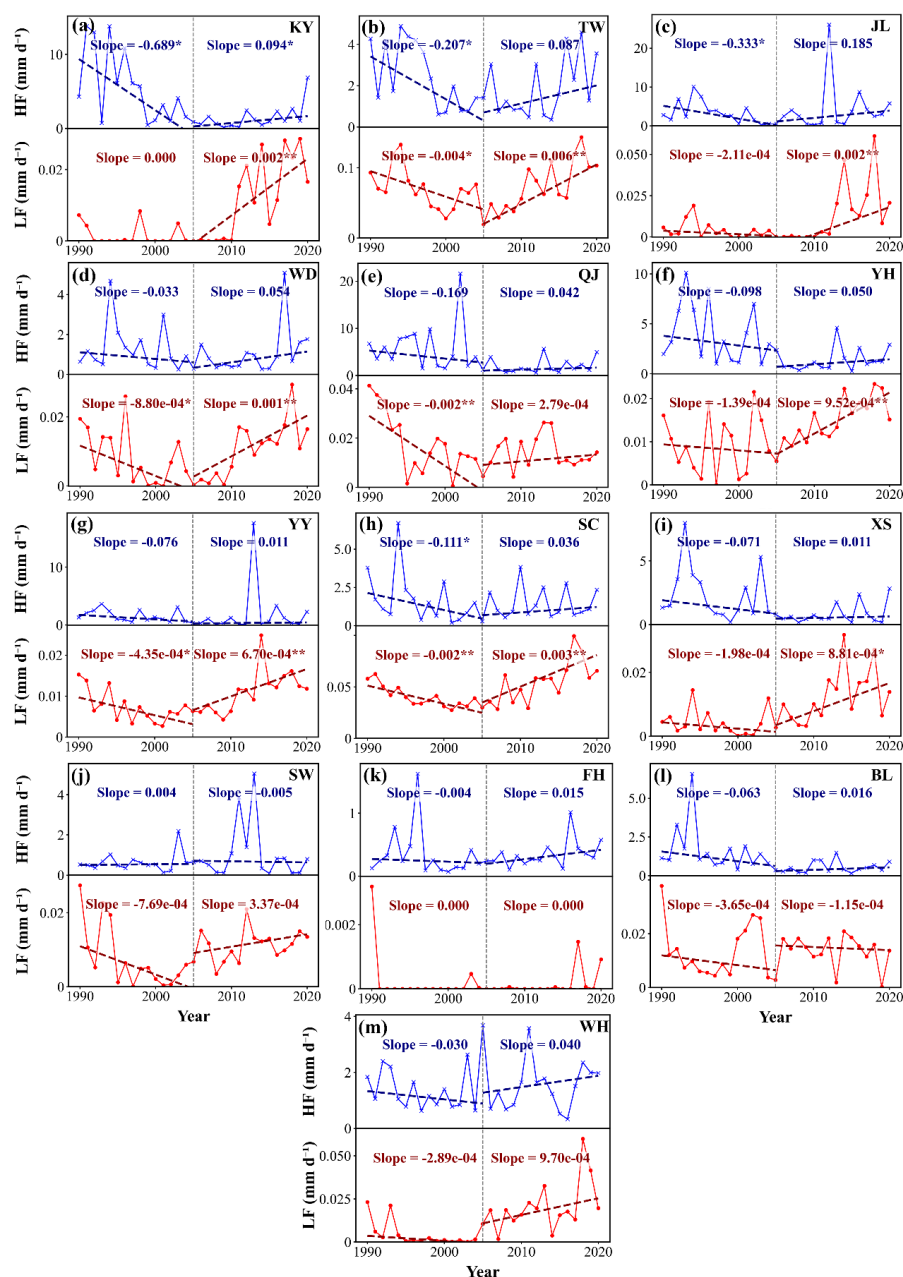


Fig. 2. Trends in annual extreme flow characteristics across basins during 1990–2020. LF and HF denote low flows and high flows, respectively. * and ** denote significance at the levels of $p < 0.05$ and $p < 0.01$, respectively.

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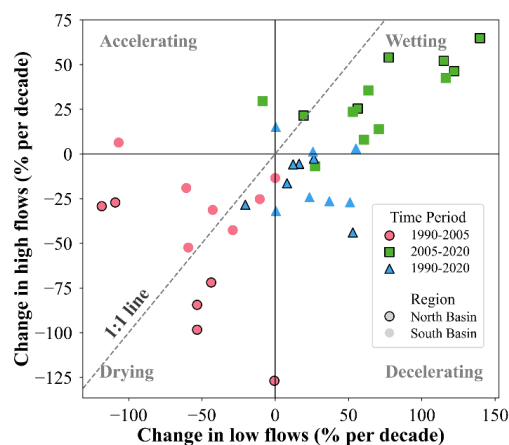


Fig. 3. the hydrological regime categorized based on extreme flows.

4.2 Changes in climate and human activities and their spatial variability

From 1990 to 2020, both climate conditions and human activities on the Loess Plateau experienced notable changes. Overall, WU and VC increased significantly across the Loess Plateau, with slower growth after 2005, whereas IWU shifted from a significant increase before 2005 to a significant decrease afterward (Table 2). Both precipitation and evapotranspiration increased over the full period (Table 2), with Mean P-ET decreasing before 2005 and partially recovered afterward, with no statistically significant trend over the full period (Table 2). Max. P-ET increased significantly over the full period, though the increases during 1990–2005 and 2005–2020 were not statistically significant (Table 2). Min. P-ET showed a significant overall decline, with a more pronounced decrease before 2005 (Table 2). Climatic and anthropogenic changes were generally more pronounced in the northern basins (Fig. 5). Trends in human activities were also more consistent among northern basins, whereas southern basins exhibited greater between-basin variability (Fig. 4).

Table 2. Median trends of streamflow and their drivers of all basins.

	1990-2020	1990-2005	2005-2020
	(per decade)	(per decade)	(per decade)
LF	36.4%**	-76.0%*	61.6%**
HF	-23.1%*	-54.7%*	57.1% (p=0.05)
VC	4.6 p.p.***	5.5 p.p.***	2.0 p.p.***
WU	15.9%***	17.1%***	7.8%*



IWU	1.9% (p=0.54)	11.6%**	-13.2%**
Mean P-ET	-30.1% (p=0.16)	-97.0% (p=0.09)	10.2% (p=0.89)
Max. P-ET	11.7%*	4.5% (p=1)	8.0% (p=0.31)
Min. P-ET	-14.8%**	-31.6% (p=0.09)	-8.4% (p=0.40)
P	5.2% (p=0.14)	-6.3% (p=0.39)	7.0% (p=0.35)
ET	7.6%***	6.5% (p=0.5)	5.4% (p=0.09)

LF denotes low flows, HF denotes high flows, VC denotes vegetation cover, WU denotes total water use, IWU denotes irrigation water use, P denotes precipitation, ET denotes actual evapotranspiration, Mean P-ET, Max. P-ET and Min. P-ET denote the annual daily mean, maximum 14-day, and minimum 90-day available water, respectively. p.p. denotes percentage points. *, ** and *** denote significance at the level of $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively.

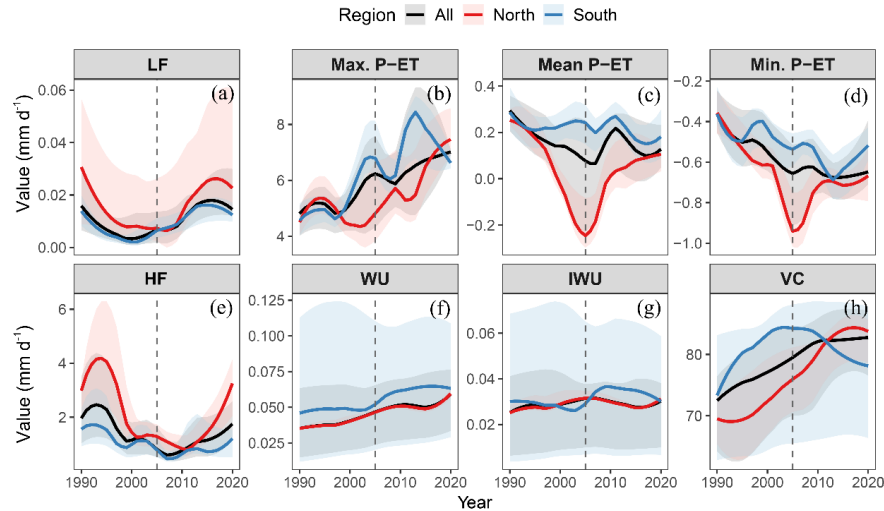
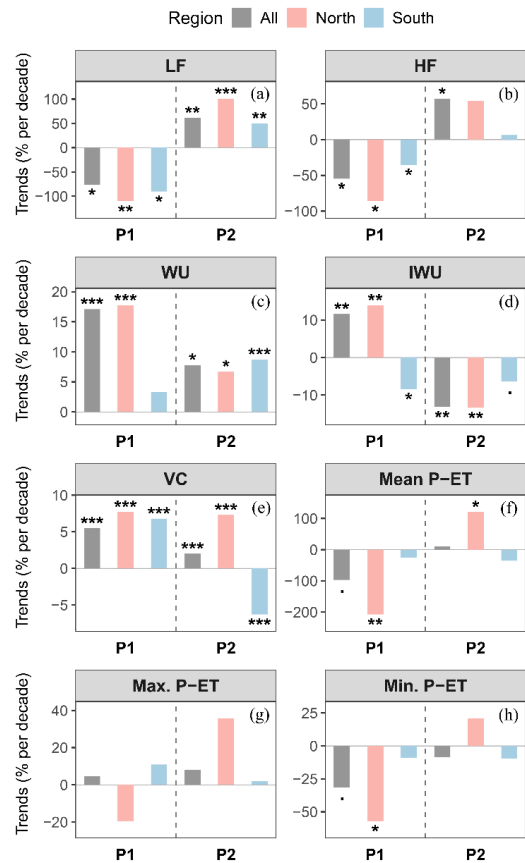


Fig. 4. Temporal evolution of streamflow and their drivers in the northern and southern basins of the Loess Plateau. Lines represent the median and bands indicate the spatial variability within each region (25th and 75th percentiles). The dashed lines represent the year of 2005. The time series were smoothed using the LOESS method with a smoothing parameter of 0.5. The unit of VC is % (h). LF denotes low flows, HF denotes high flows. VC denotes vegetation cover, WU denotes total water use, IWU denotes irrigation water use, Mean P-ET, Max. P-ET and Min. P-ET denote the annual daily mean, maximum 14-day, and minimum 90-day available water, respectively.



320

Fig. 5. Trends of streamflow and their drivers in the northern and southern basins of the Loess Plateau. Boxes represent the trends of the median, calculated as the Theil–Sen slope divided by the mean and scaled to a decadal basis. Symbols denote significance of the slope at different levels ($p < 0.1$, $*$ $p < 0.05$, $**$ $p < 0.01$, $***$ $p < 0.001$). The dashed lines represent the year of 2005. The unit of VC is percentage points per decade (e). LF denotes low flows; HF denotes high flows. VC denotes vegetation cover, WU denotes total water use, IWU denotes irrigation water use, Mean P-ET, Max. P-ET and Min. P-ET denote the annual daily mean, maximum 14-day, and minimum 90-day available water, respectively. P1 denotes 1990-2005, P2 denotes 2005-2020.

325

4.3 Impacts of climate change and human activities on extreme flow trends

The hydrological regime shifts in the Loess Plateau are affected by climate factors and human activities (Fig. 6). Changes in low flows are primarily driven by human activities, particularly VC, though the impact of VC on low flows reversed direction from the drying phase (1990-2005) to the wetting phase (2005-2020) (Fig. 6a, c). By contrast, changes in high flows were primarily driven by human activities

330



during the drying phase, while climate change exerted the dominant influence during the wetting phase (Fig. 6b, d).

335 From 1990 to 2005, VC had the largest standardized coefficient for low flows, followed by IWU, Mean P-ET, and Min. P-ET. VC was significantly negatively associated with low flows ($\beta = -0.547$, $p < 0.001$), whereas IWU also had a negative coefficient but was not statistically significant ($\beta = -0.239$, $p > 0.1$). During the same period, WU and VC had relatively large negative coefficient estimates for high flows ($\beta = -0.390$ and -0.289 , respectively), but neither association was statistically significant, indicating
340 considerable uncertainty in these estimates. In contrast, Mean P-ET ($\beta = 0.149$, $p = 0.056$) and Max. P-ET ($\beta = 0.104$, $p < 0.05$) were positively associated with high flows, with the effect of Max. P-ET being statistically significant and that of Mean P-ET being marginally significant.

From 2005 to 2020, VC had the largest standardized coefficient for low flows and was statistically significant ($\beta = 0.896$, $p < 0.05$), followed by IWU, Min. P-ET, and Mean P-ET. During the same period,
345 Max. P-ET was significantly positively associated with high flows ($\beta = 0.462$, $p < 0.01$), while WU showed a significant negative association ($\beta = -0.351$, $p < 0.05$). VC also had a negative coefficient, but the association was only marginally significant ($\beta = -0.322$, $p < 0.1$).

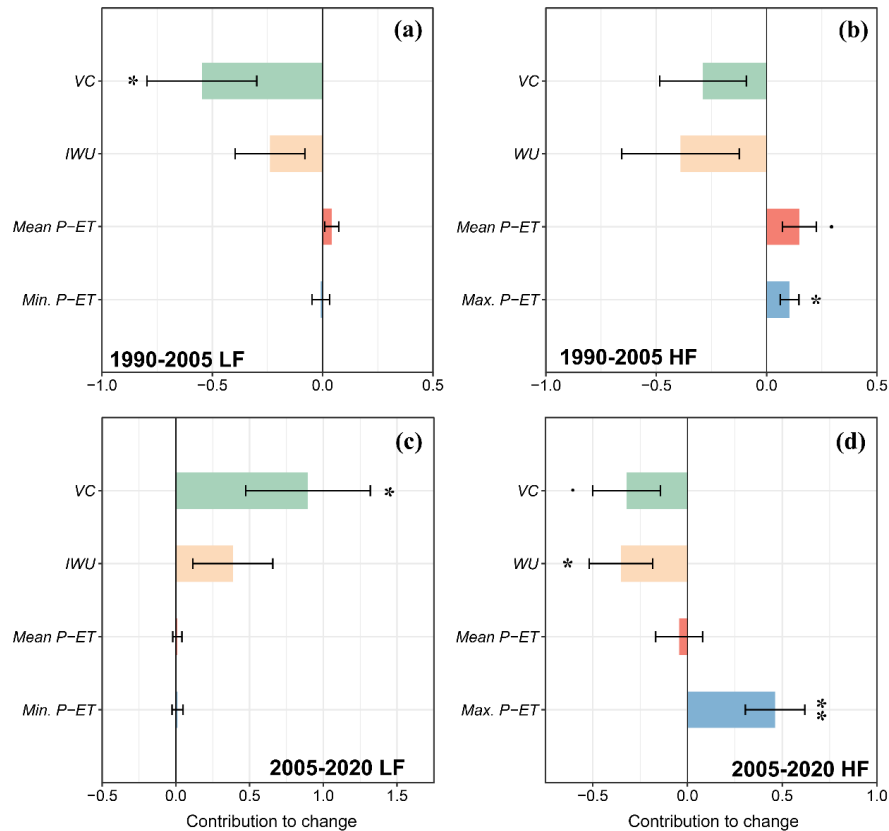


Fig. 6. Contributions of drivers to extreme flows. (a) Low flows in 1990-2005, (b) high flows in 1990-2005, (c) low flows in 2005-2020, (d) high flows in 2005-2020. LF denotes low flows; HF denotes high flows. VC denotes vegetation cover, WU denotes total water use, IWU denotes irrigation water use, Mean P-ET, Max. P-ET and Min. P-ET denote the annual daily mean, maximum 14-day, and minimum 90-day available water, respectively. ., *, and ** denote significance at the levels of $p < 0.1$, $p < 0.05$, and $p < 0.01$, respectively. Error bars represent the standard error.

Extreme streamflow is more strongly driven by human activities in the northern basins than in the southern basins (Fig. 7). In combination with the panel regression results, it can be shown that VC significantly affected low flows in the Loess Plateau, particularly the northern basins (Fig. 7a, c). Although the effect of WU on high flows was not significant across the Loess Plateau during 1990–2005, it exhibited a significant negative effect in the northern basins (Fig. 7b). By contrast, during 2005–2020, WU exerted a significant negative effect on high flows throughout the Loess Plateau, specifically in the



southern basins (Fig. 7d). However, no statistically significant difference was observed between the northern and southern basins in the effects of climate change on extreme flows (Table A1).

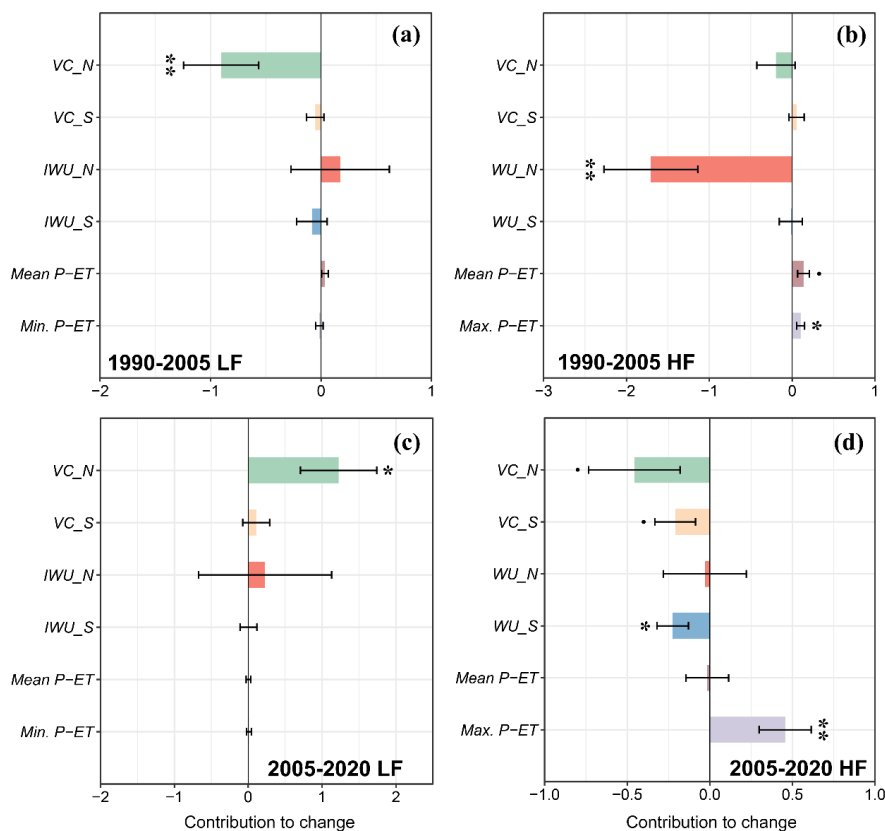


Fig. 7. Regional differences in contributions of drivers to extreme flows. (a) Low flows in 1990-2005, (b) high flows in 1990-2005, (c) low flows in 2005-2020, (d) high flows in 2005-2020. LF denotes low flows; HF denotes high flows. VC denotes vegetation cover, WU denotes total water use, IWU denotes irrigation water use, Mean P-ET, Max. P-ET and Min. P-ET denote the annual daily mean, maximum 14-day, and minimum 90-day available water, respectively. The suffixes _N and _S indicate results for northern and southern basins, respectively. ., *, and ** denote significance at the levels of $p < 0.1$, $p < 0.05$, and $p < 0.01$, respectively. Error bars represent the standard error.

5. Discussion

5.1 Human activity impacts on the hydrological regime shift

Human activities exerted significant influences on the hydrological regime across the Loess Plateau, especially through changes in VC associated with vegetation restoration. The driving mechanism of VC



on hydrological regime, low flows specifically, has undergone a transformation during the drying-to-wetting transition. From 1990 to 2005, as VC increased due to vegetation restoration, low flows decreased (Fig. 6a). This reduction in low flows could be attributed to increased land evapotranspiration driven by higher vegetation cover (Sun et al., 2006; Wang et al., 2011), in cases where this elevated water loss was not offset by increased precipitation. From 2005 to 2020, low flows increased with the rise in VC, especially in the northern region (Fig. 6c, Fig. 7c). This reversal in trend may be attributed to the eventual stabilization of deep soil moisture consumption by vegetation (Li et al., 2021). Furthermore, more plant roots promoted the formation of preferential flow pathways as vegetation restoration continued (Xu et al., 2010; Li et al., 2017; Wen et al., 2025), particularly during peak rainfall events, facilitating deeper percolation (Liu et al., 2025), and decreasing high flows (Fig. 6d, Fig. 7d). Canopy and litter cover may also protect the soil surface from raindrop impact, potentially limiting physical crusting and helping maintain infiltration capacity in loess soils (Wang et al., 2016; Niu et al., 2024). Such surface protection could complement root-induced preferential flow, although canopy effects on throughfall kinetic energy depend on canopy structure and saturation (Nanko et al., 2008). As a result, the delayed recharge of groundwater following the flood season contributed to the increase in low flows (Zhang et al., 2019). Furthermore, the slower rate of vegetation restoration during 2005-2020 compared to 1990-2005 (Fig. 4h) may have led to a reduction in water consumption by newly restored vegetation, which was likely outweighed by the enhancement of preferential flow driven by the root systems of more mature vegetation. This positive trend has been observed in several small basins on the Loess Plateau, where recent studies have reported an increase in low flows coinciding after vegetation restoration (Gao et al., 2015; Zhang et al., 2022), signalling a potential reversal of the previously dominant drying trend. To sum up, the trade-off between changes in actual evapotranspiration and infiltration after afforestation determines the net impact on groundwater recharge and low flows (Bruijnzeel, 2025).

Spatially, vegetation restoration was more intensive in the northern basins than in the southern basins of the Loess Plateau (Wu et al., 2021). Thus, the larger increase in vegetation cover in the north amplified its regulation of extreme flows, resulting in more pronounced hydrological responses that corresponded to the spatial pattern of VC changes (Fig. 4a, e, Fig. 5a, b). In contrast, in some southern basins, land consolidation and high-standard farmland construction after 2010 (the State Council of China, 2012a, 2013) converted portions of grassland into terraced fields and check-dam farmland, leading to a decline



405 in VC (Fig. 4h, Fig. 5e). However, these land-use types can enhance infiltration by increasing runoff residence time, thereby partly offsetting the hydrological effects of vegetation loss on high flows.

The changes in land use types, agricultural policies and water use structure during 1990–2020 have determined the effects of IWU and WU on the hydrological regime. The low-flow metric used in this study is closely associated with dry-season baseflow (Reilly and Kroll, 2003; Zhang and Kroll, 2007).

410 Since baseflow is primarily maintained by groundwater discharge to streams, variations in low flows are likely to be influenced by IWU, particularly groundwater abstraction. In contrast, the high-flow metric is more strongly associated with shallower flow paths, potentially including overland flow, generated by intense rainfall events (Zhao, 1984, pp. 55–70). Consequently, variations in high flows are likely to be influenced by WU, especially surface-water withdrawals. During 1990–2005, less than 50% of IWU

415 across the Loess Plateau was supplied by groundwater (Fig. B3b), whereas less than 50% of WU was derived from surface water (Fig. B3a). As a result, the overall effects of human water use on extreme flows were not significant (Fig. 6). Notably, in the northern basins, 56% of WU originated from surface water sources, resulting in a certain degree of reduction in high flows; however, this effect was statistically significant only in the random-effects model (Fig. 7, A2). During 2005–2020, driven by the

420 implementation of the Grain for Green Program, agricultural water-saving policies, and groundwater abstraction control measures (Yan, 2005; the State Council of China, 2012b, 2012c), IWU generally declined and the proportion of groundwater withdrawals decreased markedly (Fig. 4g, Fig. 5d, Fig. B3a). Consequently, the overall effect of IWU on low flows across the Loess Plateau remained insignificant (Fig. 6c). In contrast, WU continued to increase under the combined influences of urbanization and

425 industrialization (Wang et al., 2023; Zhou et al., 2020). Together with the substantial increase in the proportion of surface-water withdrawals (Fig. 4f, Fig. 5c), this led to a significant mitigating effect of WU on high flows, particularly in the southern basins (Fig. 7d, A2d).

5.2 Climate change impacts on the hydrological regime shift

Climate factors, especially Max. P-ET, had a more pronounced impact on high flows. Max. P-ET exerted

430 a consistently significant positive effect on high flows in both the northern and southern basins during the two sub-periods (Fig. 7). This is because Max. P-ET represents an extended period when precipitation greatly exceeds evaporative demand, leading to near-saturated soil moisture and reduced infiltration capacity, thus promoting overland flow. Recent increases in annual extreme precipitation (Yin et al.,



2023), together with the Plateau's geographical and soil conditions, have facilitated the rapid conversion
435 of intense rainfall into surface runoff, further enhancing high flows (Mu et al., 2024). However, Min. P-
ET showed no significant effect on low flows, a plausible mechanism of which is that low flows respond
more slowly to atmospheric water availability (Fang et al., 2020; Chagas et al., 2024). Mean P-ET had
nearly no significant effect on either high flows or low flows, especially in the fixed-effects model (Fig.
A1, A2). This is because flood generation is not driven by average annual wetness but more likely by
440 extreme atmospheric water condition in the Loess Plateau (Qin et al., 2024).

5.3 Advantages of coupled low-high metrics in diagnosing hydrological shifts and management implications

Previous studies on hydrological regime changes in the Loess Plateau have primarily focused on
variations in total water resources based on annual runoff or mean daily streamflow (Feng et al., 2016;
445 Yin et al., 2021), whereas the present study further examined changes in extreme-flow indicators to
characterize variations in low flows during dry periods and high flows during the flood season. Although
both indicators followed the same decrease–increase pattern as total runoff during 1990–2020 (Fig. B4),
the relative rate of increase in high flow was lower than that of low flows in most basins during 2005–
2020 (Fig. 3). This suggests that although the overall increase in Max. P-ET during 2005–2020 was
450 slightly greater than that during 1990–2005 (Fig. 4b, Fig. 5g), vegetation exerted contrasting effects on
the two flow regimes by suppressing high flow while enhancing low flows (Fig. 6). Consequently, a
larger proportion of the increase in total runoff was allocated to low flows, which may help to satisfy
ecological water demands during dry periods, improve the reliability of water withdrawals for human
use, and promote a more stable riverine hydrological regime.

455 Given the divergent hydrological regimes observed over the two study periods—drying from 1990 to
2005 due to increased VC, and wetting from 2005 to 2020 driven by increased VC and Max. P-ET—
targeted strategies are required to address the evolving hydrological cycle dynamics on the Loess Plateau.

In the future, precipitation in the Loess Plateau is expected to continue increasing (Gao et al., 2017; Han
et al., 2024), which could lead to more water resource and extreme rainfall. These observations suggest
460 that future basin management should strengthen the construction and maintenance of flood control
infrastructure such as levees and reservoirs, and enhance flood early warning systems in order to mitigate
the potential adverse impacts of flood events on socio-ecological systems. Recently, influenced by global



climate warming and regulated by El Niño-Southern Oscillation (ENSO) events—particularly sea surface temperature anomalies in the central-western and northern equatorial Pacific—the frequency of extreme rainfall events has increased in the northern Loess Plateau (Li et al., 2020). Thus, the northern basins may require stronger management efforts in flood control. Secondly, the impact of revegetation on streamflow, particularly on low flows, necessitates long-term monitoring in the future. At the same time, the pace of vegetation restoration should be moderated to reduce the inhibition of low flows by newly planted vegetation during their early growth stages, especially in the northern basins.

6. Conclusions

This study reveals a clear hydrological regime shift in 13 Loess Plateau basins, with a transition from a drying phase (1990–2005) to a wetting phase (2005–2020), with a turning point identified around 2002–2007. Unlike previous studies focusing on total runoff, our results demonstrate that hydrological changes are better understood from a water-resource structure perspective, particularly through the contrasting dynamics of low and high flows. Vegetation and climatic drivers jointly controlled this regime shift, with vegetation consistently regulating low flows across both periods, while exerting contrasting effects on high flows by suppressing high flows and enhancing low flows during 2005–2020. This asymmetric regulation altered runoff partitioning and promoted a more stable hydrological regime in the later period. The findings highlight the increasing importance of vegetation–hydrology interactions under a changing climate, suggesting that future basin management should prioritize flood-risk mitigation, particularly in the northern basins, while promoting adaptive revegetation to balance ecological restoration and water availability.



Appendix A. Robustness and sensitivity analyses

A1. Panel regression model specification and robustness checks

To assess the robustness of the RE results, the baseline and regional specifications described in Sect. 3.4 were re-estimated using basin fixed effects. The fixed-effects specifications were represented by the following general expression:

$$LF_{i,t} = \beta_1 \overline{P} - \overline{ET}_{i,t} + \beta_2 \overline{P} - \overline{ET}_{i,t,90}^{min} + \beta_3 IWU_{i,t} + \beta_4 VC_{i,t} + \gamma t_c + \alpha_i + \varepsilon_{i,t}, \quad (A1)$$

$$HF_{i,t} = \beta_1 \overline{P} - \overline{ET}_{i,t} + \beta_2 \overline{P} - \overline{ET}_{i,t,14}^{max} + \beta_3 WU_{i,t} + \beta_4 VC_{i,t} + \gamma t_c + \alpha_i + \varepsilon_{i,t}, \quad (A2)$$

$$LF_{i,t} = \beta_1 \overline{P} - \overline{ET}_{i,t} + \beta_2 \overline{P} - \overline{ET}_{i,t,90}^{min} + \beta_3 IWU_{i,t} + \beta_4 VC_{i,t} + \beta_5 North + \beta'_3 IWU_{i,t} \times North + \beta'_4 VC_{i,t} \times North + \gamma t + \alpha_i + \varepsilon_{i,t} \quad (A3)$$

$$HF_{i,t} = \beta_1 \overline{P} - \overline{ET}_{i,t} + \beta_2 \overline{P} - \overline{ET}_{i,t,14}^{max} + \beta_3 WU_{i,t} + \beta_4 VC_{i,t} + \beta_5 North + \beta'_3 WU_{i,t} \times North + \beta'_4 VC_{i,t} \times North + \gamma t + \alpha_i + \varepsilon_{i,t} \quad (A4)$$

where α_i represents a basin-specific fixed intercept accounting for unobserved, time-invariant basin characteristics. The remaining variables and coefficient interpretations follow those defined in Sect. 3.4.

Table A1 Selection of interaction terms based on individual significance tests

	$VC \times North$	$WU \times North$ $IWU \times North$	$Mean P - ET \times North$	$Max. P - ET \times North$ $Min. P - ET \times North$
RE-P1-LF	*			
RE-P1-HF		**		
RE-P2-LF	***			
RE-P2-HF				
FE-P1-LF	*			
FE-P1-HF	.	*		
FE-P2-LF	***			
FE-P2-HF		.		
Selected	Yes	Yes	No	No

VC denotes vegetation cover, WU denotes total water use, IWU denotes irrigation water use, Mean P-ET, Max. P-ET and Min. P-ET denote the annual daily mean, maximum 14-day, and minimum 90-day available water, respectively. VC×North, WU×North, IWU×North, Mean P-ET×North, Max. P-ET×North and Min. P-ET×North represent interaction terms constructed by multiplying North with each explanatory variable. Each interaction term was tested separately by adding it individually to the original models (RE: random-effect model, FE: Fixed-effect model; P1 :1990-2005, P2: 2005-2020; LF: low flows, HF: high flows), and only those with significant effects were retained in the final model: ., *, **, and *** denote significance at $p < 0.1$, $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.

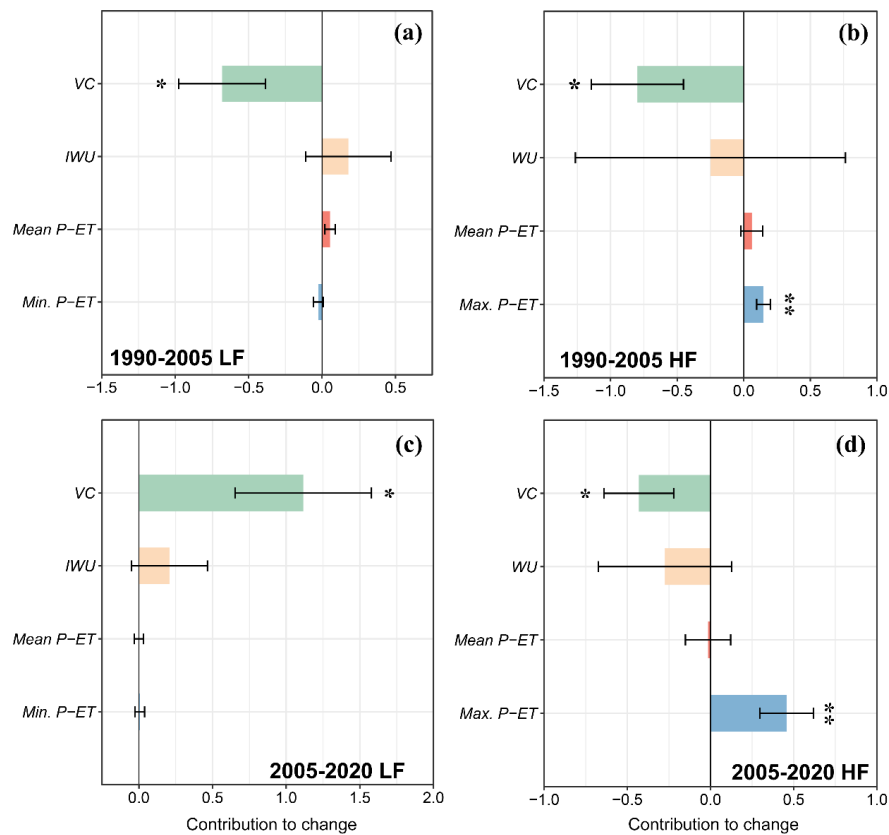


Fig. A1. Results of fixed-effect model. (a) Low flows in 1990-2005, (b) high flows in 1990-2005, (c) low flows in 2005-2020, (d) high flows in 2005-2020. LF denotes low flows; HF denotes high flows. VC denotes vegetation cover, WU denotes total water use, IWU denotes irrigation water use, Mean P-ET, Max. P-ET and Min. P-ET denote the annual daily mean, maximum 14-day, and minimum 90-day available water, respectively. The suffixes _N and _S indicate results for northern and southern basins, respectively. * and ** denote significance at the level of $p < 0.05$ and $p < 0.01$, respectively. Error bars represent the standard error.

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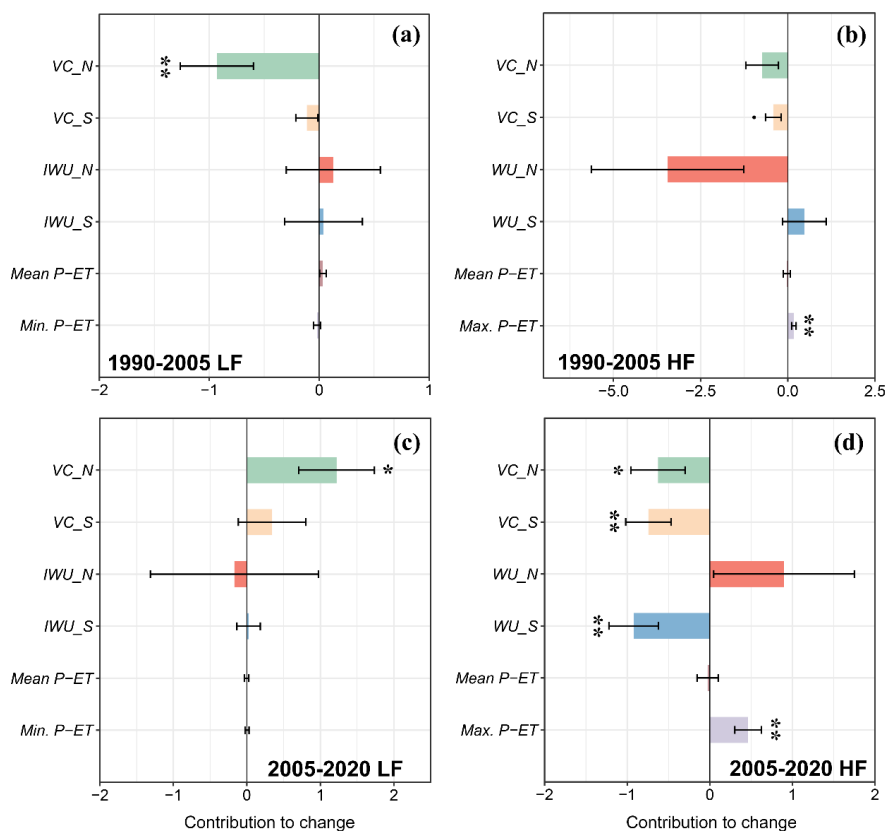


Fig. A2. Results of fixed-effect model for regional difference. (a) Low flows in 1990-2005, (b) high flows in 1990-2005, (c) low flows in 2005-2020, (d) high flows in 2005-2020. LF denotes low flows; HF denotes high flows. VC denotes vegetation cover, WU denotes total water use, IWU denotes irrigation water use, Mean P-ET, Max. P-ET and Min. P-ET denote the annual daily mean, maximum 14-day, and minimum 90-day available water, respectively. The suffixes _N and _S indicate results for northern and southern basins, respectively. ., *, and ** denote significance at levels of $p < 0.1$, $p < 0.05$, and $p < 0.01$, respectively. Error bars represent the standard error.



A2. Change-point sensitivity analysis

520 The Pettitt (1979) and Bai–Perron (1998) methods were applied separately to the annual low-flow and high-flow series of each basin over 1990–2020 as a sensitivity analysis of change-point timing. In the following equations, X_t denotes the annual flow index at time t , and n is the number of observations.

525 The Pettitt test assesses whether a time series exhibits a single change in its central tendency. For a potential change point after observation k , the rank-based statistic is calculated as:

$$U_k = 2 \sum_{t=1}^k r_t - k(n+1), \quad (A5)$$

where r_t is the rank of X_t within the complete series, and k is the index separating the two parts of the series. The test statistic is:

$$K = \max_{1 \leq k < n} |U_k|, \quad (A6)$$

The estimated change point corresponds to the value of k at which $|U_k|$ reaches its maximum.

530 We estimated a single breakpoint in each annual flow series using an intercept-only specification of the Bai–Perron least-squares framework (Bai and Perron, 1998). The model is expressed as:

$$X_t = \alpha + \delta \mathbb{I}(t > k) + \varepsilon_t, \quad (A7)$$

where α is the mean before the change; δ is the change in the mean; k is the index of the last observation before the change; $\mathbb{I}(t > k)$ is an indicator equal to 1 after the change and 0 otherwise; and ε_t is the error term.

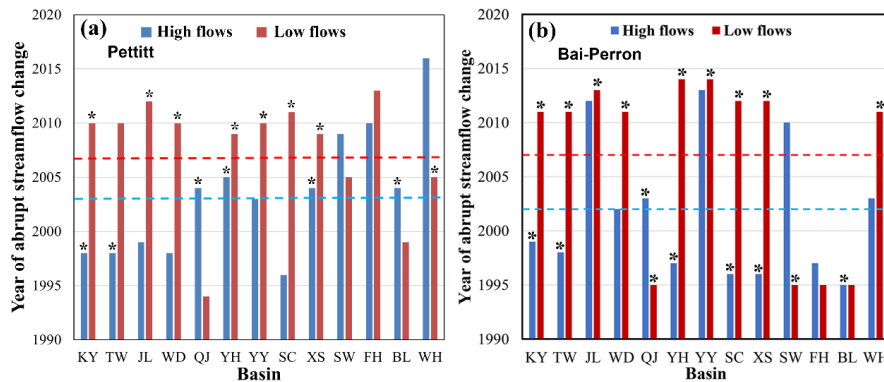
For each candidate breakpoint, the residual sum of squares is calculated as:

$$RSS(k) = \sum_{t=1}^k [X_t - \bar{X}_{pre}(k)]^2 + \sum_{t=k+1}^n [X_t - \bar{X}_{post}(k)]^2, \quad (A8)$$

535 where n is the number of observations, and $\bar{X}_{pre}(k)$ and $\bar{X}_{post}(k)$ are the sample means before and after the candidate breakpoint, respectively. The estimated breakpoint is:

$$\hat{k} = \arg \min_{k \in \mathcal{K}} RSS(k), \quad (A9)$$

where $\mathcal{K}$ is the set of admissible breakpoint indices. In the implementation used here, candidate indices ranged from 5 to $n - 5$, ensuring at least five annual observations in each segment.





540 Fig. A3. Sensitivity analysis for year of abrupt streamflow changes during 1990-2020. (a) The Pettitt test
 results of the basins. (b) The Bai-Perron test results of the basins. * denotes significance at $p < 0.05$. The red
 and blue dashed lines denote the average breakpoint of low flows and high flows, respectively, from which
 can be seen that the change point for low flows was identified around 2007, and for high flows, around 2002.
 Consequently, 2005 was detected as the change point year.

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Appendix B. Additional information on hydroclimatic and anthropogenic variables

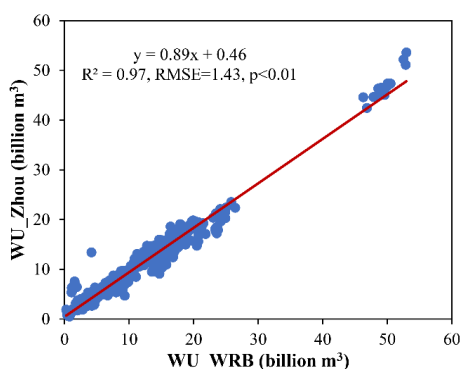


Fig. B1. Comparison between water use data from Water Resources Bulletins (WU_WRB) and from the reconstructed dataset (WU_Zhou)

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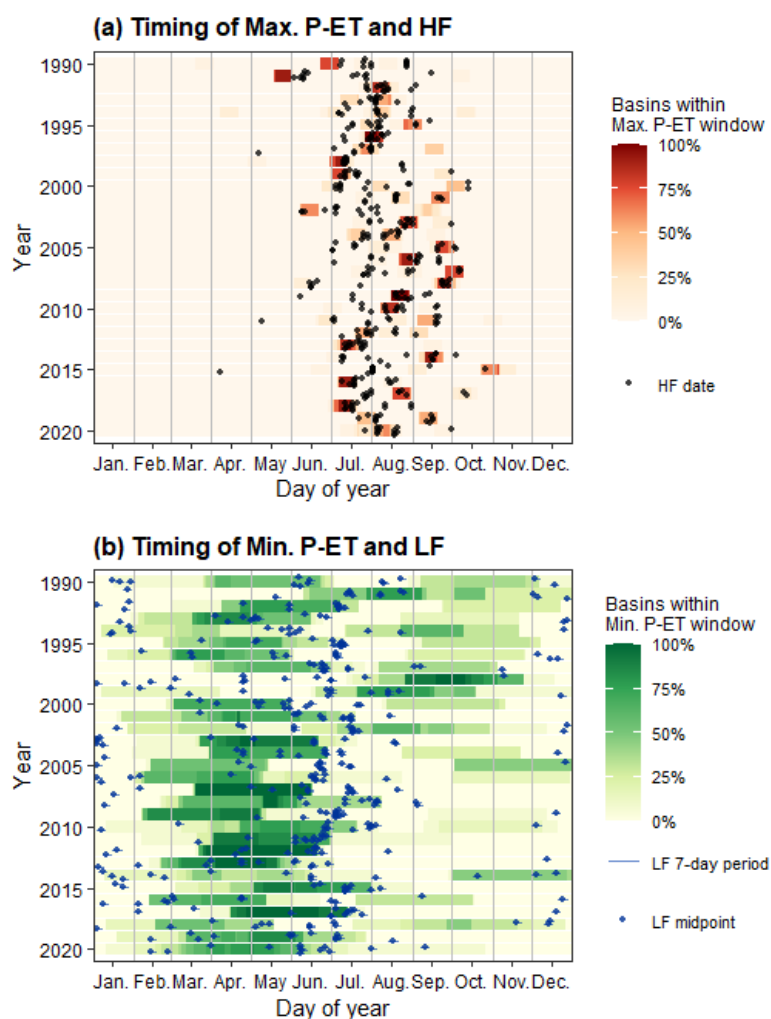


Fig. B2. Timing of annual P-ET extremes and flow extremes. (a) Timing of Max. P-ET and HF, (b) Timing of Min. P-ET and LF. Background: proportion of 13 basins within the Max. P-ET or Min. P-ET window. Points: basin-specific HF dates or LF midpoints. Segments: basin-specific LF 7-day periods. Max. P-ET denotes the 14-day maximum P-ET, Min. P-ET denotes the 90-day minimum P-ET, HF denotes high flows, LF denotes low flows.

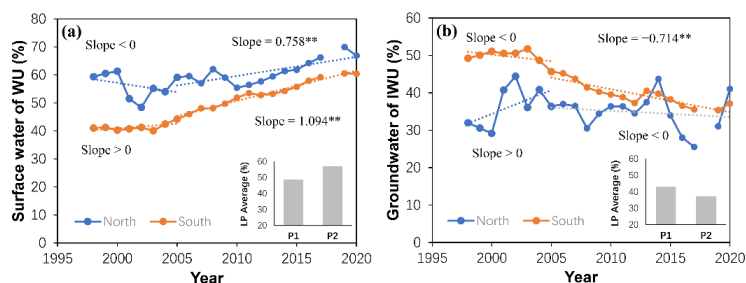


Fig. B3. Water source utilization structure of human water use. (a) Regional surface water of total water use (WU, %) and the averages across the Loess Plateau. (b) Regional groundwater of irrigation water use (IWU, %) and the averages across the Loess Plateau. Data were collected from the Water Resource Bulletins of the Yellow River Basin from 1998-2020 (1990-1997 and 2018 unavailable). *, **, and * denote significance at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively. P1 and P2 denotes 1998-2005 and 2005-2020, respectively.**

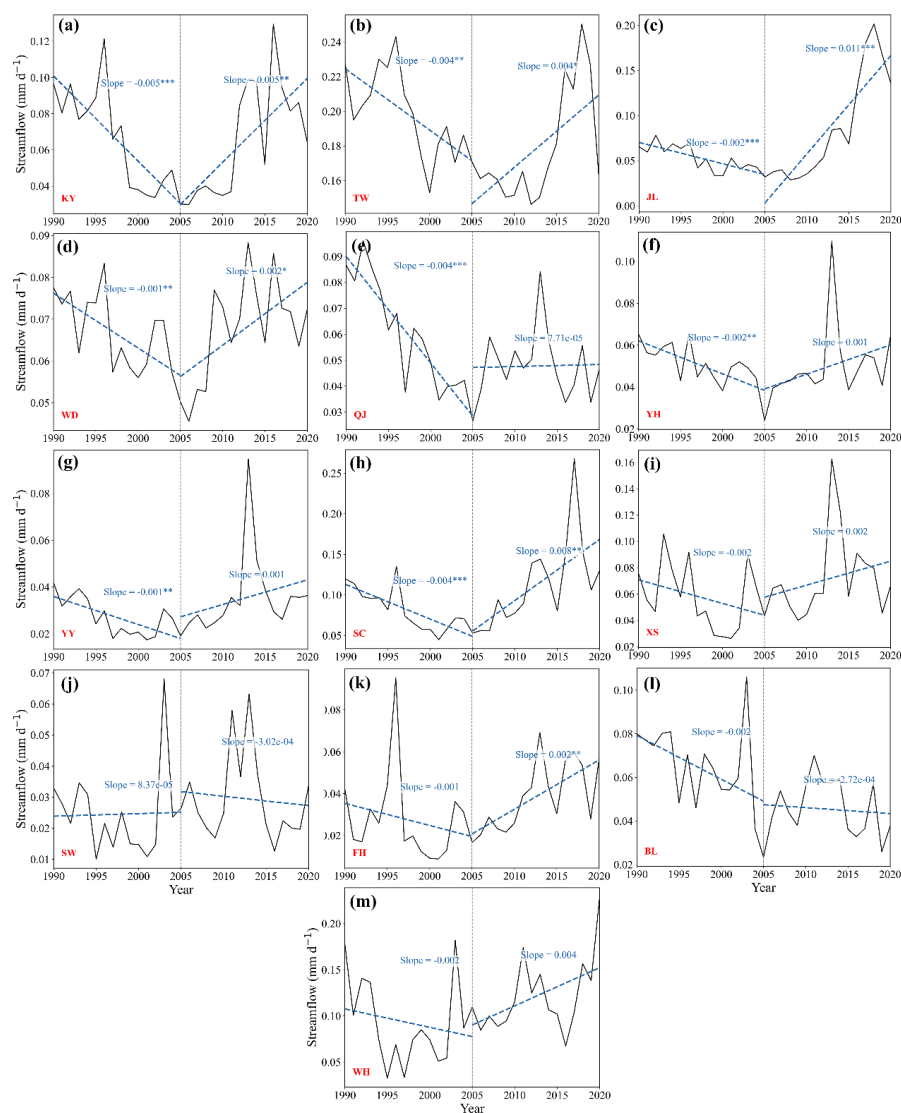


Fig. B4. Annual total streamflow of each basin from 1990-2020. *, **, and *** denote significance at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively.



Table B1 Median trends of streamflow and their drivers of the northern basins

	1990-2020	1990-2005	2005-2020
	(per decade)	(per decade)	(per decade)
LF	16.3% (p=0.29)	-110.2%**	100.7%***
HF	-18.4% (p=0.05)	-86.1%**	53.8% (p=0.14)
VC	8.7 p.p.***	7.7 p.p.***	7.3 p.p.***
WU	15.2%***	17.7%***	6.7%*
IWU	1.8% (p=0.40)	13.9%**	-13.4%**
Mean P-ET	-152.3% (p=0.28)	-941.1%**	3246.1%*
Max. P-ET	12.0% (p=0.13)	-19.5% (p=0.31)	35.6% (p=0.14)
Min. P-ET	-15.1%*	-57.0%*	20.7% (p=0.14)
P	8.8%*	-4.8% (p=0.51)	24.7%*
ET	12.1%***	26.0%*	-0.2% (p=0.96)

LF denotes low flows, HF denotes high flows, VC denotes vegetation cover, WU denotes total water use, IWU denotes irrigation water use, P denotes precipitation, ET denotes actual evapotranspiration, Mean P-ET, Max. P-ET and Min. P-ET denote the annual daily mean, maximum 14-day, and minimum 90-day available water, respectively. p.p. denotes percentage points. *, ** and *** denote significance at the level of $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively.

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Table B2 Median trends of streamflow and their drivers of the southern basins

	1990-2020	1990-2005	2005-2020
	(per decade)	(per decade)	(per decade)
LF	44.5%***	-90.2%*	49.9%**
HF	-30.6%***	-35.2%*	6.4% (p=0.82)
VC	-0.5 p.p. (p=0.52)	6.8 p.p.***	-6.3 p.p.***
WU	13.2%***	3.3% (p=0.34)	8.7%***
IWU	6.4%*	-8.4%*	-6.3%*
Mean P-ET	-9.4% (p=0.52)	-26.3% (p=0.63)	-35.8% (p=0.63)
Max. P-ET	14.0%*	10.9% (p=0.56)	2.0% (p=0.82)
Min. P-ET	-10.8% (p=0.07)	-9.0% (p=0.63)	-9.5% (p=0.40)
P	2.9% (p=0.43)	-3.2% (p=0.69)	-0.4% (p=0.89)
ET	6.1%***	2.0% (p=0.69)	6.7%*

580 LF denotes low flows, HF denotes high flows, VC denotes vegetation cover, WU denotes total water use, IWU
 denotes irrigation water use, P denotes precipitation, ET denotes actual evapotranspiration, Mean P-ET, Max. P-ET
 and Min. P-ET denote the annual daily mean, maximum 14-day, and minimum 90-day available water, respectively.
 p.p. denotes percentage points. *, ** and *** denote significance at the level of $p < 0.05$, $p < 0.01$ and $p < 0.001$,
 respectively.

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Data availability

The daily streamflow records used in this study were obtained from the Yellow River Basin Hydrological Yearbook (1990–2020) and are subject to access restrictions; therefore, the original records cannot be redistributed by the authors. Land-cover data were obtained from the China Annual Land Cover Dataset (Yang and Huang, 2021), evapotranspiration data from GLEAM v4.1a (Miralles et al., 2025), precipitation data from the National Meteorological Information Center (Zhao and Zhu, 2015), and water-use data from the National Long-term Water Use Dataset of China (Zhou et al., 2020) and provincial water resources bulletins. The processed basin-scale data of this study are available online in a Zenodo repository (Zeng and Wang, 2026).

Author contribution

Conceptualization: CW. Data curation: YZ. Formal analysis: YZ. Methodology: VBPC. Project administration: CW. Resources: GG, SW, YuL, MS. Funding acquisition: BF, YiL. Supervision: BF, YiL. Visualization: YZ. Writing–original draft: YZ. Writing–review and editing: JWK, VBPC, GG, CW.

Competing interests

The authors declare that they have no conflict of interest.

Financial support

This study was jointly funded by the State Key Project of Research and Development Plan (Grant No. 2023YFF1305105, 2022YFF1300405), the National Natural Science Foundation of China (Grant No. 42041007), and the Ordos City Major Science and Technology Project (Grant No. ZD20232324).



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