Journal of
Water & Climate Change

 Journal of Water and Climate Change Vol 16 No 9, 2829 doi: 10.2166/wcc.2025.063

Contribution of climate change and human activities to streamflow and lake water level variations at regional scales

Qianya Yang[a,b,*], Jianhui Wei[c], Lifeng Wu[b], Chuanguo Yang[a], Liang Li[b], Jiayi Luo[d], Chaofeng Chen[d], Huanghe Gu[a], Mingzhong Xiao[e], Qian Wang[f], Harald Kunstmann[c,g,h] and Zhongbo Yu[a]

[a] The National Key Laboratory of Water Disaster Prevention, Hohai University, Nanjing, China
[b] School of Soil and Water Conservation, Jiangxi University of Water Resources and Electric Power, Nanchang, China
[c] Institute of Meteorology and Climate Research (IMKIFU), Karlsruhe Institute of Technology, Campus Alpin, Garmisch-Partenkirchen, Germany
[d] YaoHu Honors College, Jiangxi University of Water Resources and Electric Power, Nanchang, China
[e] School of Civil Engineering, Sun Yat-Sen University, Zhuhai, China
[f] School of Engineering, College of Systems & Society, The Australian National University, Canberra, ACT, Australia
[g] Institute of Geography, University of Augsburg, Augsburg, Germany
[h] Centre for Climate Resilience, University of Augsburg, Augsburg, Germany
*Corresponding author. E-mail: yangqy@nit.edu.cn

QY, 0009-0007-9657-6993

ABSTRACT

Global warming has been intensifying the water cycle, thereby altering regional climate systems and hydrological processes. This is particularly the case for the Poyang Lake Basin (PLB) in monsoon-controlled southeast China, where climate changes and human activities are evident. Our study aims to quantify the contributions of climate change and human activities to the spatiotemporal variations of the relevant variables across meteorological and hydrological compartments on the basin scale. This study applies the moving *t*-test, Mann–Kendall test, and linear regression models to quantify the impacts of climate change and human activities on changes in streamflow and lake level from 1960 to 2019. Results show that precipitation, streamflow, and air temperature have increased, but Poyang Lake level has declined. Change points in streamflow trends are identified in 1991 and 2002 and in lake level in 2003. Contribution analysis indicates that climate change is the primary driver of increased streamflow. However, after 2002, the contribution of climate change declined, while that of human activities increased. The abrupt decline in lake level is mainly attributed to anthropogenic interventions. These findings identify the dominant factors of hydrological change and provide guidance for ensuring water security and sustainable water resource management in the basin.

Key words: climate change, human activities, lake water level, Poyang Lake Basin, streamflow

HIGHLIGHTS

- Precipitation, streamflow, and temperature increased; lake level declined over the Poyang Lake Basin (1960–2019).
- The 1991 streamflow change point was driven primarily by climate change.
- The 2003 change point in the Poyang Lake water level was mainly driven by human activities.
- Climate change increased streamflow; human activities reduced lake level.

1. INTRODUCTION

Global warming is becoming increasingly severe due to both natural and anthropogenic impacts (Magnan *et al.* 2021; Tollefson 2021). It has recently been reported that 2024 is the first year to exceed 1.5 °C above the pre-industrial level (IPCC 2021). Meanwhile, the global climate system has been undergoing unprecedented changes due to rising air-temperature. Consequently, this rapid acceleration of global warming leads to higher variability of the water cycle, particularly at regional scales (Taylor *et al.* 2013; Yang, D. *et al.* 2021; Wei *et al.* 2024; Rakkasagi & Goyal 2025). Such larger variability of regional water cycle eventually results in higher frequency of severe floods and/or droughts (Ali *et al.* 2019; Pokhrel *et al.* 2021; Zhang *et al.* 2022), thereby causing notable socioeconomic losses (Dottori *et al.* 2018; Rakkasagi *et al.* 2023).

Often, regional climate systems are modulated by changes in sea surface temperatures. For example, it is well acknowledged that El Niño–Southern Oscillation (ENSO) can further exacerbate precipitation variability (Rakkasagi *et al.* 2024), as El Niño events are associated with intense precipitation events or prolonged droughts in East Asia (Yang, Q. *et al.* 2021; Yang, X. *et al.* 2021; Xing *et al.* 2022). In addition to warmer atmosphere and ocean, human activities, such as irrigation practices, reservoir operations, and land-use changes, also play critical roles in altering the regional water cycle (Ahn *et al.* 2018; Cooley *et al.* 2021; Dong *et al.* 2022, 2023; Kim *et al.* 2023; Yang *et al.* 2024; Yang *et al.* 2025). Under these circumstances, a wide range of weather and climate extreme events, as well as natural hazards, have frequently occurred. Therefore, it is necessary to revisit the changing regional climate and hydrology by the timely accommodation of new datasets and evolving climate extremes (Xing *et al.* 2024). This facilitates improved understanding of particularly the relationship between meteorological and hydrological variables at regional scales.

Our regional climate and hydrology analysis focuses on the East-Asia-monsoon-controlled Poyang Lake Basin (PLB) in southeast China. The Poyang Lake is not only the largest freshwater lake in China but also serves as a natural reservoir and seasonal flood buffer. The dynamic water exchanges among its five tributaries and the Yangtze River are vital for maintaining the ecological balance and water availability downstream, especially during periods of extreme weather. For example, during flooding seasons, the lake moderates high water flow of rivers such as the Gan River, reduces flood peaks, and alleviates water disasters in the middle and lower reaches. During dry seasons, it supplements the Yangtze River, maintains water levels, ensures shipping, water intake, and ecological water use. Ecologically, the Poyang Lake supports one of the most diverse and productive wetland ecosystems in East Asia, providing critical habitat for migratory birds. The lake also sustains local fisheries and agriculture, making it essential for regional biodiversity, livelihoods, and water security. However, recent climate changes, hydrological alterations, and human interventions have disrupted its natural rhythms, raising concerns over its long-term hydroecological health and resilience. New challenges have been posed to optimal water resource management and sustainable socioeconomic development. Therefore, revisiting recent hydrometeorological situations in the PLB is essential for attributing these variations to climate change and human activities there.

Numerous studies have shaded light on changes in the regional climate systems of the PLB from different perspectives. For example, Ye *et al.* (2013) analyzed hydrometeorological changes in the basin from 1960 to 2007 and found that the impacts of climate change and human activities on terrestrial hydrological processes differ across five sub-basins. In the Fu River Basin, extensive agricultural water use led to reduced streamflow, particularly during drought years. Liu, G. *et al.* (2016) used the Mann–Kendall (MK) test to analyze streamflow changes in the Gan River Basin from 1955 to 2010, discovering that land-use changes there have no significant impacts on the annual streamflow variations, while human activities have significantly redistributed water resources in the streams from one season to another season. Using the conceptual lumped Australian Water Balance Model and multiple regression, Zhang *et al.* (2016a) assessed the impacts of climate change and human activities on the flow changes in five tributaries of the PLB. Their results indicate that, on an annual scale, the increase in streamflow from the 1970s to the 1990s is mainly attributed to climate change and human activities, while the decrease in streamflow is identified in the 2000s. On a finer temporal scale, the variations of streamflow during spring and summer are different from those during autumn and winter, due to the different roles of climate change and human activities (Zhang *et al.* 2016a). These findings generally highlight the complexity of the impacts of climate change and human activities on hydrological cycles across different spatial and temporal scales, particularly under changing environments. Therefore, it is necessary to revisit the respective contributions of these two factors in order to better understand their impacts on regional water resources in a timely manner.

To this end, our study focuses on: (1) analyzing the spatiotemporal variations of key hydrometeorological variables in the PLB to derive the regional climate information; and (2) quantitatively assessing the contributions of climate change and human activities to changes in the basin-wide streamflow and water levels of the Poyang Lake. It is expected that our study will provide timely knowledge and practical guidance for water security and sustainable water resource management in the PLB.

2. STUDY AREA AND DATA

2.1. Study area

The PLB (27°N–30°N, 115°E–118°E) is located in the central region of southeast China and covers an area of approximately 162,200 km^2. The climate of the basin is classified as subtropical humid monsoon climate. The average annual temperature of the basin ranges from 16.3 to 19.5 °C. The annual average precipitation across the basin ranges from approximately 1,300 to 1,900 mm, with a spatial distribution characterized by higher precipitation in the southeastern regions and lower amounts in the northwestern regions. Regarding the seasonality of the precipitation, around 42%–53% of the annual precipitation falls during the period from April to June. The basin exhibits high interannual variability in precipitation, with annual totals in wetter years reaching nearly twice those of drier years. Consequently, the region frequently experiences both droughts and floods.

The topography of the PLB is characterized by higher elevations in the south and lower elevations in the north (Figure 1). The region features a dense river network that converges into five major tributaries: Ganjiang River, Fuhe River, Xinjiang River, Raohe River, and Xiuhe River (Figure 1). The Poyang Lake receives inflows from the five tributaries and discharges into the Yangtze River. Streamflow variations in the basin are largely influenced by precipitation associated with the East Asian monsoon, resulting in a high-flow period in summer and a low-flow period in winter. With respect to human activities, irrigation withdrawals account for about 60% of total water withdrawals in the basin. In addition, the PLB contains more than 10,000 large, medium, and small reservoirs, which play a significant role in regulating streamflow and managing water resources.

2.2. Data

In this study, *in situ* meteorological and hydrological records are used for the analysis. The daily meteorological data are collected from 13 meteorological stations in the basin (Figure 1 and Table 1), and cover the period from 1960 to 2019. The data from the 13 stations is selected due to their high-quality control standards, particularly in terms of temporal continuity and geographical representativeness. Specifically, these 13 meteorological stations are managed by the National Meteorological Information Center of the China Meteorological Administration, and the corresponding quality control has been conducted by the operational department in accordance with the QX/T 118-2020 industry standard. In our analysis, we have further

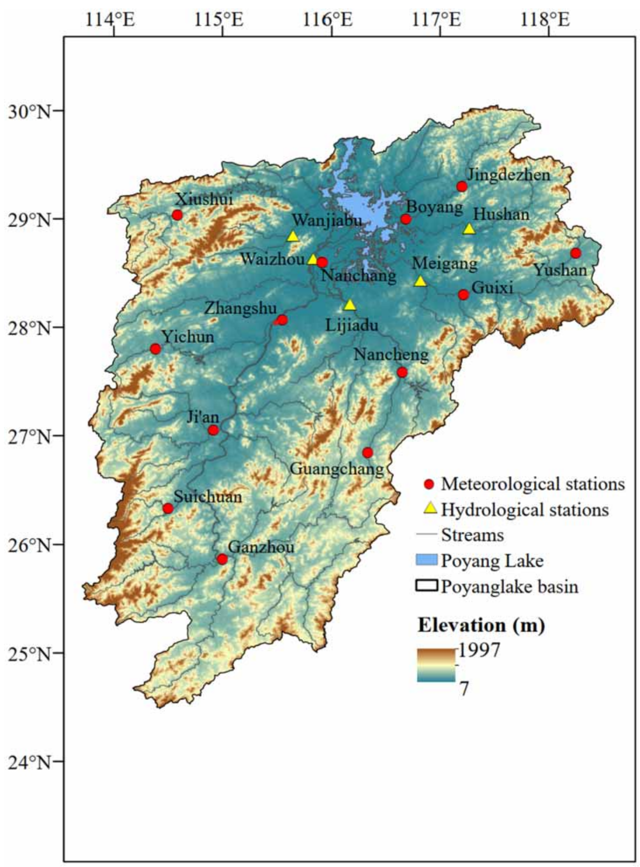

Figure 1 | Locations of the meteorological and hydrological stations in the PLB.

Table 1 | Information about the meteorological stations in the PLB

Station	Longitude	Latitude	Sub-basin
Xiushui	124°34′	29°1′	Xiushui basin
Yichun	114°13′	27°28′	Ganjiang basin
Ji'an	114°34′	27°4′	Ganjiang basin
Suichuan	114°30′	27°4′	Ganjiang basin
Ganzhou	114°34′	25°30′	Ganjiang basin
Nanchang	115°32′	28°21′	Ganjiang basin
Zhangshu	115°19′	28°2′	Ganjiang basin
Poyang	116°40′	29°	Poyang Lake
Jiangdezhen	117°7′	29°48′	Raohe basin
Guixi	117°7′	28°10′	Xinjiang basin
Yushan	118°9′	28°24′	Xinjiang basin
Nancheng	116°39′	27°34′	Fuhe basin
Guangchang	116°12′	29°30′	Fuhe basin

applied quality control measures to remove missing values, such as interpolating short gaps, to enhance the reliability of our results.

Daily streamflow data from 1960 to 2019 are obtained from five major hydrological stations in the basin, namely, the Waizhou, Meigang, Hushan, Wanjiabu, and Lijiadu stations. These five hydrological stations are located at the outlet of these five sub-basins, namely, the Ganjiang River, Xinjiang River, Raohe River, Xiuhe River, and Fuhe River basins. These stations effectively capture the terrestrial hydrological characteristics of their corresponding regions. The spatial distribution of the meteorological and hydrological stations is illustrated in Figure 1 and detailed in Table 2.

3. METHODS

3.1. Trend analysis and change point analysis

3.1.1. Trend rate

In this study, the trend of an investigated hydrometeorological variable is quantitatively estimated by fitting a linear equation with least squares:

$$\hat{z}_n(t) = p_0 + p_1 t \quad (1)$$

where p_1 is the increasing or decreasing rate for the investigated variables. Here, we calculate the change rate for every ten years; $p_1 > 0$ indicates an increasing trend, and $p_1 < 0$ indicates a decreasing trend. This method has assumptions of normal distribution and no autocorrelation.

Table 2 | Information about the hydrological stations at the five major tributaries in the PLB

Station	Longitude	Latitude	Sub-basin
Waizhou	115°49′	28°37′	Ganjiang basin
Meigang	116°49′	28°25′	Xinjiang basin
Hushan	117°16′	28°55′	Raohe basin
Lijiadu	116°10′	28°13′	Fuhe basin
Wanjiabu	115°39′	28°51′	Xiushui basin

3.1.2. Sen's slope

Sen's slope (Sen 1968) is additionally applied here to detect and quantify monotonic trends (Dong *et al.* 2021; Dorjsuren *et al.* 2024). It is a robust non-parametric statistical method to estimate monotonic trends and is particularly useful when data are subject to outliers or non-normal distributions. The slope S_{ij} is calculated as follows:

$$S_{ij} = \frac{y_j - y_i}{x_j - x_i}, \ i < j \tag{2}$$

where x_i is years, and y_i is the hydrometeorological data on a yearly scale. The Sen's slope estimator β is the median of all derived slopes S_{ij}:

$$\beta = \text{median } (S_{ij}) \tag{3}$$

where $\beta > 0$ indicates an increasing annual trend, and $\beta < 0$ indicates a decreasing annual trend. The magnitude of β means the average change rate per year, and is particularly useful for the identification of long-term trends.

3.1.3. Moving *t*-test

To identify change points in the long-term trends, the moving *t*-test with appropriate sliding window sizes is used here. We perform the *t*-test at a certain significance level (e.g., $p > 0.05$) to analyze two subsamples to test if their means are significantly different. For our analysis, the window size ranges from 2 to 30, and the formula for the *t*-test is as follows:

$$t = \frac{\overline{y_1} - \overline{y_2}}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}} \tag{4}$$

where $\overline{y_1}$ and $\overline{y_2}$ are the means of the two subsamples of a given time-series x_n, s_1 and s_2 are their standard deviations, and n_1 and n_2 are the number of points in each subsample.

3.1.4. MK trend test

The MK test is used in this study to examine the trend in time series and evaluate the importance of monotonic trends in time series. It is a non-parametric statistical method initially proposed by Mann and Kendall (Mann 1945; Kendall 1975). This method has the advantages of (1) less demand in computational resources, (2) no assumption of a specific distribution for the data, and (3) accounting for missing values and outliers in the data.

Assume a time series $z_1, z_2, \ldots, z_i, \ldots, z_n$, consisting of n independent observations:

$$S = \sum_{i=2}^{n} \sum_{j=1}^{i-1} \text{sign}(z_i - z_j) \tag{5}$$

$$\text{sign}(z_i - z_j) = \begin{cases} 1, & z_i > z_j \\ 0, & z_i = z_j \\ -1, & z_i < z_j \end{cases} \tag{6}$$

$$Z = \begin{cases} \dfrac{(S-1)}{\sqrt{n(n-1)(2n+5)/18}}, & S > 0 \\ 0, & S = 0 \\ \dfrac{(S+1)}{\sqrt{n(n-1)(2n+5)/18}}, & S < 0 \end{cases} \tag{7}$$

where the value of Z indicates the direction and strength of the trend. A positive (negative) value of Z means an increasing (decreasing) trend. For a two-tailed test with a significance level of 0.05, the critical Z-value is 1.96. This value defines the boundaries of the rejection for the significance test of the increasing trend.

3.2. Model set-up and attribution analysis

3.2.1. Model set-up

Linear regression analysis is performed to assess the relationship between precipitation and its hydrological responses (streamflow and lake water level). This method helps quantify the strength and characteristics of these relationships, helping to identify trends and make predictions about future hydrological responses. The regression equations used are:

$$Q_{\mathrm{m}} = \alpha \times P_{\mathrm{obs}} + C_1 \quad (8)$$

$$H_{\mathrm{m}} = \beta \times P_{\mathrm{obs}} + C_2 \quad (9)$$

where Q_{m} and H_{m} represent simulated streamflow and simulated lake water level, respectively. P_{obs} is observed precipitation, α and β are streamflow and lake water level regression coefficients, respectively, and C_1 and C_2 are constants.

3.2.2. Attribution analysis

In this study, we assume that the change in streamflow is mainly caused by natural climate change and human activities. Therefore, we attribute the changes in streamflow (ΔQ_{t}) to two aspects, including the change of climate change (ΔQ_{c}) and human activities (ΔQ_{h}), which are calculated as follows:

$$\Delta Q_{\mathrm{c}} = Q_{\mathrm{am}} - Q_{\mathrm{b}} \quad (10)$$

$$\Delta Q_{\mathrm{h}} = Q_{\mathrm{a}} - Q_{\mathrm{am}} \quad (11)$$

$$\Delta Q_{\mathrm{t}} = \Delta Q_{\mathrm{c}} + \Delta Q_{\mathrm{h}} = Q_{\mathrm{a}} - Q_{\mathrm{b}} \quad (12)$$

where Q_{am} is the modeled streamflow after the change point, and Q_{b} and Q_{a} are the observed streamflow before and after the change point, respectively.

The contributions of climate change (U_{c}) and human activities (U_{h}) were calculated as follows:

$$U_{\mathrm{c}} = \frac{|\Delta Q_{\mathrm{c}}|}{|\Delta Q_{\mathrm{h}}| + |\Delta Q_{\mathrm{c}}|} \quad (13)$$

$$U_{\mathrm{h}} = \frac{|\Delta Q_{\mathrm{h}}|}{|\Delta Q_{\mathrm{h}}| + |\Delta Q_{\mathrm{c}}|} \quad (14)$$

As for Poyang Lake water level, the change of climate change (ΔH_{c}), human activities (ΔH_{h}), and the total change (ΔH_{t}) in lake water level were calculated as follows:

$$\Delta H_{\mathrm{c}} = H_{\mathrm{am}} - H_{\mathrm{b}} \quad (15)$$

$$\Delta H_{h} = H_{\mathrm{a}} - H_{\mathrm{am}} \quad (16)$$

$$\Delta H_{\mathrm{t}} = H_{\mathrm{a}} - H_{\mathrm{b}} \quad (17)$$

where H_{am} is the modeled lake water level after the change point, and H_{b} and H_{a} are the observed lake water level before and after the change point, respectively.

The contributions to lake level from climate (P_{c}) and human activities (P_{h}) are calculated as follows:

$$P_{\mathrm{c}} = \frac{|\Delta H_{\mathrm{c}}|}{|\Delta Q_{\mathrm{h}}| + |\Delta H_{\mathrm{c}}|} \quad (18)$$

$$P_{\mathrm{h}} = \frac{|\Delta H_{\mathrm{h}}|}{|\Delta Q_{\mathrm{h}}| + |\Delta H_{\mathrm{c}}|} \quad (19)$$

3.2.3. Monte Carlo-based uncertainty quantification

To quantify uncertainty, we conduct a Monte Carlo simulation by generating 10,000 sets of regression coefficients based on the parameters of the baseline model. For each set, we re-calculate contributions, and the median values along with the 95% confidence intervals are derived from the resulting distribution, providing robust estimates of uncertainty.

4. RESULTS

4.1. Temporal characteristics and spatial distribution of precipitation and temperature

4.1.1. Temporal characteristics

The annual precipitation in the PLB from 1960 to 2019 has a slightly wetting trend with considerable fluctuations. The highest annual precipitation occurs in 2012 (around 2,170 mm/year), while the lowest is recorded in 1963 (1,130 mm/year) (Figure 2). The trend slope for annual precipitation is 3.43 mm/year, but statistically insignificant ($Z < 1.96$) (Table 3). The five-year moving averages of precipitation smooth out the short-term fluctuations and highlight the long-term upward trends in observed streamflow. The temporal variation of the five-year moving average shows increasing precipitation trends in the 1970s, the 1990s, and the 2010s. For example, a steady upward trend is found in the 1970s. In the 1990s, the upward trend was more pronounced, and the steeper slope and smaller fluctuations indicate a faster wetting rate in precipitation. In the 2010s, the wetting trend continues despite minor fluctuations.

As for the trend in 2 m air temperature (Figure 3), a fluctuating warming trend (blue dashed line) is found for the basin over the past 60 years. The highest recorded temperature (19 °C) occurred in 1998, and the lowest temperature (17 °C) occurred in 1976 (black line). The temperature has increased significantly at a rate of 0.02 °C per year over the past 60 years ($Z > 1.96$) (Table 3), and the overall average temperature has increased about 1.1 °C (Figure 3). Using the five-year moving average (red line) to smooth short-term fluctuations, a downward (cooling) temperature trend is observed in the basin from the 1960s to

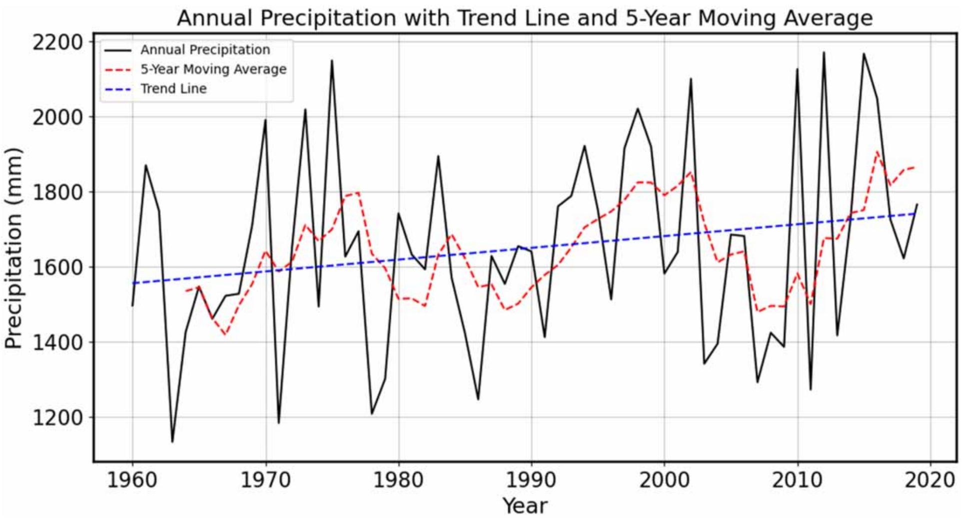

Figure 2 | Annual basin-averaged precipitation trends in the PLB; annual values (black), five-year moving average (red dashed), and linear trend (blue dashed).

Table 3 | Sen's slope (β), linear trend (p), Z-statistic of MK of precipitation, and temperature

Variable	β	p	Z
Precipitation	3.43 mm/year	31.39 mm/10a	1.59
Temperature	0.021 °C/year	0.199 °C/10a	5.70***

Note: *** denotes statistical significance at the $p < 0.001$ level.

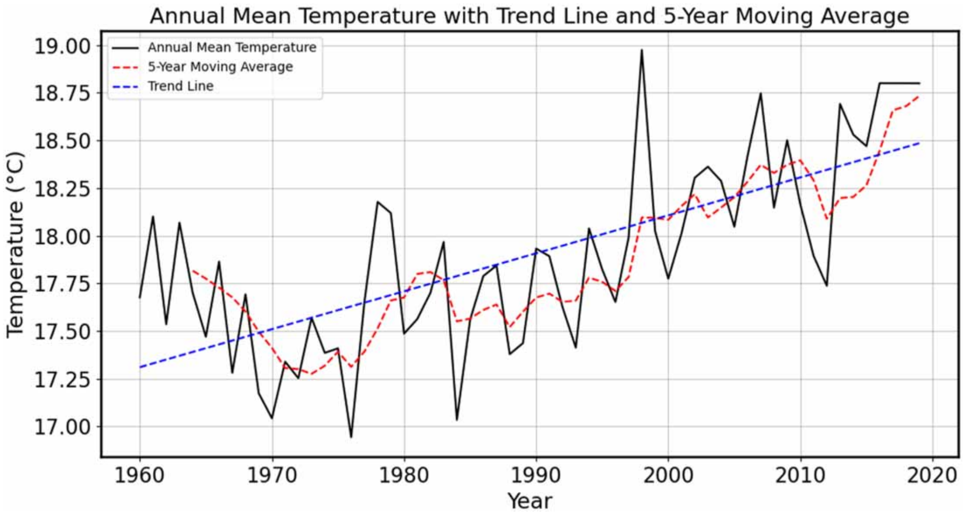

Figure 3 | Annual basin-averaged temperature trends in the PLB (1960–2019); annual values (black), five-year moving average (red dashed), and linear trend (blue dashed).

the early 1970s. A slight increase in the temperature is found from the mid-1970s to the early 1990s. However, from the mid-1990s to the early 2010s, the increase rate became more pronounced (Figure 3).

4.1.2. Spatial distribution

The spatial distribution of the multi-year average temperature in the PLB from 1960 to 2019 is depicted in Figure 4. The temperature values across the basin range from approximately 15.8 to 18.4 °C. Notably, the average temperature in the northern regions is lower than that in the southern regions. The lowest temperatures were observed particularly in the northwest part of the basin. Figure 4 illustrates the temperature trends observed at the selected meteorological stations. The *Z*-values of each

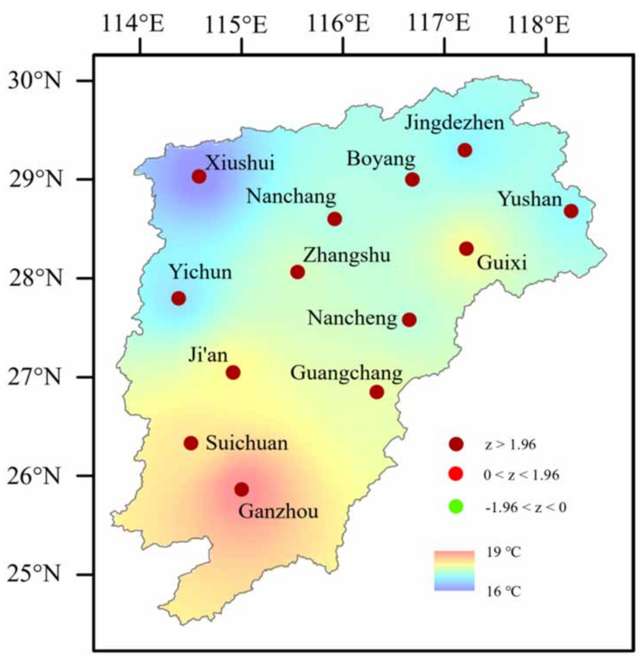

Figure 4 | Spatial distribution of multi-year average temperature and MK trend significance (*Z*-values) at meteorological stations in the PLB (1960–2019).

station are greater than 1.96, indicating that the annual average temperature at all stations in the basin from 1960 to 2019 shows a statistically significant warming trend.

The spatial distribution of multi-year average annual precipitation in the PLB from 1960 to 2019 is shown in Figure 5. Precipitation ranges from approximately 1,443 to 1,941mm/year. The northern regions of the basin generally receive more precipitation than the southern regions. The highest precipitation (1941.24 mm/year) is found in the northeastern part of the basin. Over the past 60 years, the annual precipitation at all selected stations in the basin shows an increasing trend, but only the trend at Ji'an station passes the 0.05 significance test (Figure 5).

4.2. Variability of streamflow and lake water level

Figure 6 depicts the annual streamflow variations from 1960 to 2019 at five hydrological stations in the PLB: (a) Lijiadu, (b) Hushan, (c) Meigang, (d) Waizhou, and (e) Wanjiabu. Overall, the streamflow at each station exhibits significant interannual variability, with a slight increasing trend observed over the study period. Nevertheless, the change trends in all sub-basins fail to pass the 0.05 significance test (Table 4). A pronounced increase in streamflow is observed at all stations during the 1960s to the mid-1970s, the late 1980s to the mid-2000s, and the late 2000s to the mid-2010s. In contrast, the remaining period is characterized by a notable decrease. Peak streamflow is particularly high in the late 1970s, the early 2000s, and the mid-2010s. The streamflow varies significantly among the stations. For example, the streamflow at Waizhou ranges from 1,000 to 3,500 m^3/s, whereas at Wanjiabu, it ranges from 50 to 225 m^3/s, indicating that the streamflow at the Wanjiabu station is much lower than that at the Waizhou station. In terms of long-term trends, the streamflow at the Lijiadu station remains relatively stable, whereas the Meigang, Hushan, Waizhou, and Wanjiabu stations show an increasing trend over the 60-year period.

The annual water level variations in the Poyang Lake from 1960 to 2019 are shown in Figure 7. Significant interannual fluctuations are observed, with notable peaks in the late 1970s, the mid-1980s, and the late 1990s. Despite short-term variability, the five-year moving average indicates a general increase in water levels until the mid-1980s, followed by a decline and stabilization in recent years. From 1960 to the mid-1980s, the water level exhibits an overall upward trend, followed by a decrease and a relatively stable trend before 2000, and a clear downward trend during the 2000s. The overall trend line indicates a slight decrease in water levels over the six-decade period. However, the trend is not statistically significant ($Z = -1.26$).

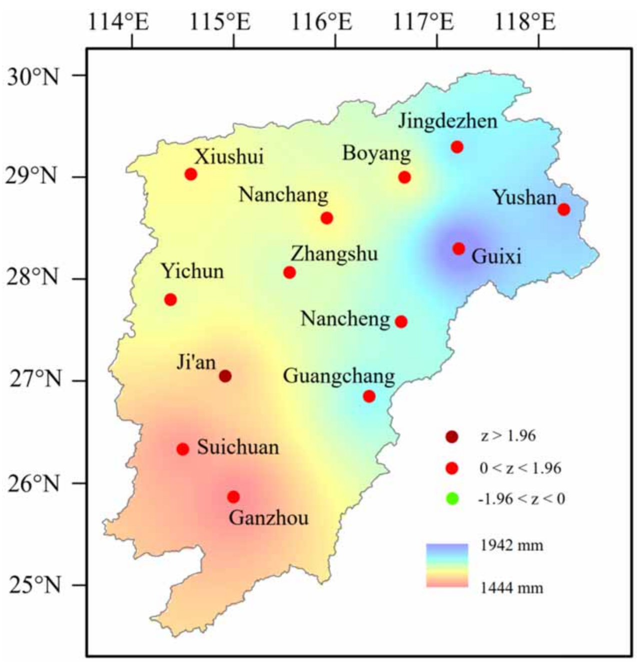

Figure 5 | Spatial distribution of multi-year average annual precipitation and MK trend significance (*Z*-values) at meteorological stations in the PLB (1960–2019).

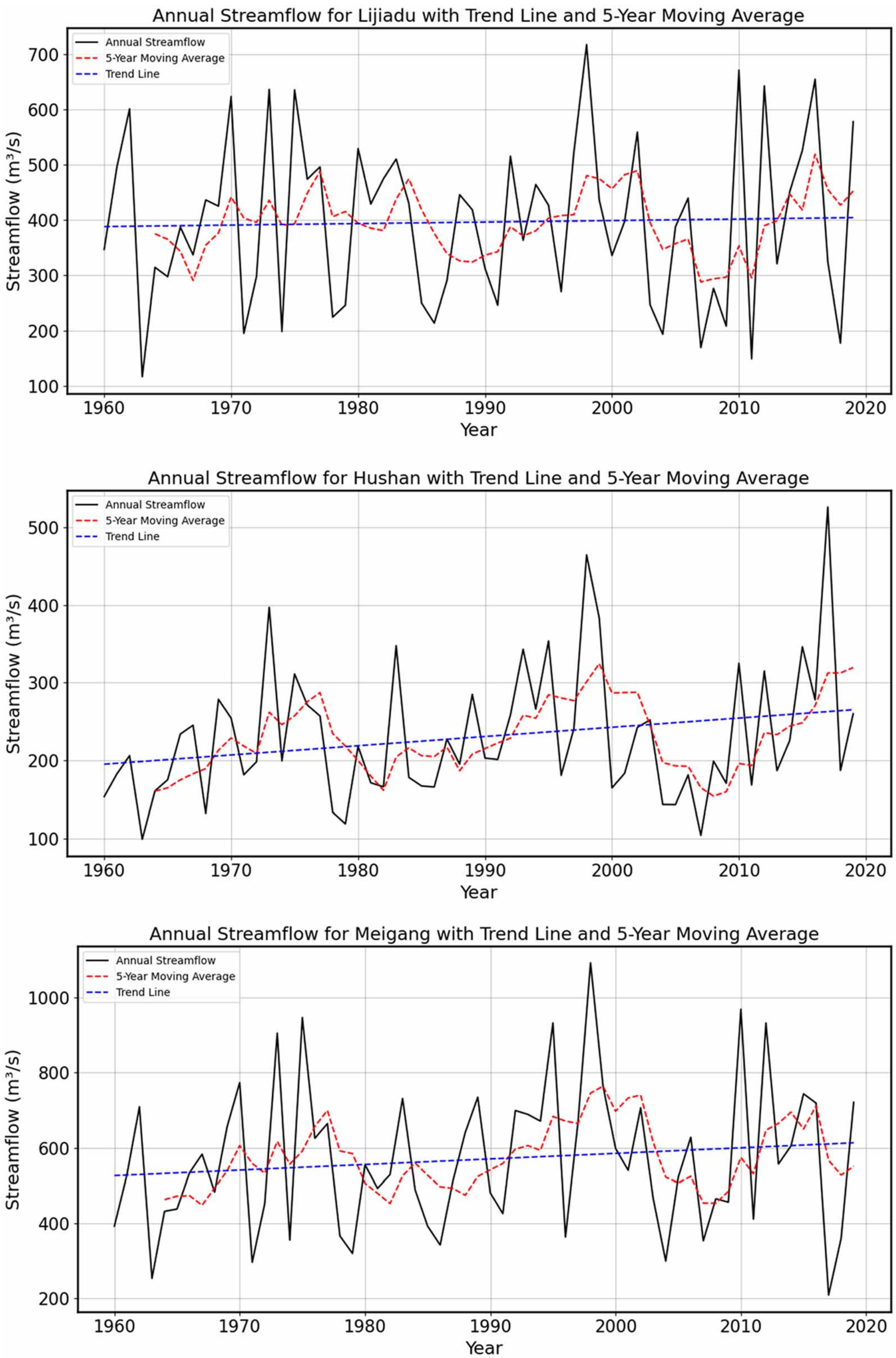

Figure 6 | Annual streamflow trends at five sub-basin stations (Lijiadu, Hushan, Meigang, Waizhou, and Wanjiabu) in the PLB (1960–2019); annual values (black solid), five-year moving average (red dashed), and linear trend (blue dashed). (*continued.*).

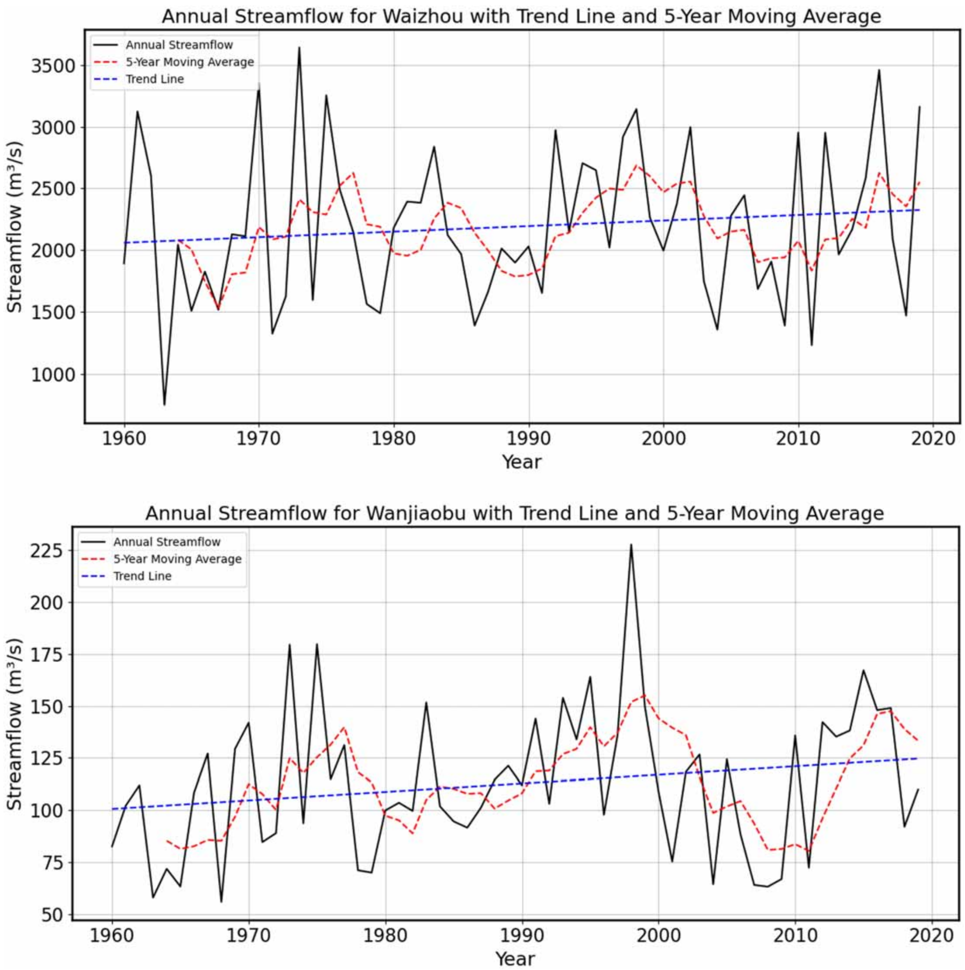

Figure 6 | Continued.

Table 4 | Annual streamflow MK statistical values and linear trends in sub-basins of the PLB

Station **Basin**	**Meigang** **Xinjiang basin**	**Waizhou** **Ganjiang basin**	**Hushan** **Raohe basin**	**Wanjiabu** **Xiushui basin**	**Lijiadu** **Fuhe basin**
MK *Z*-value	1.41	0.71	1.15	1.70	−0.02
Tendency rate (m^3 s/10a)	47.98	10.48	39.40	36.24	0.79

4.3. Change points in hydroclimate at regional scales

Here, we detect abrupt change years by applying the moving *t*-test (Section 3.1.3). Figure 8 illustrates the frequency distribution of these abrupt years in precipitation, streamflow, and lake water level, derived from different window sizes in the moving *t*-test.

For precipitation (Figure 8(a)), the most frequently identified abrupt years occur between 1989 and 1992, with 1991 showing the highest detection frequency across multiple moving window sizes. This indicates that 1991 is a robust change point in precipitation regimes. A notable cluster of abrupt years is also observed around 2002. These clusters

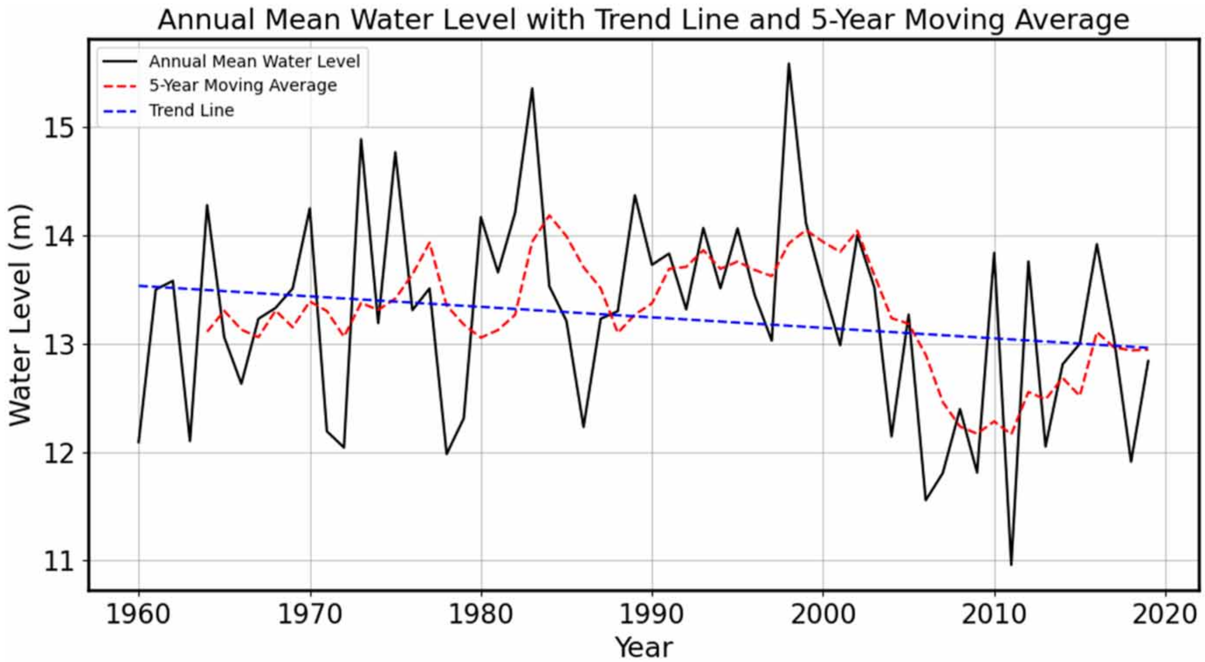

Figure 7 | Annual mean Poyang Lake water level trends (1960–2019); annual values (black solid), five-year moving average (red dashed), and linear trend (blue dashed).

suggest periods of instability in the precipitation variations, with especially frequent regime shifts in the early 1990s and the early 2000s. For streamflow (Figure 8(b)), change points are predominantly identified in the late 1980s, the early 1990s, and the early 2000s. The year 1991 stands out with the highest frequency of detected breakpoints, followed by 2002. These findings are consistent with the precipitation results, suggesting a potential linkage in hydrological shifts. For the Poyang Lake water level (Figure 8(c)), change years are densely concentrated between 1998 and 2005, with 2003 showing the highest frequency. This pattern indicates a strong phase of hydrological regime shift during this period. Although fewer abrupt years are identified before the late 1990s, some changes also occur in the late 1980s and the early 2000s.

Figure 8 collectively illustrates that abrupt changes in precipitation, streamflow, and lake water level are temporally clustered rather than uniformly distributed. Two critical periods emerge – around 1991 and 2002–2003 – during which all three hydrological variables exhibit heightened change point frequencies. This temporal coincidence suggests potential common drivers, such as large-scale climatic shifts or intensified human activities, which warrant further investigation.

4.4. Contribution of climate and human activities to streamflow and lake water level changes

To further quantitatively assess the contribution of climate change and human activities to streamflow and lake water level changes, the attribution analysis (Section 3.2.2) is performed. We divide the entire study period into sub-periods obtained from the change point analysis (Section 4.3). Table 5 presents a quantitative assessment of the relative contributions of climate change and human activities to the changes in streamflow and lake water levels in the PLB, with associated 95% confidence intervals. For streamflow (Q), during the period 1991–2001, climate change is the dominant driver, contributing 91.3% (70.0%–99.6%), while human activities only account for 8.7% (0.4%–30.0%). However, this pattern changes in the later period. From 2002 to 2019, the contribution of climate change declined to 66.3% (60.6%–84.2%), while the influence of human activities increased to 33.7% (15.8%–39.4%). This reflects the growing impact of anthropogenic interventions, such as land-use change and water engineering projects, on streamflow regulation in the basin.

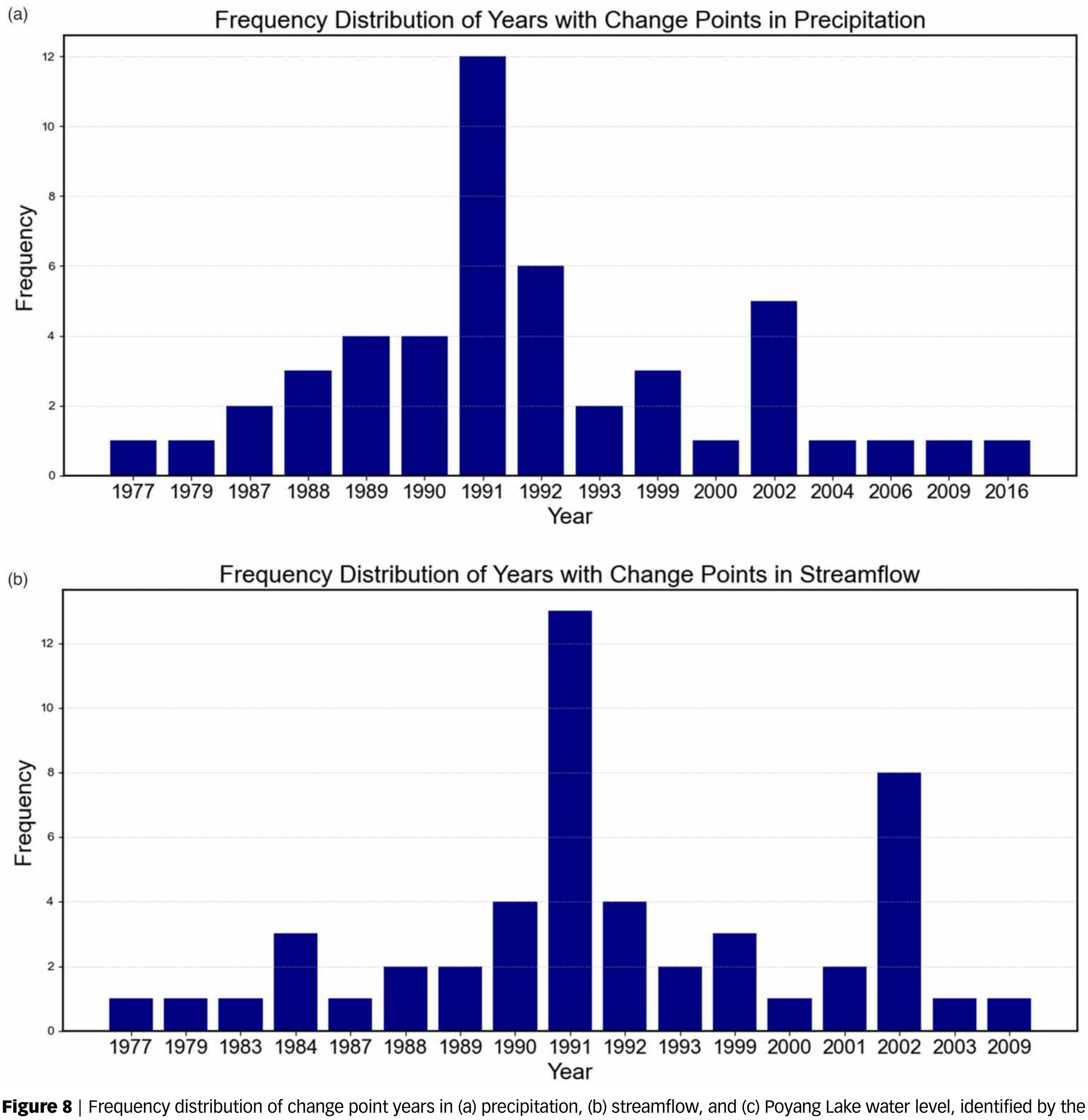

Figure 8 | Frequency distribution of change point years in (a) precipitation, (b) streamflow, and (c) Poyang Lake water level, identified by the moving *t*-test using different window sizes. (*continued.*).

In terms of lake water level (H), the attribution results are more striking (Table 5). During 2003–2019, climate change accounted for only 7.2% (0.4%–18.4%) of the observed decline, whereas human activities contributed a dominant 92.8% (81.6%–99.6%). These findings suggest that despite fluctuations in precipitation, lake level changes are now overwhelmingly governed by anthropogenic factors, such as upstream reservoir operations, lake outlet erosion, and regional water withdrawals. The difference in contribution between Q and H also implies that while streamflow changes may still be influenced by natural variability, the Poyang Lake water level is far more significantly governed by direct human regulation.

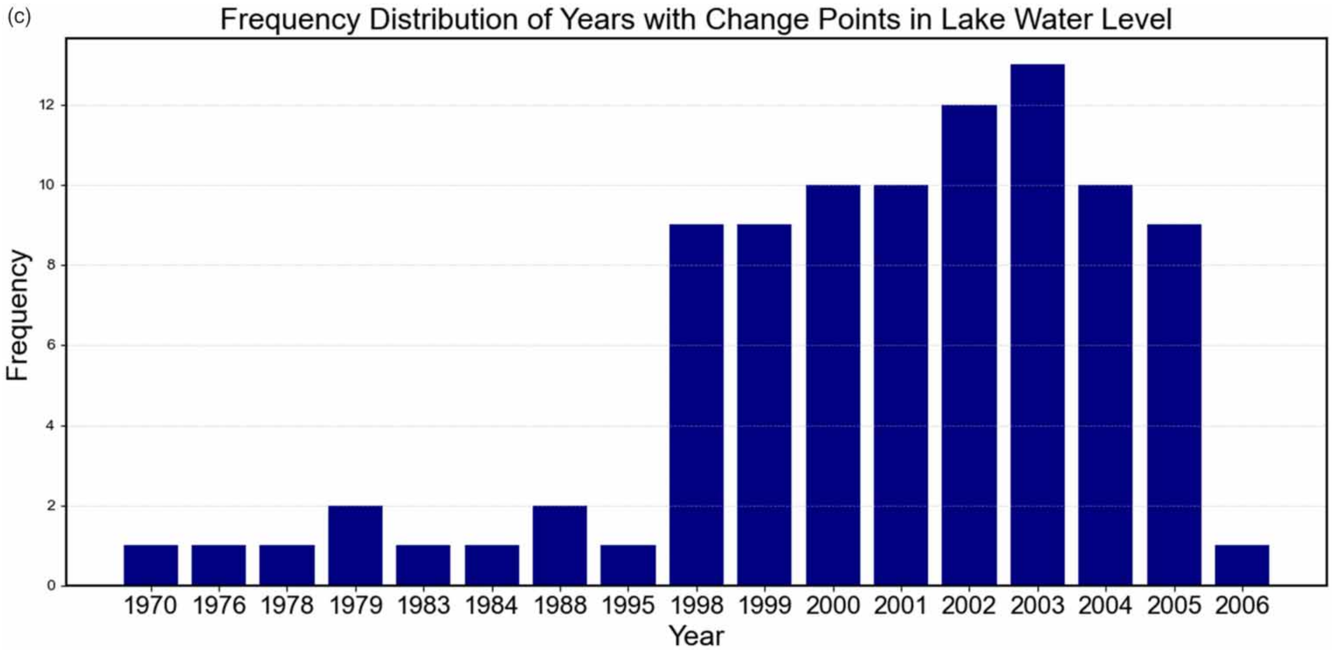

Figure 8 | Continued.

Table 5 | Contribution of climate change and human activities to the streamflow and water level changes with 95% confidence intervals in the PLB

Variable	**Before abrupt**	**After abrupt**	U_c **(%)**	U_h **(%)**
Q	1960–1990	1991–2001	91.3 (70, 99.6)	8.7 (0.4, 30)
		2002–2019	66.3 (60.6, 84.2)	33.7 (15.8, 39.4)
Variable	**Before abrupt**	**After abrupt**	P_c **(%)**	P_h **(%)**
H	1960–2002	2003–2019	7.2 (0.4, 18.4)	92.8 (81.6, 99.6)

5. DISCUSSION

This study reveals that between 1960 and 2019, precipitation, streamflow, and temperature have generally increased, whereas the Poyang Lake water level has declined over the study period. These findings are consistent with relevant studies (Zhang *et al.* 2016b; Guo *et al.* 2020; Lei *et al.* 2021). Change point detection identifies breakpoints in precipitation and streamflow over the past 60 years, with notable transitions occurring in 1991 and 2002, respectively. This result aligns with the findings of Wang *et al.* (2020), which indicate a decreasing trend in precipitation before 1991, an increasing trend after 1991, and another decline starting in 2002.

The change points in precipitation and streamflow in the PLB around 1991 may be attributed to a major change in the global weather shift triggered by the 1991 ENSO event. ENSO events typically modulate China's precipitation patterns by affecting the intensity of the East Asian monsoon (Piao *et al.* 2020), with notable impacts in the 1990s. Yang, D. *et al.* (2021) reported that ENSO-related anomalies around 1991 significantly enhanced the frequency of heavy precipitation events in the PLB.

The declining trend in precipitation and streamflow after 2002 may be attributed to the effects of global warming on regional scales. Studies suggest that rising temperatures have intensified the frequency and intensity of drought events within the basin (Zhao *et al.* 2010). Additionally, our results from Section 4.4 on the contributions of climate change and human activities to streamflow changes (Table 5) indicate that human activities have significantly influenced streamflow variations since 2002. Therefore, in addition to global climate impacts, human activities such as reservoir operations, agricultural irrigation, land-use changes, sand mining, and urban expansion have disrupted hydrological processes. These alterations have led to an uneven distribution of water resources within the basin, further affecting the temporal and spatial distribution of precipitation and streamflow (Gu *et al.* 2016; Liu, J. *et al.* 2016; Zhang *et al.* 2016a; Lei *et al.* 2021; Wei *et al.* 2021).

The impoundment of water by the Three Gorges Dam starting from 2003 has significantly altered the hydrological cycle of the Yangtze River and its tributaries. Its operation has reduced water inflow to the Poyang Lake, thereby exacerbating drought conditions in the basin (Zhang *et al.* 2012; Zhang *et al.* 2015). This explains the significant decline in lake water level since 2003 (Figure 7). Additionally, intensive sand mining has further contributed to falling water levels (Li *et al.* 2021).

This study employs a linear regression model to attribute changes in streamflow and lake water levels to climate and human drivers. Although this approach simplifies the complex hydrological and human interactions in the PLB, it provides valuable first-order estimates. It is worth noting that this approach does not explicitly account for reservoir operations, irrigation water withdrawals, or land-use changes, which may affect water levels. We acknowledge that the attribution of streamflow changes to human activities in our study remains conceptual, as the results are inferred from deviations between observed streamflow and modeled natural streamflow driven solely by climatic factors. This conceptual method has been commonly employed in numerous hydrological attribution studies when long-term data for human interventions, such as reservoir operations, irrigation practices, land-use changes, and population density, are either unavailable, inconsistent, or insufficiently detailed for comprehensive statistical analysis (Wang *et al.* 2020; Lei *et al.* 2021). Moreover, the analysis period is restricted to 1960–2019 to ensure data quality and consistency, as post-2019 datasets for key variables (e.g., precipitation) are incomplete.

6. SUMMARY AND CONCLUSIONS

This study provides a comprehensive analysis of the hydrometeorological trends in the PLB from 1960 to 2019, focusing on the impacts of climate change and human activities on precipitation, temperature, streamflow, and lake water level. The findings reveal that while precipitation, streamflow, and temperature have generally increased, the Poyang Lake water level has declined. The abrupt change and contribution analyses reveal that significant changes occurred in precipitation, river flow, and the Poyang Lake water level during the early 1990s and the early 2000s, respectively.

The contribution analysis reveals a shift in the relative influence of climate change and human activities on hydrological changes in the PLB since the early 2000s. Streamflow changes during 1991–2001 are primarily driven by climate change, contributing 91.3% (70%–99.6%), whereas human activities contribute to a lesser extent, accounting for 8.7% (0.4%–30%). However, after 2002, the contribution of human activities rises to 33.7% (15.8%–39.4%), indicating an increasing influence on streamflow regulation. In terms of lake water levels, the situation is even more pronounced: between 2003 and 2019, human activities account for 92.8% (81.6%–99.6%) of the decline, whereas the contribution of climate change is limited to 7.2% (0.4%–18.4%). These results suggest that since the early 21st century, human interventions have become an increasingly important factor influencing hydrological changes in the PLB. While climate change remains the primary driver of streamflow variation, the influence of human activities has increased. In contrast, lake water level changes are now largely governed by human activities.

Future research should focus on precisely quantifying the impact of specific human activities on the hydrological cycle using advanced physical models. This will provide deeper insights into the causative factors and support the development of targeted interventions to mitigate the adverse effects of both climate change and human activities on the basin's water resources. A better understanding of these complex interactions will enhance water resource management and help protect this vital ecological and hydrological region.

ACKNOWLEDGEMENTS

This work was financially supported by the Belt and Road Special Foundation of the National Key Laboratory of Water Disaster Prevention (2022490111) and Jiangxi Provincial Natural Science Foundation (20224BAB214080), and the National Natural Science Foundation of China (U2240217, 42271020). J.W. was supported financially by the German Research Foundation (DFG) through funding of the AccHydro project (KU 2090/11-1).

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

Ahn, S., Abudu, S., Sheng, Z. & Mirchi, A. (2018) Hydrologic impacts of drought-adaptive agricultural water management in a semi-arid river basin: case of Rincon Valley, New Mexico, *Agricultural Water Management*, **209**, 206–218. https://doi.org/10.1016/j.agwat.2018.07.040.

Ali, H., Modi, P. & Mishra, V. (2019) Increased flood risk in Indian sub-continent under the warming climate, *Weather and Climate Extremes*, **25**, 100212. https://doi.org/10.1016/j.wace.2019.100212.

Cooley, S. W., Ryan, J. C. & Smith, L. C. (2021) Human alteration of global surface water storage variability, *Nature*, **591**, 78–81. https://doi.org/10.1038/s41586-021-03262-3.

Dong, Y., Zhao, Y., Zhai, J., Zhao, J., Han, J., Wang, Q., He, G. & Chang, H. (2021) Changes in reference evapotranspiration over the non-monsoon region of China during 1961–2017: relationships with atmospheric circulation and attributions, *International Journal of Climatology*, **41** (S1), E734–E751. https://doi.org/10.1002/joc.6722.

Dong, N., Wei, J., Yang, M., Yan, D., Yang, C., Gao, H., Arnault, J., Laux, P., Zhang, X., Liu, Y., Niu, J., Wang, H., Wang, H., Kunstmann, H. & Yu, Z. (2022) Model estimates of China's terrestrial water storage variation due to reservoir operation, *Water Resources Research*, **58** (6), e2021WR031787. https://doi.org/10.1029/2021WR031787.

Dong, N., Yang, M., Wei, J., Arnault, J., Laux, P., Xu, S., Wang, H., Yu, Z. & Kunstmann, H. (2023) Toward improved parameterizations of reservoir operation in ungauged basins: a synergistic framework coupling satellite remote sensing, hydrologic modeling, and conceptual operation schemes, *Water Resources Research*, **59** (3), e2022WR033026. https://doi.org/10.1029/2022WR033026.

Dorjsuren, B., Zemtsov, V. A., Batsaikhan, N., Demberel, O., Yan, D., Hongfei, Z., Yadamjav, O., Chonokhuu, S., Enkhbold, A., Ganzorig, B., Bavuu, E., Namsrai, O., Xiang, L., Yingjie, Y. & Siyu, W. (2024) Trend analysis of hydro-climatic variables in the Great Lakes Depression region of Mongolia, *Journal of Water and Climate Change*, **15** (3), 940–957. https://doi.org/10.2166/wcc.2024.379.

Dottori, F., Szewczyk, W., Ciscar, J.-C., Zhao, F., Alfieri, L., Hirabayashi, Y., Bianchi, A., Mongelli, I., Frieler, K., Betts, R. A. & Feyen, L. (2018) Increased human and economic losses from river flooding with anthropogenic warming, *Nature Climate Change*, **8** (9), 781–786. https://doi.org/10.1038/s41558-018-0257-z.

Gu, C., Mu, X., Zhao, G., Gao, P., Sun, W. & Yu, Q. (2016) Changes in stream flow and their relationships with climatic variations and anthropogenic activities in the Poyang Lake Basin, China, *Water*, **8** (12), 564. https://doi.org/10.3390/w8120564.

Guo, R., Zhu, Y. & Liu, Y. (2020) A comparison study of precipitation in the Poyang and the Dongting Lake Basins from 1960–2015, *Scientific Reports*, **10** (1), 3381. https://doi.org/10.1038/s41598-020-60243-8.

IPCC (2021) *Climate Change 2021: The Physical Science Basis. Working Group I Contribution to the IPCC Sixth Assessment Report*. Cambridge, UK and New York, NY, USA: Cambridge University Press.

Kendall, M. G. (1975) *Rank Correlation Methods*, 4th edn. London, UK: Griffin.

Kim, S., Hwang, S., Song, J.-H., Lee, H. & Kang, M.-S. (2023) Impact of irrigation reservoirs on budget of the watershed-scale water cycle under climate change, *Agricultural Water Management*, **283**, 108327. https://doi.org/10.1016/j.agwat.2023.108327.

Lei, X., Gao, L., Wei, J., Ma, M., Xu, L., Fan, H., Li, X., Gao, J., Dang, H., Chen, X. & Fang, W. (2021) Contributions of climate change and human activities to runoff variations in the Poyang Lake Basin of China, *Physics and Chemistry of the Earth*, **123**, 103019. https://doi.org/10.1016/j.pce.2021.103019.

Li, Q., Lai, G. & Devlin, A. T. (2021) A review on the driving forces of water decline and its impacts on the environment in Poyang Lake, China, *Journal of Water and Climate Change*, **12** (5), 1370–1391. https://doi.org/10.2166/wcc.2020.216.

Liu, G., Qi, S., Zhu, J., Xiong, M. & Wang, D. (2016) Quantitative estimation of runoff changes in Ganjiang River, Lake Poyang Basin under climate change and anthropogenic impacts, *Journal of Lake Sciences*, **28** (3), 682–690 (in Chinese).

Liu, J., Zhang, Q., Deng, X., Ci, H. & Chen, X. (2016) Quantitative analysis of the influences of climate change and human activities on hydrological processes in Poyang Basin, *Hupo Kexue/Journal of Lake Sciences*, **28** (2), 432–443 (in Chinese). https://doi.org/10.18307/2016.0224.

Magnan, A. K., Pörtner, H.-O., Duvat, V. K. E., Garschagen, M., Guinder, V. A., Zommers, Z., Hoegh-Guldberg, O. & Gattuso, J.-P. (2021) Estimating the global risk of anthropogenic climate change, *Nature Climate Change*, **11** (10), 879–885. https://doi.org/10.1038/s41558-021-01156-w.

Mann, H. B. (1945) Nonparametric tests against trend, *Econometrica*, **13** (3), 245–259. https://doi.org/10.2307/1907187.

Piao, J., Chen, W., Chen, S., Gong, H., Chen, X. & Liu, B. (2020) The intensified impact of El Niño on late-summer precipitation over East Asia since the early 1990s, *Climate Dynamics*, **54** (11–12), 4793–4809. https://doi.org/10.1007/s00382-020-05254-x.

Pokhrel, Y., Felfelani, F., Satoh, Y., Boulange, J., Burek, P., Gädeke, A., Gerten, D., Gosling, S. N., Grillakis, M., Gudmundsson, L., Hanasaki, N., Kim, H., Koutroulis, A., Liu, J., Papadimitriou, L., Schewe, J., Müller Schmied, H., Stacke, T., Telteu, C.-E., Thiery, W., Veldkamp, T., Zhao, F. & Wada, Y. (2021) Global terrestrial water storage and drought severity under climate change, *Nature Climate Change*, **11** (3), 226–233. https://doi.org/10.1038/s41558-020-00972-w.

Rakkasagi, S. & Goyal, M. K. (2025) Are rapid onset drying events escalating forest fires across India's ecoregions? *Environmental Research Letters*, **20** (6), 064004. https://doi.org/10.1088/1748-9326/add1f5.

Rakkasagi, S., Poonia, V. & Goyal, M. K. (2023) Flash drought as a new climate threat: drought indices, insights from a study in India and implications for future research, *Journal of Water and Climate Change*, **14** (9), 3368–3384. https://doi.org/10.2166/wcc.2023.347.

Rakkasagi, S., Goyal, M. K. & Jha, S. (2024) Evaluating the future risk of coastal Ramsar wetlands in India to extreme rainfalls using fuzzy logic, *Journal of Hydrology*, **632**, 130869. https://doi.org/10.1016/j.jhydrol.2024.130869.

Sen, P. K. (1968) Estimates of the regression coefficient based on Kendall's tau, *Journal of the American Statistical Association*, **63** (324), 1379–1389. https://doi.org/10.1080/01621459.1968.10480934.

Taylor, R. G., Todd, M. C., Kongola, L., Maurice, L., Nahozya, E., Sanga, H. & Macdonald, A. M. (2013) Evidence of the dependence of groundwater resources on extreme rainfall in East Africa, *Nature Climate Change*, **3** (4), 374–378. https://doi.org/10.1038/nclimate1731.

Tollefson, J. (2021) IPCC climate report: Earth is warmer than it's been in 125,000 years, *Nature*, **596** (7871), 171–172. https://doi.org/10.1038/d41586-021-02179-1.

Wang, R., Peng, W., Liu, X., Jiang, C., Wu, W. & Chen, X. (2020) Characteristics of runoff variations and attribution analysis in the Poyang Lake Basin over the past 55 years, *Sustainability*, **12** (3), 944. https://doi.org/10.3390/su12030944.

Wei, J., Dong, N., Fersch, B., Arnault, J., Wagner, S., Laux, P., Zhang, Z., Yang, Q., Yang, C., Shang, S., Gao, L., Yu, Z. & Kunstmann, H. (2021) Role of reservoir regulation and groundwater feedback in a simulated ground–soil–vegetation continuum: a long-term regional scale analysis, *Hydrological Processes*, **35** (8), e14341. https://doi.org/10.1002/hyp.14341.

Wei, J., Arnault, J., Rummler, T., Fersch, B., Zhang, Z., Olschewski, P., Laux, P., Dong, N., Yang, Q., Xing, Z., Li, X., Yang, C., Zhang, X., Ma, M., Gao, L., Xu, L., Yu, Z. & Kunstmann, H. (2024) Acceleration of the hydrological cycle under global warming for the Poyang Lake Basin in southeast China: an age-weighted regional water tagging approach, *Journal of Hydrometeorology*, **25** (11), 1627–1647. https://doi.org/10.1175/JHM-D-23-0227.1.

Xing, Z., Yu, Z., Wei, J., Zhang, X., Ma, M., Yi, P., Ju, Q., Wang, J., Laux, P. & Kunstmann, H. (2022) Lagged influence of ENSO regimes on droughts over the Poyang Lake Basin, China, *Atmospheric Research*, **275**, 106218. https://doi.org/10.1016/j.atmosres.2022.106218.

Xing, Z., Wei, J., Li, Y., Zhang, X., Ma, M., Yi, P., Ju, Q., Laux, P. & Kunstmann, H. (2024) Disentangling the spatially combined and temporally lagged influences of climate oscillations on seasonal droughts in the East Asian monsoon influenced Poyang Lake Basin, *Atmospheric Research*, **310**, 107603. https://doi.org/10.1016/J.ATMOSRES.2024.107603.

Yang, D., Yang, Y. & Xia, J. (2021) Hydrological cycle and water resources in a changing world: a review, *Geography and Sustainability*, **2** (2), 115–122. https://doi.org/10.1016/j.geosus.2021.05.003.

Yang, Q., Yu, Z., Wei, J., Yang, C., Gu, H., Xiao, M., Shang, S., Dong, N., Gao, L., Arnault, J., Laux, P. & Kunstmann, H. (2021) Performance of the WRF model in simulating intense precipitation events over the Hanjiang River Basin, China – a multi-physics ensemble approach, *Atmospheric Research*, **248**, 105206. https://doi.org/10.1016/j.atmosres.2020.105206.

Yang, X., Wu, J., Liu, J. & Ye, X. (2021) Changes of extreme precipitation and possible influence of ENSO events in a humid basin in China, *Atmosphere*, **12** (11), 1522. https://doi.org/10.3390/atmos12111522.

Yang, X., Wu, F., Yuan, S., Ren, L., Sheffield, J., Fang, X., Jiang, S. & Liu, Y. (2024) Quantifying the impact of human activities on hydrological drought and drought propagation in China using the PCR-GLOBWB v2.0 model, *Water Resources Research*, **60** (1), e2023WR035443. https://doi.org/10.1029/2023WR035443.

Yang, Q., Wei, J., Yang, C., Gu, H., Ma, J., Dong, N., Arnault, J., Laux, P., Fersch, B., Shang, S., Yu, Z. & Kunstmann, H. (2025) A crop-specific dynamic irrigation scheme in a regional land surface-hydrologic modeling framework for improving human water-use estimation and irrigation impact assessment, *Journal of Hydrology*, **659**, 133322. https://doi.org/10.1016/j.jhydrol.2025.133322.

Ye, X., Zhang, Q., Liu, J., Li, X. & Xu, C. Y. (2013) Distinguishing the relative impacts of climate change and human activities on variation of streamflow in the Poyang Lake catchment, China, *Journal of Hydrology*, **494**, 83–95. https://doi.org/10.1016/j.jhydrol.2013.04.036.

Zhang, Q., Li, L., Wang, Y. G., Werner, A. D., Xin, P., Jiang, T. & Barry, D. A. (2012) Has the Three-Gorges Dam made the Poyang Lake wetlands wetter and drier? *Geophysical Research Letters*, **39** (20), L20402. https://doi.org/10.1029/2012GL053431.

Zhang, Z., Chen, X., Xu, C. Y., Hong, Y., Hardy, J. & Sun, Z. (2015) Examining the influence of river–lake interaction on the drought and water resources in the Poyang Lake Basin, *Journal of Hydrology*, **522**, 510–521. https://doi.org/10.1016/j.jhydrol.2015.01.008.

Zhang, Q., Liu, J., Singh, V. P., Gu, X. & Chen, X. (2016a) Evaluation of impacts of climate change and human activities on streamflow in the Poyang Lake Basin, China, *Hydrological Processes*, **30** (14), 2562–2576. https://doi.org/10.1002/hyp.10814.

Zhang, Q., Xiao, M., Singh, V. P. & Wang, Y. (2016b) Spatiotemporal variations of temperature and precipitation extremes in the Poyang Lake basin, China, *Theoretical and Applied Climatology*, **124** (3–4), 855–864. https://doi.org/10.1007/s00704-015-1470-6.

Zhang, S., Zhou, L., Zhang, L., Yang, Y., Wei, Z., Zhou, S., Yang, D., Yang, X., Wu, X., Zhang, Y., Li, X. & Dai, Y. (2022) Reconciling disagreement on global river flood changes in a warming climate, *Nature Climate Change*, **12** (12), 1160–1167. https://doi.org/10.1038/s41558-022-01539-7.

Zhao, G., Hörmann, G., Fohrer, N., Zhang, Z. & Zhai, J. (2010) Streamflow trends and climate variability impacts in Poyang Lake Basin, China, *Water Resources Management*, **24** (4), 689–706. https://doi.org/10.1007/s11269-009-9465-7.

First received 11 March 2025; accepted in revised form 8 August 2025. Available online 9 September 2025