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Spatiotemporal Evolution of River Runoff Across Major Water Regions in China: Observed Trends and Regional Disparities (1960–2024)

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ABSTRACT

River runoff is a key component of surface water resources and is essential for water resource management because of its dynamic variability and long-term changes. However, research focusing on the most recent decade, a period characterized by rapid environmental change, remains limited. Moreover, traditional trend assessment methods based on absolute runoff values often limit meaningful comparisons across basins with contrasting hydrological conditions. To address this limitation, we proposed a unit-normalized runoff index (URI), a standardized metric designed to facilitate robust cross-basin comparisons of runoff variability. Using observational data from 24 hydrological stations across ten major water regions in China from 1960 to 2024, we identified pronounced spatial and temporal heterogeneity in runoff dynamics. The results showed significant declines in annual runoff in the Haihe, Yellow, Huaihe, and Pearl River basins, whereas increases were observed in the northwestern endorheic river basins, the Liaohe River basin, and most Qinghai–Xizang Plateau rivers, particularly in snowmelt-dominated systems. In contrast, annual runoff remained generally stable in the middle and lower reaches of the Yangtze and Songhua River basins. Seasonal analysis revealed widespread increases in winter runoff across many basins, whereas extensive decreases were observed in summer and autumn. Stations in western China showed consistent increases throughout all seasons, most notably at Changmabu and Zhimenda. Conversely, stations in the Haihe and Yellow River basins exhibited year-round declines. Although long-term records (1960–2024) continue to reflect the classic "south-abundant/north-deficient" pattern, recent trends (2010–2024) indicate a notable shift, including increased runoff in the northwest and northeast, continued water scarcity in North China, and emerging declines in southern regions. Collectively, these changes indicate a transition from a pattern of "western increase, northern depletion, and southern stability" to one characterized by "continued western gain, partial northern recovery, and emerging southern drying." These findings improve understanding of long-term hydrological variability in China and provide a scientific basis for developing regionally differentiated and adaptive water resource management strategies under changing climatic and anthropogenic conditions.

1. Introduction

The global climate has experienced substantial warming since 1900, with mean temperatures from 2010 to 2020 reaching 1.09 °C above pre-industrial levels, accompanied by major alterations in precipitation patterns [1]. Concurrently, rapid economic development in China, including the construction of 94 608 reservoirs, irrigation of 817 430 km^2 of farmland, and implementation of conservation measures across 1.627 million km^2 by 2024 [2], has led to pronounced hydrological modifications. Together, these climatic and anthropogenic pressures have substantially reshaped watershed-scale water distribution, intensifying supply–demand imbalances and creating critical water management challenges. Given that river runoff constitutes a core component of surface water resources and that water security underpins socioeconomic

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stability, an accurate understanding of evolving runoff patterns under these changing environmental conditions is essential for sustainable development.

River runoff dynamics and surface water resource evolution are critical to watershed management and hydrological research. Global river systems exhibit pronounced regional heterogeneity in streamflow under the dual pressures of climate change and anthropogenic activities [3]. In high-latitude and tropical regions, increases in both mean and extreme flows have been widely documented [4,5]. For example, winter flow in the Yenisei River has increased by 20% owing to permafrost degradation and enhanced precipitation [6]. In contrast, many subtropical and mid- to low-latitude basins, including the Missouri River [7], Niger River [8], and Murray–Darling [9], have experienced persistent declines associated with aridification and intensified human water use. Large transcontinental river systems, including the Columbia and Danube rivers, are also undergoing hydrological regime shifts characterized by earlier snowmelt and altered seasonal flow patterns, with increased winter–spring flows and reduced summer discharge [10,11]. Similarly, rivers in High-Mountain Asia show sustained runoff increases driven by glacial melt and rising precipitation [12,13]. These changes are primarily attributed to climatic drivers, particularly shifts in precipitation regimes and rising temperatures, thereby altering evaporation and snowmelt processes. Simultaneously, human activities, including land-use changes and water withdrawals, further modulate runoff variability across multiple timescales [14,15]. Although climate variability remains the dominant driver of long-term runoff changes in most basins, anthropogenic influences are becoming increasingly important in heavily managed catchments [16]. Understanding these drivers and their relative contributions is essential for developing adaptive water resource strategies in a changing world.

In China, recent studies have increasingly documented divergent runoff patterns across major river systems, reflecting the complex interplay between climate change and human activities. Northern river basins have experienced the most substantial changes; for instance, natural runoff in the Haihe River Basin has decreased by more than 40% owing to the combined effects of climatic aridification and intensive water withdrawals [17,18], with some river reaches transitioning to intermittent flow regimes [19]. Similarly, the Yellow River has exhibited major discharge declines, particularly in its middle and lower reaches [20,21]. In contrast, the southern river systems have remained relatively stable overall, although increased flow variability and more frequent extreme events have been reported in the Yangtze and Pearl rivers [22,23]. The most pronounced increases have occurred on the Qinghai–Xizang Plateau [24], where glacial melt has enhanced runoff by 15%–22% in the Yarlung Zangbo River [25,26] and 18%–30% in the Lhasa River [27]. Northwest inland rivers have presented a distinct pattern: While headwaters show discharge increases of 5%–15%, downstream segments face increasing water scarcity driven by agricultural demand [28,29]. These spatial patterns largely reflect regional differences in climate sensitivity and water-use intensity [30,31], with northern river basins being particularly vulnerable owing to their limited natural runoff capacity [32]. These emerging hydrological transformations have important implications for water security and highlight the need for basin-specific adaptation strategies that account for divergent trends.

Existing observational evidence consistently indicates that global and Chinese river systems are undergoing substantial hydrological changes driven by environmental change, posing new challenges for water resource management. Despite substantial research progress, important gaps remain in the understanding of runoff evolution. Most existing studies have focused on individual regions or specific river basins [26 29], whereas comprehensive nationwide analyses remain relatively limited [30,33]. Moreover, inconsistencies in data sources and observation periods hinder robust comparative assessments across basins [17,18]. This limitation is particularly evident in the most recent decade, a period characterized by rapid environmental and socioeconomic change that has received comparatively little attention [30,33]. Furthermore, commonly used indicators, such as runoff magnitude and tendency rate, require careful interpretation, as substantial differences in climatic conditions and mean annual runoff levels can lead to inconsistent assessments of hydrological change across basins. Identical absolute changes or trend rates may represent markedly different degrees of hydrological alteration, thereby complicating cross-basin comparisons.

To address these gaps and limitations, we aimed to introduce a unit-normalized runoff index (URI), a standardized metric that enables consistent comparison of runoff variability across basins with contrasting hydrological conditions. Moreover, we systematically analyzed the spatiotemporal characteristics of runoff evolution using a unified 65-year observational dataset (1960–2024) from 24 benchmark hydrological stations across ten major water regions in China. The findings of this study are anticipated to provide a scientific basis for national water resource assessment and offer critical insights into future river development, management, and protection under ongoing environmental change.

2. Data and methods

2.1. Study regions and data sources

China exhibits pronounced hydroclimatic diversity, characterized by humid, water-abundant conditions in the south and arid, water-scarce conditions in northern areas. The primary challenge in conducting a nationwide analysis of runoff evolution lies in data acquisition. We systematically assessed long-term hydrological changes by selecting 24 benchmark hydrological stations along principal rivers in ten major water regions in China based on three key principles: ① spatial representativeness, ② long-term and consistent data availability, and ③ overall data accessibility. Continuous monthly runoff observations from 1960 to 2024 were obtained from the Department of Hydrology, Ministry of Water Resources of China. These data have undergone rigorous verification and systematic processing, which guarantees their high quality and reliability.

The geographical distribution of the selected hydrological stations reveals three distinctive patterns that reflect the hydrogeographical conditions in China (Fig. 1). ① Relatively uniform meridional (north–south) coverage ensures the representation of the latitudinal climate gradient. ② Pronounced zonal (east–west) clustering is evident, with station concentrations near 100°E and east of 110°E. This pattern results directly from the predominant west-to-east river flow in China, leading to the natural concentration of outlet stations in the eastern regions. ③ To systematically capture spatial heterogeneity, the monitoring network comprises representative stations across the upper, middle, and lower reaches of most major rivers, forming a three-dimensional observational matrix that resolves longitudinal and altitudinal variations in hydrological behavior.

The major river systems in China include the Yangtze, Yellow, Songhua, Liaohe, Haihe, Huaihe, and Pearl River basins. Based on the integrity of these seven major river basins and the spatial distribution of water resources and geographical characteristics, China can be divided into ten primary water resource regions: Songhua River (I), Liaohe River (II), Haihe River (III), Yellow River (IV), Northwest Rivers (V), Southwest Rivers (VI), Yangtze River (VII), Huaihe River (VIII), Southeast Rivers (IX), and Pearl River (X) regions. According to regional hydroclimatic features and the

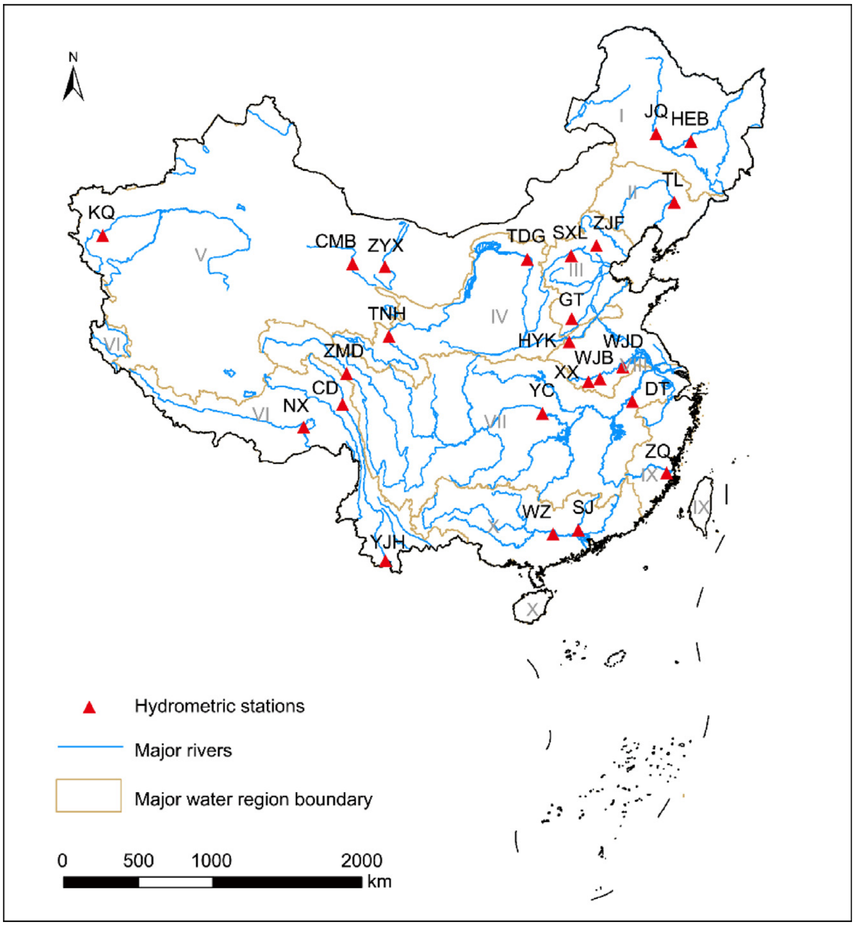


Fig. 1. Geographical distribution of the ten major water regions, principal rivers, and 24 hydrological stations along main stems in China. Station abbreviations correspond to those listed in Table 1. I–X represent the major water region number.

geographical distribution of the selected hydrological stations, China may be roughly categorized into three major regions: ① western China, which encompasses the area west of approximately 105°E longitude; ② northern China, which pertains to the region drained by, and located north of, the Yellow River; and ③ southern China, which includes the areas associated with and situated south of the Huaihe River.

This comprehensive dataset enabled robust analyses of decadal-scale runoff trends and spatial patterns across contrasting hydro-climatic regions. The study network spanned the full spectrum of hydrological regimes in China, with stations strategically distributed to represent: ① the water-rich Yangtze and Pearl River basins in the south; ② the water-stressed Yellow and Haihe River basins in the north; and ③ the alpine-influenced headwaters of western rivers.

Table 1 presents the key characteristics of each water resource region and its representative stations, providing essential context for interpreting spatial variability in the observed hydroclimatic conditions. The annual air temperature across the ten water resource regions ranged from 2.63 °C in the northernmost Songhua River Region to over 20 °C in the southernmost Pearl River Region. Annual precipitation exhibited pronounced spatial variability, increasing from less than 200 mm in the Northwest Rivers Region to more than 1500 mm in the Pearl River and Southeast Rivers regions. Annual pan evaporation, measured using the Pan E601 evaporator (Nanjing Research Institute of Hydrology and Water Conservation Automation, Ministry of Water Resources of China), ranged from 729.2 mm in the Songhua River Region to 1266.3 mm in the Northwest Rivers Region. Higher values were generally observed in arid river basins in western China, whereas lower values were mainly concentrated in colder northern regions. The multiyear mean surface water resources in China were approximately 2724.6 billion m^3 per year.

Table 1 illustrates the substantial regional heterogeneity of surface water resources in China. The monitoring network reveals three key distribution patterns. ① Extreme spatial concentration: four water regions (Yangtze River, Southeast Rivers, Southwest Rivers, and Pearl River regions) collectively account for more than 80% of the national water resources. ② Downstream integration: major outlet control stations (e.g., Huayuankou on the Yellow River and Datong on the Yangtze River) monitor more than 90% of their basin areas, whereas composite water resource regions associated with multi-river systems show smaller coverage (e.g., the Haihe River Basin). ③ Pronounced runoff contrasts: Annual runoff depths range from > 600 mm in southeastern coastal basins to < 50 mm in northern arid regions, with Shixiali Station (12.4 mm) in the Haihe River Basin representing only approximately 2% of the yield in southern basins.

These tripartite patterns of concentration, integration, and contrast fundamentally shape water security challenges in China, highlighting the need for differentiated management strategies across hydroclimatic regions. The selected stations capture the full hydrological spectrum from tropical high-flow systems to temperate ephemeral rivers, thereby establishing a robust observational foundation for national water resource assessment under changing environmental conditions.

Table 1
Fundamental characteristics of the ten major water regions and principal hydrological stations along the main river stems in China.

Region	Station No.	Hydrometric station	River	Drainage area (km^2)	Annual runoff (mm)	Major water region No.	Major water resource region	Water region area (km^2)	Surface water resources ($\times 10^8$ m^3)	Precipitation (mm)	Air temperature (°C)	Annual E601 Pan evaporation (mm)
Northern China	1	Harbin (HEB)	Songhua River	389 769	105.0	I	Songhua River Region	934 802	1249.3	561.4	2.63	729.2
	2	Jiangqiao (JQ)	Nen River	162 569	125.4	I						
	3	Tieling (TL)	Liao River	120 764	22.8	II	Liaohe River Region	314 146	393.3	657.7	7.50	907.2
	4	Zhangjiafen (ZJF)	Bai River	8 506	45.6	III	Haihe River Region	320 041	171.4	558.3	10.20	1055.5
	5	Shixiali (SXL)	Sanggan River	23 627	12.4	III						
	6	Guantai (GT)	Zhang River	17 800	38.0	III						
	7	Huayuankou (HYK)	Yellow River	730 036	48.2	IV	Yellow River Region	795 043	583.6	495.0	7.93	1059.1
	8	Toudaoguai (TDG)	Yellow River	367 898	57.1	IV						
Western China	9	Tangnaihai (TNH)	Yellow River	121 972	169.1	IV						
	10	Kaqun (KQ)	Yarkant River	45 881	146.1	V	Northwest Rivers Region	3 362 261	1207.1	197.2	6.67	1266.3
	11	Changmabu (CMB)	Changma River	10 961	97.5	V						
	12	Zhengyixia (ZYX)	Hei River	35 634	29.6	V						
	13	Changdu (CD)	Lancang River	54 228	289.5	VI	Southwest Rivers Region	844 114	5753.8	902.9	10.64	1156.5
	14	Yunjinghong (YJH)	Lancang River	141 779	375.0	VI						
	15	Nuxia (NX)	Yarlung Zangbo River	191 235	314.4	VI						
	16	Zhimenda (ZMD)	Tongtian River	137 704	101.3	VII	Yangtze River Region	1 782 715	9775.7	1221.9	14.76	917.3
Southern China	17	Yichang (YC)	Yangtze River	1 005 501	423.7	VII						
	18	Datong (DT)	Yangtze River	1 705 383	519.8	VII						
	19	Xixian (XX)	Huaihe River	10 190	346.6	VIII	Huaihe River Region	330 009	688.8	880.7	14.27	999.7
	20	Wangjiaba (WJB)	Huaihe River	30 630	270.4	VIII						
	21	Wujiadu (WJD)	Huaihe River	121 330	210.4	VIII						
	22	Zhuqi (ZQ)	Min River	54 500	958.4	IX	Southeast Rivers Region	244 574	2682.6	1597.2	17.79	975.9
	23	Wuzhou (WZ)	West River	327 006	614.8	X	Pearl River Region	578 974	4740.3	1660.2	20.39	1071.2
	24	Shijiao (SJ)	North River	38 363	1069.2	X						

The abbreviations in parentheses following the hydrometric station names represent the shortened forms of the respective station names. No.: number.

2.2. Methods

(1) **Trend analysis methods.** The Mann–Kendall (M–K) test was utilized to detect monotonic trends and assess their statistical significance in the runoff time series. As a nonparametric method, the M–K test offers three key advantages for hydrological applications [34,35]: ① It does not require assumptions regarding data distribution; ② it is robust to outliers and non-normal data; and ③ it remains effective across diverse hydrological regimes. The test statistic Z_s determines trend direction and significance: When $|Z_s|$ exceeds the critical value $Z_{1-\alpha/2}$ (where a common significance level value of α = 0.05 corresponds to ±1.96), the trend is considered statistically significant at the 95% confidence level. This method has gained prominence as a standard diagnostic tool in hydroclimatological studies because of its theoretical rigor and resistance to artificial influences. It is particularly suitable for detecting gradual changes in environmental time series, where extreme values may arise but should not disproportionately affect trend detection [30,36]. The reliability of this approach has been shown in numerous global hydrological trend studies, facilitating comparisons with international research.

Linear trend analysis quantifies long-term temporal patterns by fitting a linear regression model to time series data, with the slope coefficient representing the rate of change per unit of time [36]. This approach provides a straightforward interpretation of both trend direction (positive/negative slope) and magnitude (slope steepness), thereby displaying advantages such as computational simplicity and intuitive result presentation. However, as a parametric method, it exhibits sensitivity to extreme values, which may disproportionately influence slope estimates. To address this limitation (while retaining its advantages), linear regression was used in combination with nonparametric trend tests, enabling a more robust characterization of both gradual trends and extreme events [30]. Specifically, linear regression provides quantitative rates of change, whereas nonparametric methods assess trend significance without strong sensitivity to outliers, thereby offering a more comprehensive understanding of system dynamics.

(2) **URI.** Owing to substantial differences in observed runoff among rivers, identical linear trend rates may reflect markedly different magnitudes of change across river systems. Although linear trend rates can effectively characterize runoff changes within individual basins, they are not suitable for comparative analyses of runoff variations across river basins because the baseline runoff levels vary widely.

To overcome the inherent limitations of conventional linear trend analysis in cross-basin comparisons, we developed a URI, a standardized metric that enables robust inter-basin assessment of hydrological change. The calculation is presented below:

$$\mathrm{URI}_{ij} = \frac{R_{ij}}{\overline{R_{\mathrm{a}}}} \tag{1}$$

$$\mathrm{URI}_{i} = \sum_{j=1}^{12} \mathrm{URI}_{ij} = \sum_{j=1}^{12} \frac{R_{ij}}{\overline{R_{\mathrm{a}}}} \tag{2}$$

where R_{ij} (mm) is the monthly runoff; $\overline{R_{\mathrm{a}}}$(mm) is the multiyear average annual runoff; URI_{ij} and URI_{i} are URIs at the monthly and annual scales; and i and j are the year and month, respectively.

The annual URI series has a multiyear mean value of 1, representing a multiple of the long-term mean annual runoff. The URI retains two key hydrological characteristics: ① interannual wet–dry variability patterns of the original annual runoff series, and ② standardized monthly runoff indices and intra-annual distribution features embedded in the annual index. A key methodological advantage of the URI is its cross-basin comparability, as all basins share the same reference value of 1. Consequently, the linear trend rates derived from standardized indices allow direct and meaningful comparisons of runoff variability across different river systems. This property is particularly valuable for large-scale hydrological assessments because it removes scaling effects caused by inherent differences in absolute runoff magnitudes among basins while preserving essential temporal variability at both annual and monthly timescales.

3. Results and discussion

3.1. Variation of measured annual runoff in China's major water regions

Fig. 2 presents the annual URI time series (1960–2024) for 24 representative hydrological stations across ten major water regions in China, illustrating the historical evolutionary trends and variability of measured runoff across different regions.

As shown in Fig. 2, the URIs fluctuated around 1, whereas variability differed markedly among the stations. Most stations exhibited URI ranges of 50%–200%. In contrast, the three stations in the Haihe River Basin displayed substantially larger variability, with Guantai Station showing the greatest fluctuation range (more than 600%). This was followed by Tieling Station in the Liaohe River Basin. Conversely, Yichang and Datong stations in the Yangtze River Basin showed relatively stable runoff, exhibiting the smallest amplitudes in the URIs. In addition, the Huaihe River Basin displayed the most pronounced alternating wet–dry cycles.

In the Northwest Rivers Region (Figs. 2(j)–(l)), all three stations exhibited increasing runoff trends; however, their variability patterns differed. Kaqun Station exhibited relatively steady growth. Zhengyixia Station experienced strong fluctuations prior to 1990, followed by an increase–decrease pattern from 1991 to 2014, with runoff peaking in 2016. In contrast, Changmabu Station underwent an eight-year consecutive dry period (1990–1997) before entering a marked upward trend.

The Southwest Rivers Region exhibited distinct runoff behaviors among the stations (Figs. 2(m)–(o)). Nuxia Station (Yarlung Zangbo River) exhibited a clear increasing trend, with an abrupt regime shift in 1997 and sustained higher flows during the 1998–2001 wet period (four years) than pre-1997 levels. Changdu Station (upper Lancang River) also demonstrated increasing runoff, including a five-year wet period (1962–1966) and accelerated growth after 1994. Conversely, Yunjinghong Station (lower Lancang River) demonstrated an overall decreasing trend. While maintaining natural fluctuations prior to 2000, it entered a pronounced decline between 2001 and 2013, including a five-year low-flow period (2009–2013), before stabilizing at approximately 90% of the long-term mean discharge.

Stations in the Songhua and Liaohe River basins exhibited complex hydrological variability without significant long-term trends; however, they also showed strong periodicity and extreme flows (Figs. 2(a)–(c)). Harbin and Jiangqiao stations on the Songhua River exhibited consistent evolutionary patterns, characterized by sustained decreases before 1980, above-average flows between 1981 and 1998, and a prolonged 14-year dry period (1999–2012). From 2013 to 2024, variability increased substantially, with peak discharges exceeding more than twice the multiyear mean. Moreover, minimum flows decreased to approximately 60% of the mean. Tieling Station on the Liaohe River showed a partially analogous pattern, with relatively high flows from 1960 to 1964, followed by a declining phase. An abrupt hydrological shift occurred in 1985, marking the onset of a new regime (1985–2024) defined by initial decreases and subsequent increases with amplified variability. Extreme fluctuations were observed: Record discharges in 1986 and 2022 were 2.76 and 3.35 times the long-term mean, respectively, whereas the 2001–2003 drought reduced runoff to approximately 15% of the average.

The three stations in the Haihe River Basin collectively showed a significant decreasing trend in measured runoff (Figs. 2(d)–(f)). During the 1960s, water abundance was particularly evident at Guantai and Shixiali stations, with annual runoff frequently exceeding twice the multiyear mean. Notable peaks were recorded at Guantai Station in 1963 (6.9 times mean) and Shixiali Station in 1967 (4 times mean). The 2000–2010 period constituted a prolonged dry phase characterized by annual runoff typically falling below 30% of the mean. However, all stations exhibited recovery from 2011 to 2024. Guantai and Zhangjiafen stations recorded exceptional flows in 2021 (3.53 and 2.01 times mean, respectively). In 2022, Shixiali Station exceeded 1.3 times mean. These patterns indicate intensified hydrological variability, with recent extremes (2021–2022, 1.3–3.5 times mean) surpassing those observed in the 1990s, suggesting fundamental shifts in the water regime of the basin due to climate change.

The three stations in the Yellow River Basin collectively demonstrated a "decrease–increase–decrease" pattern in measured runoff from 1960 to 2024 (Figs. 2(g)–(i)), with notable declines observed at Toudaoguai and Huayuankou stations. All stations experienced substantially low flows around 2000: Tangnaihai Station recorded merely 51.6% of its multiyear mean in 2002, whereas Toudaoguai and Huayuankou stations dropped below 50% in 1997. In contrast, runoff from 2018 to 2021 was consistently above average across all stations, with annual values exceeding the long-term means. Tangnaihai Station showed particularly persistent high flows, exceeding its average in six of the most recent seven years.

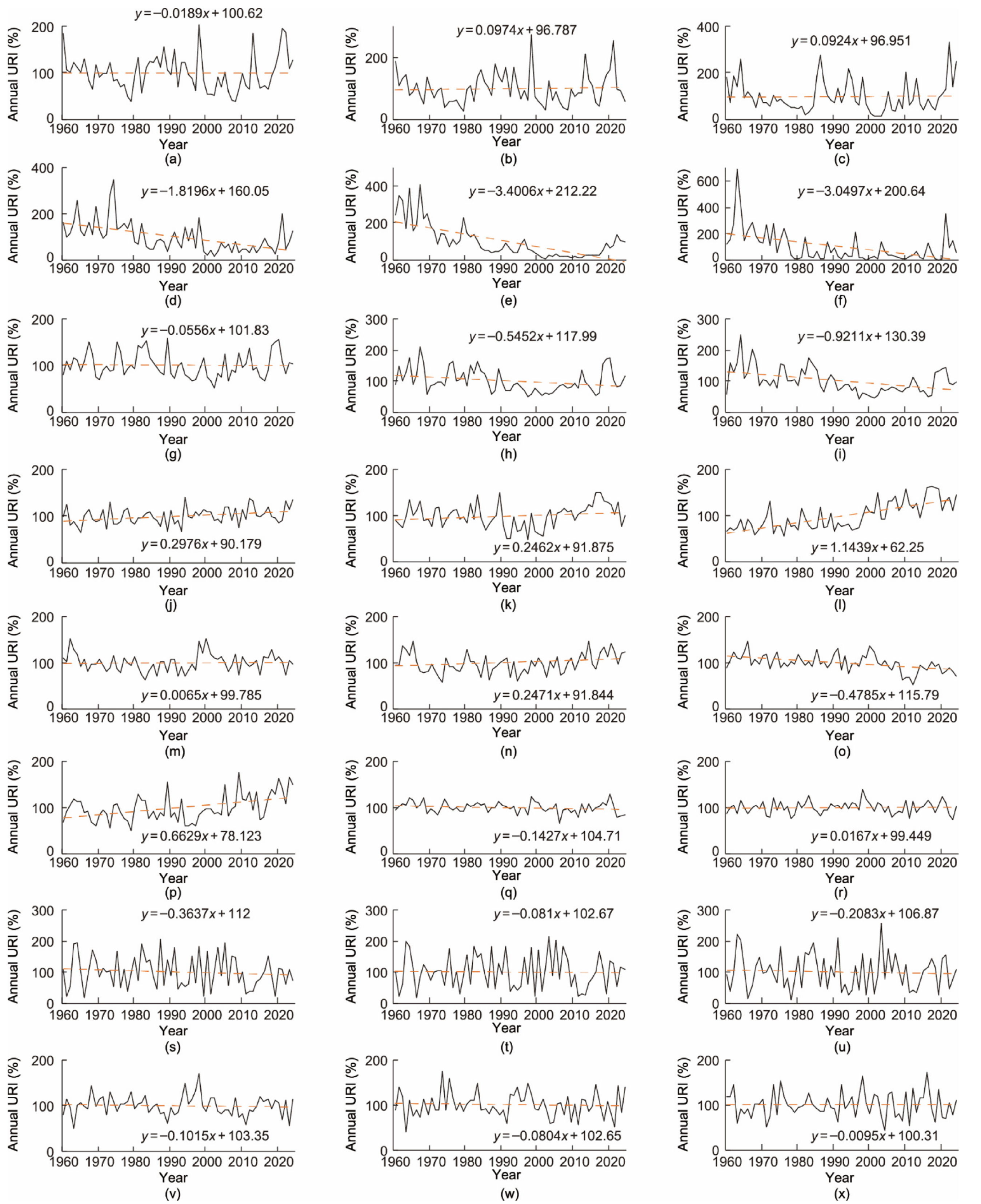


Fig. 2. Interdecadal evolution of annual URIs at representative hydrological stations in ten major water regions. (a) Harbin, (b) Jiangqiao, (c) Tieling, (d) Zhangjiafen, (e) Shixiali, (f) Guantai, (g) Tangnaihai, (h) Toudaoguai, (i) Huayuankou, (j) Kaqun, (k) Zhengyixia, (l) Changmabu, (m) Nuxia, (n) Changdu, (o) Yunjinghong, (p) Zhimenda, (q) Yichang, (r) Datong, (s) Xixian, (t) Wangjiaba, (u) Wujiadu, (v) Wuzhou, (w) Shijiao, and (x) Zhuqi.

The three stations in the Huaihe River Basin (Xixian, Wangjiaba, and Wujiadu) exhibited naturally fluctuating runoff characterized by a slight overall decreasing trend (Figs. 2(s)–(u)). Strong hydrological coherence was evident with synchronous wet–dry cycles and alternating high- and low-flow years. Statistically, the occurrence probabilities of extreme events were relatively balanced: years with runoff exceeding 150% of the multiyear mean (wet years) and years below 50% of the mean (dry years) each accounted for approximately 20%–25% of the record. A particularly severe drought occurred from 2011 to 2013, when all three stations consistently recorded flows below 40% of their long-term averages.

The runoff trends along the Yangtze River exhibited distinct spatial characteristics (Figs. 2(p)–(r)). The upstream Zhimenda Station showed a persistent increasing trend, transitioning from weak natural fluctuations before 1997 to pronounced growth after 1998, with eight of the last ten years exceeding the multiyear mean. At Yichang Station in the middle reaches, a slight decreasing trend contrasted with a weak increasing trend downstream at Datong Station; however, both stations maintained remarkable flow stability. Their synchronous wet–dry cycles exhibited limited variability. For instance, peak flow at Yichang in 2020 (1.27 times mean) and minimum flow at Datong in 2023 (0.74 times mean) reflected this stable regime. Longitudinal coherence was particularly evident, with annual flow variations at all stations generally remaining within 30% of historical averages.

Distinct hydrological patterns were observed in the southeastern basin (Figs. 2(v)–(x)). The Zhuqi Station (Southeast Rivers Region) and Wuzhou/Shijiao stations (Pearl River Region) showed naturally fluctuating runoff with slightly decreasing trends. Notably, Zhuqi Station demonstrated increasing variability, as its maximum (2016: 1.73 times mean) and minimum (2004: 0.43 times mean) annual flows both occurred after 2000. The Pearl River stations displayed pronounced phase characteristics. Wuzhou Station experienced consecutive dry (1987–1992, all below average) and wet (1993–1998, all above average) periods, peaking in 1998 (1.7 times mean). Similarly, Shijiao Station exhibited an eight-year dry phase (1984–1991, 0.84 times mean) followed by a seven-year wet phase (1992–1998, 1.25 times mean), thereby indicating clear decadal-scale hydrological oscillations.

Between 1960 and 2024, the runoff evolution in China exhibited distinct regional patterns. Northern China (Yellow and Haihe River regions) experienced significant long-term declines intensified by human water use, although recent extreme high-flow events suggested increasing volatility. Western China (Northwest and Southwest Rivers regions) showed marked increases, largely driven by glacial melt and increased precipitation. The eastern and southern basins (Yangtze, Huaihe, and Pearl River, and Southeast Rivers regions) remained relatively stable with slight decreases; however, they exhibited enhanced variability and clear decadal wet–dry fluctuations. The northeastern basins (Liaohe and Songhua River regions) were characterized by strong cyclic variations and amplified extremes, including recent peak flows exceeding the historical average by more than three times. Across most regions, hydrological variability increased with more frequent extreme events, highlighting the combined impacts of climate change and human activities.

3.2. Spatial pattern of annual runoff evolution trends in China

Linear trend analysis of the time series was applied to investigate the temporal evolution of both the measured annual runoff and URIs at 24 hydrological stations across ten major water regions in China from 1960 to 2024. The statistical significance of the identified runoff trends was rigorously assessed using the M–K test. Fig. 3 illustrates the spatial distribution of the linear trend rates and their corresponding significance for the measured annual runoff and URIs. Several key spatial patterns can be identified, as summarized below.

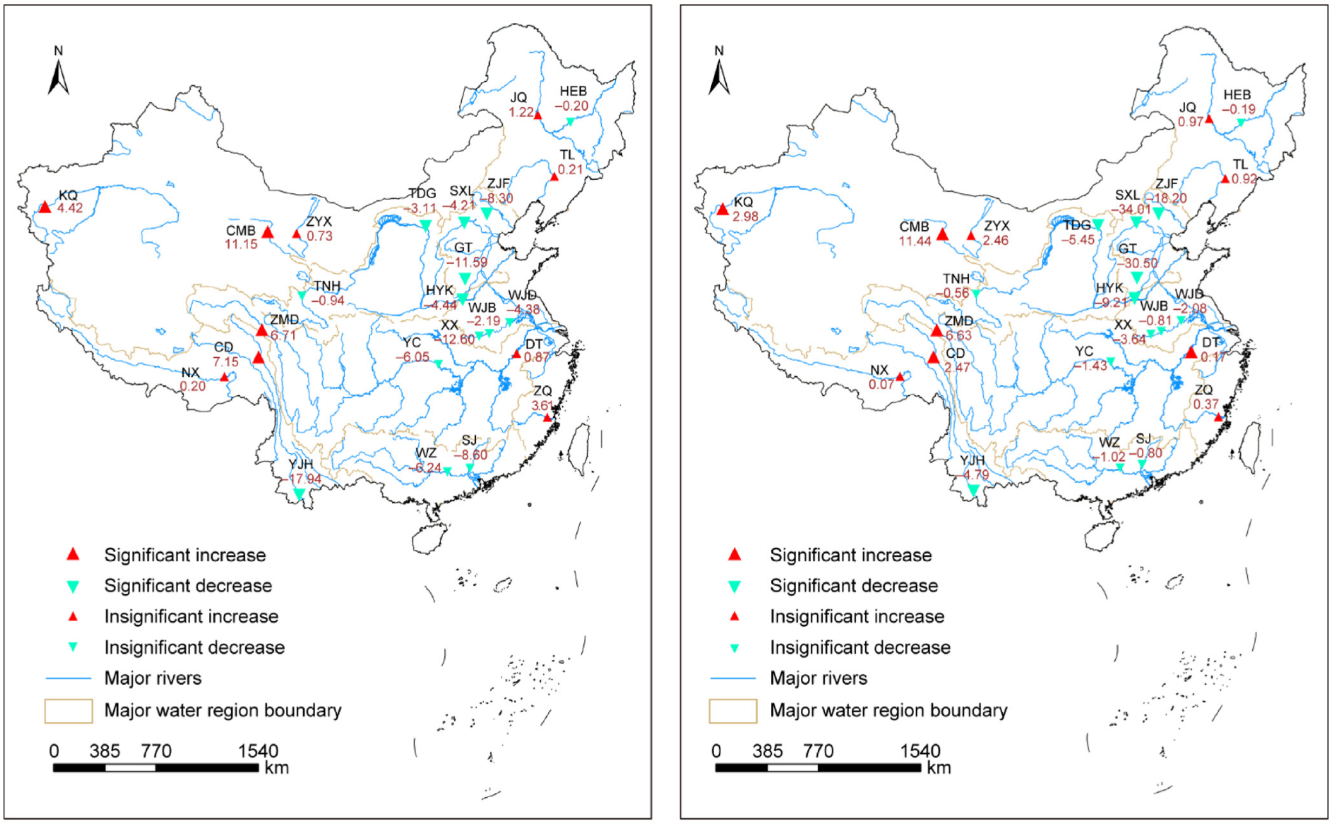
The results for the measured annual runoff and URIs, together with the M–K test outcomes, indicated consistent trends in runoff evolution. From 1960 to 2024, distinct regional patterns were evident: All stations west of approximately 100°E and most stations east of about 117.5°E exhibited increasing runoff trends, whereas all stations in middle China (approximately 100°E–117.5°E) showed decreasing trends.

The measured annual runoff at Kaqun (Yarkant River), Changmabu (Changma River), Zhimenda (upper Yangtze River), and Changdu (upper Lancang River) stations in western China exhibited statistically significant increasing trends. In contrast, statistically significant decreasing trends were observed at the Toudaoguai and Huayuankou stations (Yellow River); Zhangjiafen, Guantai, and Shixiali stations (Haihe River); and Yunjinghong Station (lower Lancang River). The remaining stations showed non-significant increasing or decreasing trends.

Stations with large linear trend magnitudes in measured annual runoff were primarily concentrated at Guantai (Haihe River), Xixian (Huaihe River), Yunjinghong (Lancang River), and Changmabu (Changma River), all exceeding 10 mm per decade ($10\ \mathrm{mm{\cdot}10a^{-1}}$). Among these, Yunjinghong Station exhibited the most pronounced decline, at approximately $-17.94\ \mathrm{mm{\cdot}10a^{-1}}$. Notably, only Changmabu Station showed an increasing trend in annual runoff, whereas the other three stations displayed decreasing trends. In addition, Zhangjiafen (Haihe River), Zhimenda and Yichang (Yangtze River), Wuzhou and Shijiao (Pearl River), and Changdu (Lancang River) demonstrated trend magnitudes of 5–$10\ \mathrm{mm{\cdot}10a^{-1}}$. Within this group, Changdu and Zhimenda stations, located on the Qinghai–Xizang Plateau, exhibited increasing trends (7.15 and $6.71\ \mathrm{mm{\cdot}10a^{-1}}$, respectively), whereas the stations in the Haihe, Yangtze, and Pearl River regions showed decreasing trends. Interestingly, despite relatively large trend magnitudes at Xixian ($-12.60\ \mathrm{mm{\cdot}10a^{-1}}$), Wuzhou ($-6.24\ \mathrm{mm{\cdot}10a^{-1}}$), and Shijiao ($-8.60\ \mathrm{mm{\cdot}10a^{-1}}$), none of these trends reached statistical significance at the 0.05 level. Conversely, Shixiali (Haihe River, $-4.21\ \mathrm{mm{\cdot}10a^{-1}}$) and Huayuankou (Yellow River, $-4.44\ \mathrm{mm{\cdot}10a^{-1}}$) showed statistically significant decreasing trends at the 0.05 level, even though their trend magnitudes are below $5\ \mathrm{mm{\cdot}10a^{-1}}$. These findings suggest that, although the linear trend rate of the measured annual runoff can reflect the magnitude of change, it does not fully capture runoff variability owing to differences in baseline runoff conditions.

For the linear trend rate of the annual URI, the most pronounced changes occurred at Zhangjiafen, Guantai, and Shixiali stations (Haihe River) and Changmabu Station (Changma River), all exceeding $10\%{\cdot}10a^{-1}$. In particular, Guantai and Shixiali stations show substantial decreases, with trend rates of $-30.50\%{\cdot}10a^{-1}$ and $-34.01\%{\cdot}10a^{-1}$, respectively. Toudaoguai ($-5.45\%{\cdot}10a^{-1}$) and Huayuankou ($-9.21\%{\cdot}10a^{-1}$) stations on the Yellow River, as well as Zhimenda Station ($6.63\%{\cdot}10a^{-1}$) on the Yangtze River, showed moderate but notable changes, with absolute values ranging from $5\%{\cdot}10a^{-1}$ to $10\%{\cdot}10a^{-1}$. Importantly, all seven stations listed above exhibited statistically significant trends in measured runoff. This suggests that the linear trend rate of the annual URI reflects the intensity of runoff evolution trends more effectively than the measured annual runoff.

Overall, among the ten major water regions in China, measured runoff at representative stations in the Haihe, Yellow, Huaihe, and Pearl River regions generally showed decreasing trends. In particular, the Haihe River Region and the middle–lower reaches of the Yellow River exhibited statistically significant declines. In contrast, most representative stations in the Northwest Rivers Region, Southwest Rivers Region, Liaohe River Region, and upper Yangtze River showed increasing annual runoff trends. Significant



(a) (b)

Fig. 3. Linear trends and their significance of (a) measured annual runoff (mm·10a^{-1}) and (b) URIs (%·10a^{-1}) at 24 hydrological stations across the ten major water regions in China from 1960 to 2024. Red upright triangles indicate increasing trends, cyan inverted triangles indicate decreasing trends; large triangles denote significant trends at the 95% confidence level, while small triangles denote non-significant trends.

increasing trends were particularly evident in the Northwest and Southwest Rivers regions and upper Yangtze River, where snow and glacial melt dominated runoff generation. The middle–lower Yangtze and Songhua River regions remained hydrologically stable, showing no statistically significant trends in runoff variation.

3.3. Spatiotemporal evolution trends and seasonal runoff characteristics

Based on the intra-annual distribution characteristics of climate and runoff in China, the four seasons were defined as follows: spring (March–May), summer (June–August), autumn (September–November), and winter (December–February of the following year). We analyzed observed seasonal runoff data (1960–2024) from representative hydrological stations across ten major water regions in China to assess temporal trends in seasonal runoff variations and their statistical significance. Fig. 4 summarizes the linear trend rates and their significance for both measured seasonal runoff and unit-normalized seasonal runoff indices at these stations from 1960 to 2024.

Fig.4 illustrates that spring runoff changes displayed a clear west-increasing and east-decreasing spatial pattern, with significant declines particularly evident in the Haihe River Basin. Approximately 50% of the stations showed increasing runoff, predominantly located in the Northwest Rivers Region (Kaqun and Changmabu stations), Southwest Rivers Region, Liaohe River and Yangtze River regions, as well as at Wuzhou station in the Pearl River Region. Notably, six stations exhibited statistically significant increasing trends. Conversely, although half of the stations showed decreasing trends, statistical significance was achieved only at three stations in the Haihe River Region (Zhangjiafen, Shixiali, and Guantai), thereby highlighting the particularly vulnerable conditions in this region.

Summer runoff exhibited a predominantly decreasing trend across most of China, with only limited increases observed in western China and the upper Yangtze River region. Summer runoff showed a more conservative pattern, with only 20.8% (5/24) of stations displaying positive trends. These stations were located in western China (Kaqun, Changmabu, and Changdu) and along the main stem of the Yangtze River (Zhimenda and Datong). Notably, Changmabu (Northwest Rivers Region) and Zhimenda (upper Yangtze River) were the only stations showing statistically significant increases. In contrast, most stations (79.2%) exhibited negative trends, with statistically significant declines observed across the Haihe River Region, Yellow River Region (Toudaoguai), Southwest River Region (Yunjinghong), and middle Yangtze River Region (Yichang), thereby suggesting considerable summer water stress in these regions.

Autumn runoff maintained a widespread decreasing trend, with significant increases confined to the Northwest Rivers Region and upper Yangtze River Region. Autumn runoff dynamics displayed both similarities and distinct spatial differentiation relative to summer. The predominance of decreasing trends persisted (75% of stations), whereas the spatial distribution of increasing trends shifted. Six stations showed positive trends, with statistically significant increases confined to the arid Northwest Rivers Region (Kaqun, Zhengyixia, and Changmabu) and to Zhimenda Station in the upper Yangtze River Region. Statistically significant decreases formed a geographic cluster encompassing the following: ① the water-stressed Haihe River Region, ② Yunjinghong Station in the

Region	Station No.	Station	M–K value				Runoff trend slop (mm·10a⁻¹)				URI trend slop (%·10a⁻¹)				Major water region
			Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	
Northern China	1	Harbin	–1.90	–0.26	–1.52	1.17	–0.50	0.79	–0.79	0.30	–0.48	0.76	–0.75	0.28	Songhua River
	2	Jiangqiao	–0.22	–0.37	–0.61	4.97	–0.24	0.92	–0.21	0.75	–0.19	0.73	–0.17	0.60	
	3	Tieling	1.86	–1.55	–0.62	4.18	0.18	–0.12	–0.11	0.26	0.79	–0.52	–0.48	1.14	Liaohe River
	4	Zhangjiafen	–3.73	–4.51	–3.34	-5.59	–0.81	–4.91	–1.45	–1.12	–1.78	–10.77	–3.18	–2.47	Haihe River
	5	Shixiali	–6.10	–6.09	–4.03	-6.79	–1.25	–1.62	–0.76	–0.59	–10.06	–13.07	–6.12	–4.75	
	6	Guantai	–3.69	–3.32	–3.91	-4.64	–1.36	–5.26	–3.24	–1.73	–3.57	–13.84	–8.52	–4.57	
	7	Huanyuankou	–0.99	–1.51	–4.56	–1.42	–0.30	–0.82	–3.17	–0.15	–0.62	–1.71	–6.56	–0.32	Yellow River
	8	Toudaoguai	–0.15	–2.77	–1.94	2.22	0.06	–1.56	–1.92	0.31	0.10	–2.73	–3.36	0.54	
Western China	9	Tangnaihai	–0.49	–0.28	–0.72	1.31	–0.18	0.29	–1.35	0.30	–0.10	0.17	–0.80	0.18	
	10	Kaqun	5.68	0.32	3.44	7.25	1.74	0.61	1.26	0.81	1.17	0.41	0.85	0.55	Northwest Rivers
	11	Changmabu	5.23	5.41	5.34	7.22	1.03	6.51	2.50	1.11	1.05	6.68	2.57	1.14	
	12	Zhengyixia	0.35	–0.20	2.97	0.05	0.09	–0.09	0.75	–0.02	0.31	–0.30	2.52	–0.07	
	13	Changdu	1.59	0.93	1.81	3.74	0.83	2.42	2.78	1.12	0.29	0.84	0.96	0.39	Southwest Rivers
	14	Yunjinghong	4.70	–5.23	–4.72	1.33	8.31	–17.15	–12.14	3.04	2.22	–4.57	–3.24	0.81	
	15	Nuxia	3.25	–0.35	–0.18	3.23	1.07	–1.51	–0.13	0.78	0.34	–0.48	–0.04	0.25	
	16	Zhimenda	3.94	2.12	3.15	4.08	0.71	2.97	2.74	0.29	0.70	2.94	2.71	0.29	
Southern China	17	Yichang	3.54	–2.16	–4.20	5.89	3.38	–4.09	–8.35	3.01	0.80	–0.96	–1.97	0.71	Yangtze River
	18	Datong	1.72	0.40	–2.59	5.11	2.35	1.14	–6.04	3.42	0.45	0.22	–1.16	0.66	
	19	Xixian	–0.61	–0.92	–1.30	0.31	–5.45	–6.87	–0.42	0.13	–1.57	–1.98	–0.12	0.04	Huaihe River
	20	Wangjiaba	–0.13	–0.36	–1.10	2.42	–2.73	–2.24	0.87	1.91	–1.01	–0.83	0.32	0.71	
	21	Wujiadu	0.10	–0.66	–1.19	1.85	–1.18	–1.93	–2.36	1.09	–0.56	–0.92	–1.12	0.52	
	22	Zhuqi	–0.66	–0.42	0.88	2.81	–4.88	–3.12	3.77	7.83	–0.51	–0.33	0.39	0.82	Southeast Rivers
	23	Wuzhou	1.36	–1.42	–2.00	2.76	3.26	–8.14	–4.72	3.36	0.53	–1.32	–0.77	0.55	Pearl River
	24	Shijiao	–1.17	–0.51	–0.85	1.11	–6.62	1.21	–5.36	2.17	–0.62	0.11	–0.50	0.20	

Fig. 4. Variation trend detection of seasonal runoff and URI for 24 hydrometric stations from 1960 to 2024 (red color indicates decrease, while blue color denotes increase).

Southwest Rivers Region, ③ Wuzhou Station in the Pearl River Region, and ④ multiple stations in the Yangtze River (Yichang and Datong) and Yellow River (Huayuankou) regions, with Toudaoguai showing marginal significance.

Winter runoff showed widespread and significant increases across most basins, whereas decreases were predominantly observed in the chronically water-scarce Haihe and Yellow River basins. Winter patterns revealed a striking hydrological contrast, with 83.3% of the stations exhibiting increased runoff. This positive trend was particularly evident in the Yangtze River Basin, Liaohe River Basin, Southeast Rivers Region, and at most stations in the Northwest and Southwest Rivers regions. The stations exhibiting decreasing trends were restricted to the chronically water-deficient Haihe River Basin (all three stations) and Huayuankou Station on the Yellow River.

Analyzing long-term seasonal runoff trends (1960–2024) revealed a clear east–west divergence in hydrological patterns in China, highlighting two particularly vulnerable systems. All three stations in the Haihe River Basin showed statistically significant decreases across all seasons, indicating severe year-round hydrological stress, whereas the Huayuankou Station on the Yellow River exhibited consistent declines. In contrast, several stations exhibited robust year-round increases, such as Kaqun and Changmabu stations (the latter demonstrating all-season significance) in the Northwest Rivers Region, Changdu Station (Southwest Rivers Region) on the Qinghai–Xizang Plateau, and Zhimenda Station (upper Yangtze River), all showing statistically significant trends throughout the seasons. These contrasting patterns indicated a fundamental geographical split: The western headwater regions generally gained water resources, whereas the eastern consumption regions faced increasing scarcity. This underscores the intricate spatial dynamics of hydrological change in China amid ongoing climatic and anthropogenic pressures.

Fig. 5 presents quartile plots of the linear trend rates for seasonal runoff and the unit-normalized seasonal runoff index across all 24 stations in the major water regions in China. Quartile analysis of seasonal runoff trends from 1960 to 2024 showed that absolute runoff trends (mm·10a^{-1}) exhibited distinct seasonal patterns across the major basins in China. Spring runoff shows the widest variation (–6.6 to 8.3 mm·10a^{-1}), with the maximum increase recorded at Yunjinghong Station in the Southwest Rivers Region and maximum decrease observed at Shijiao Station in the Pearl River Basin. Summer and autumn demonstrated predominantly decreasing trends, with median values of –1.67 and –1.44 mm·10 a^{-1}, respectively. Summer also exhibited greater variability, with trend rates ranging from 6.51 mm·10a^{-1} at Changmabu Station to –17.15 mm·10a^{-1} at Yunjinghong Station. Winter presented a contrasting pattern, with a median increase of 1.20 mm·10a^{-1}. The maximum decrease was observed at Guantai Station (Haihe River, –1.73 mm·10a^{-1}), whereas the maximum increase occurred at Zhuqi Station (Southeast Rivers Region, 7.83 mm·10a^{-1}).

URI trends (%·10a^{-1}) provided enhanced sensitivity for identifying hydrological changes. In spring, the median trend was negative (–0.424%·10a^{-1}), with extremes observed at Yunjinghong (2.22%·10a^{-1}) and Shixiali (–10.06%·10a^{-1}). Summer exhibited the strongest variability (median –1.61%·10a^{-1}), with values ranging from 6.68%·10a^{-1} at Changmabu Station to –13.84%·10a^{-1} at Guantai Station. Autumn trends (median –1.07%·10a^{-1}) peak at Zhimenda Station (2.71%·10a^{-1}) and Guantai Station (–8.52%·10a^{-1}), whereas winter shows minimal variability, with extremes of 1.14%·10a^{-1} at

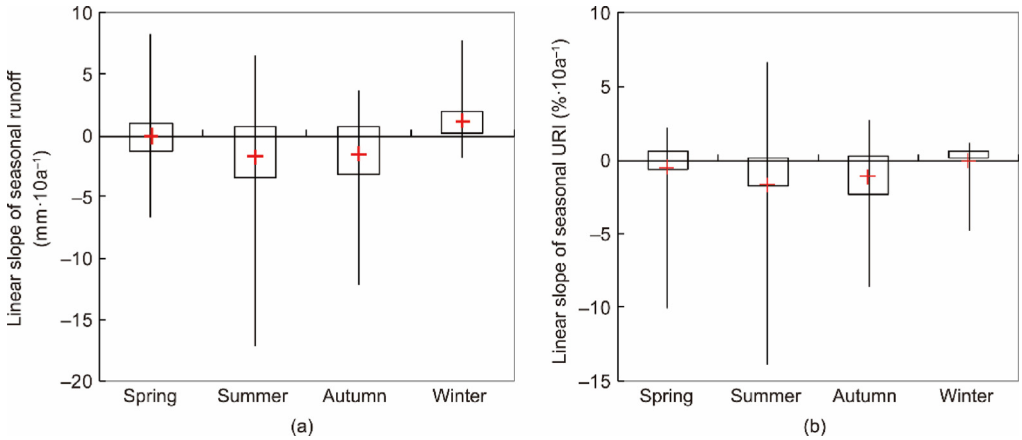


Fig. 5. Quartile plots of linear trend rates for (a) seasonal runoff and (b) seasonal unit-normalized runoff based on 24 hydrological stations across China's major water regions.

Tieling Station and $-4.75\%\cdot10a^{-1}$ at Shixiali Station. Notably, the unit-normalized metric amplified trend signals, particularly in water-stressed regions (e.g., Haihe River Basin), and verified that summer was the most hydrologically dynamic season.

3.4. Phase-based evolution characteristics of runoff since the 21st century

China has experienced rapid economic development since the beginning of the 21st century. Despite implementing stringent water resource management policies aimed at improving water-use efficiency and promoting a water-conserving society, water consumption in industrial and agricultural sectors remained high [37]. Under global warming, western China demonstrated a trend toward increased precipitation, while northern China experienced an initial decrease and a subsequent gradual increase in precipitation. These environmental changes contributed to the emerging patterns of runoff in the major rivers in China.

Table 2 provides a statistical summary of the measured runoff volumes across various phases since the early 21st century, along with their relative changes compared with the baseline period (1960–2000). Table 2 illustrates interdecadal changes in runoff across China: Since the early 21st century, runoff has exhibited distinct decadal shifts. From 2001 to 2010, severe drying occurred in northern China, particularly in the Haihe River Basin, accompanied by significant wetting in the Northwest Rivers Region and mixed trends in the southern basins. From 2011 to 2020, a moderate recovery was observed in northeastern China, while increases in the northwest intensified. In addition, the southern basins shifted toward drying conditions. The most recent phase (2021–2024) was characterized by increased spatial divergence, with accelerated increases in the northeast and northwest, ongoing water shortages in northern China, and expanding deficits across the southern regions.

Regional runoff evolution over the decades: Northern China shifted from a severe decline to partial recovery. Notably, northeastern China showed a notable rebound after 2020, while deficits in the Haihe River Basin persisted. Western China experienced sustained and intensified wetting, particularly in the northwest, whereas certain regions in the southwest continued to decline. Southern China shifted from mixed patterns to widespread reductions, with the Huaihe River Basin experiencing a reversal from increasing to decreasing trends, while the Yangtze and Pearl River basins consistently exhibited drier conditions in recent years.

Transformation of spatiotemporal runoff patterns across China: The runoff regime in China experienced substantial spatiotemporal changes, shifting from an initial pattern of "northern depletion and southern stability" to a more complex regime of "partial northern recovery and emerging southern desiccation," accompanied by widening regional disparities. Since the onset of the 21st century, the northwest and northeast regions emerged as key regions for runoff amplification, while large parts of North China continued to experience chronic water scarcity. Concurrently, southern China, previously characterized by hydrological stability, demonstrated widespread runoff reduction. This redistribution reflects a deepening imbalance in water resources under the combined pressures of climate change and anthropogenic activities. The limited northern gains and intensifying southern deficits underscore the urgent need for regionally differentiated and adaptive water governance.

Climate change and intensive human activities significantly affected total river runoff and altered intra-annual runoff distribution patterns. Fig. 6 presents the changes in seasonal runoff distribution across various periods since 2000, relative to the 1960–2000 baseline, for ten representative hydrological stations in ten major water resource regions in China.

Fig. 6 shows that monthly runoff in the northern rivers has generally increased since 2001, although it has consistently remained below baseline levels in most years. Stations, including Harbin (Songhua River), Tieling (Liaohe River), Huayuankou (Yellow River), and Shixiali (Haihe River), consistently recorded lower monthly runoff from 2001 to 2010. Although some recovery occurred between 2011 and 2020, the values predominantly remained below the baseline. From 2021 to 2024, Harbin and Tieling consistently exceeded the baseline runoff in most months, whereas Shixiali and Huayuankou surpassed the baseline levels only sporadically. This gradual recovery may be attributed to increasing human water use and rising precipitation in recent decades [38,39].

Runoff regimes in the southern rivers exhibited clear intra-annual redistributions. At Datong (Yangtze River), Wujiadu (Huaihe River), and Wuzhou (Pearl River), the monthly runoff during December–March of the following year typically exceeded the baseline across all three periods. Values from April to June were broadly comparable to the baseline, while runoff from July to November was slightly lower. In contrast, Zhuqi Station (Southeast Rivers Region) exhibited fluctuations closely aligning with the baseline. The shift toward reduced flood-season runoff and increased dry-season runoff is closely associated with reservoir regulation, while runoff variations in the Southeast Rivers Region reflect stronger climatic influences, particularly precipitation changes.

Table 2
Statistical overview of measured runoff volumes in different phases since the 21st century, along with their relative changes compared to the baseline period (1960–2000).

Region	Station No.	Station name	Annual runoff (mm)				Runoff change relative to baseline of 1960–2020 (%)			Major water region
			1960–2000	2001–2010	2011–2020	2021–2024	2001–2010	2011–2020	2021–2024	
Northern China	1	Harbin	108.54	70.09	102.44	162.20	−35.43	−5.62	49.44	Songhua River
	2	Jiangqiao	129.08	81.55	141.39	156.93	−36.82	9.54	21.57	Songhua River
	3	Tieling	23.52	14.00	18.46	48.88	−40.50	−21.54	107.82	Liaohe River
	4	Zhangjiafen	55.74	22.10	25.03	51.89	−60.36	−55.09	−6.91	Haihe River
	5	Shixiali	16.60	2.54	4.68	13.10	−84.71	−71.84	−21.07	Haihe River
	6	Guantai	47.39	14.55	13.53	61.47	−69.30	−71.44	29.72	Haihe River
	7	Huayuankou	52.59	33.18	44.45	50.74	−36.90	−15.48	−3.52	Yellow River
	8	Toudaoguai	60.06	41.24	61.37	55.14	−31.34	2.17	−8.21	Yellow River
Western China	9	Tangnaihai	170.40	146.23	186.21	169.65	−14.18	9.28	−0.44	Yellow River
	10	Kaqun	143.06	150.40	158.59	174.89	5.13	10.86	22.25	Northwest Rivers
	11	Changmabu	80.59	121.06	131.00	128.41	50.22	62.55	59.33	Northwest Rivers
	12	Zhengyixia	27.73	29.17	37.11	30.64	5.18	33.81	10.47	Northwest Rivers
	13	Changdu	276.39	268.68	343.20	341.51	−2.79	24.17	23.56	Southwest Rivers
	14	Yunjinghong	401.51	352.97	314.99	308.62	−12.09	−21.55	−23.14	Southwest Rivers
	15	Nuxia	310.95	323.72	326.55	296.53	4.10	5.02	−4.64	Southwest Rivers
	16	Zhimenda	90.52	110.10	119.81	143.33	21.62	32.35	58.34	Yangtze River
Southern China	17	Yichang	433.74	395.62	432.43	369.28	−8.79	−0.30	−14.86	Yangtze River
	18	Datong	525.97	499.33	530.40	481.95	−5.07	0.84	−8.37	Yangtze River
	19	Xixian	363.92	384.84	253.63	305.19	5.75	−30.31	−16.14	Huaihe River
	20	Wangjiaba	272.83	323.85	205.85	273.77	18.70	−24.55	0.35	Huaihe River
	21	Wujiadu	211.28	246.74	173.28	203.45	16.79	−17.99	−3.71	Huaihe River
	22	Zhuqi	963.70	926.47	1001.15	876.30	−3.86	3.89	−9.07	Southeast Rivers
	23	Wuzhou	634.13	573.13	606.73	540.87	−9.62	−4.32	−14.71	Pearl River
	24	Shijiao	1104.85	949.35	1022.57	1119.61	−14.07	−7.45	1.34	Pearl River

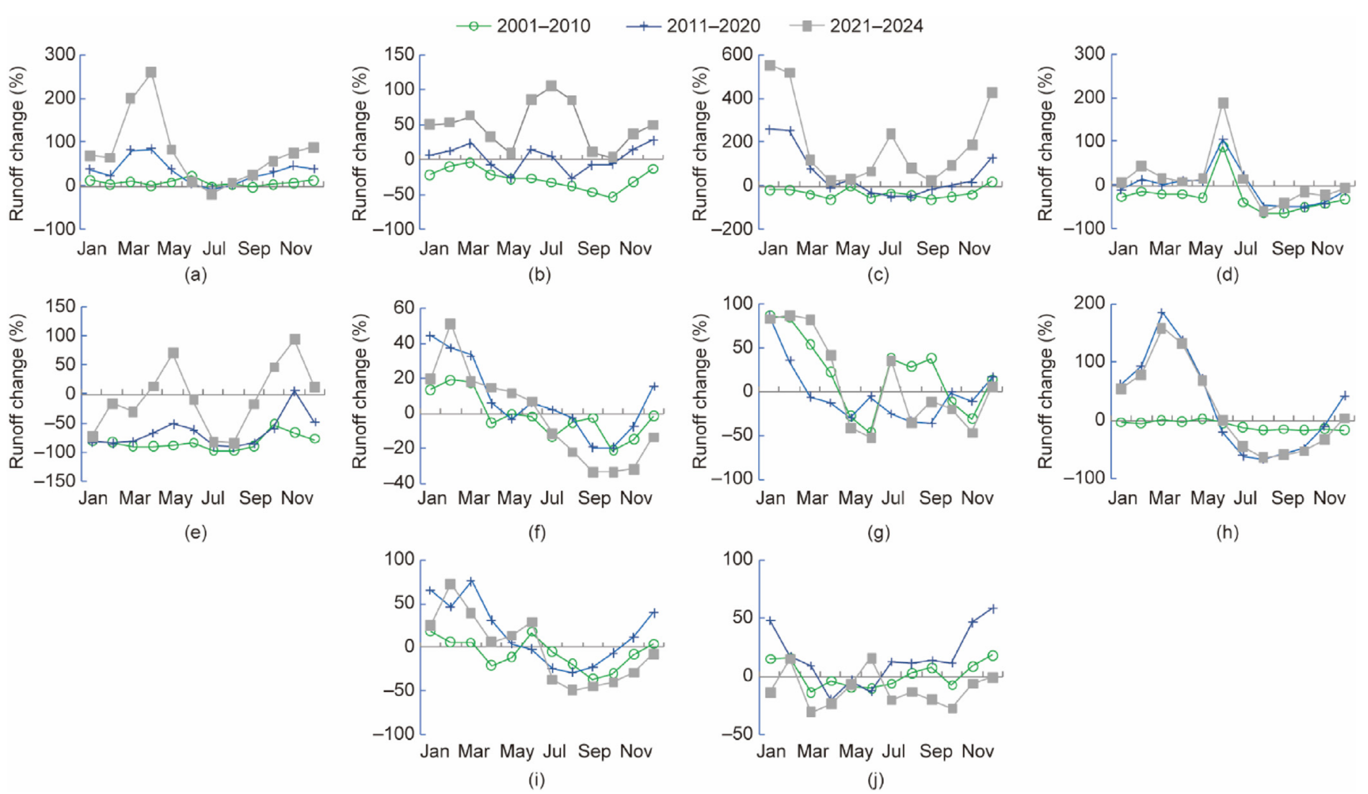


Fig. 6. Relative change in intra-annual runoff distribution patterns across different periods since 2001 compared to the 1960–2000 baseline for 10 representative stations in the ten major water regions. (a) Kaqun, (b) Harbin, (c) Tieling, (d) Huayuankou, (e) Shixiali, (f) Datong, (g) Wujiadu, (h) Yunjinghong, (i) Wuzhou, and (j) Zhuqi.

In western China, Kaqun Station (Northwest Rivers Region) exhibited consistently higher monthly runoff throughout the 21st century, with notable increases observed after 2021. Notably, runoff exceeded baseline levels by more than 20% in March and April. In contrast, Yunjinghong Station (Lancang River) showed mildly reduced runoff from 2001 to 2010, followed by pronounced dry-season increases in subsequent periods (January–May increases of > 50%, with March–April exceeding 130%). This was accompanied by a runoff decline in the wet season (July–October decreases of ~50%). The runoff shift in the northwest is consistent with the regional warm–wet trend under global warming, whereas alterations in the southwest are attributed to both precipitation deficits and water project operations [40].

3.5. Discussion

3.5.1. Trend detection methodology

Here, we employed both the M–K trend test and linear regression to assess annual and seasonal runoff trends. Comparative analysis indicated that the two methods generally yielded consistent results, although discrepancies were observed in specific cases. For example, summer runoff at Harbin Station showed a non-significant decreasing trend according to the M–K test (Z_s = –0.26) while also demonstrating a positive linear trend rate (0.79 mm·10a^{-1}). This divergence arises from differences in methodological principles: The nonparametric M–K test evaluates overall rank-based trends and demonstrates robustness to outliers [34], while linear regression quantifies trend magnitude through least-squares fitting and is susceptible to extreme values [35]. At Harbin Station, three exceptional flood events (1998, 2013, and 2021), each surpassing 2.5 times the mean summer runoff, disproportionately affected the linear regression estimate.

Importantly, both methods consistently identified statistically significant trends, with discrepancies mainly arising in relatively stable sequences. Therefore, the two approaches provide complementary diagnostic values: The M–K test reliably indicates the overall trend direction, while linear trend rates reflect the magnitude of changes potentially influenced by extreme events.

3.5.2. Runoff metric evaluation

Dual analyses using absolute and URIs demonstrated their differential sensitivities. Across the 24 stations, all cases with statistically significant unit-normalized index trends showed complete consistency between the two methods, whereas trends in absolute runoff exhibited methodological discrepancies. For example, Shijiao Station exhibited the largest spring runoff decline (–6.62 mm ·10a^{-1}), whereas Zhuqi Station showed the largest autumn increase (3.77 mm·10a^{-1}). However, neither trend reached statistical significance based on the M–K test (Z_s = –1.17 and 0.88, respectively). This finding highlights a critical limitation: Absolute linear trend rates conflate the trend magnitude with the baseline flow conditions, thereby complicating cross-basin comparisons [30,32]. In contrast, the unit-normalized index (mean = 1) effectively resolves this issue by decoupling the trend intensity from the absolute runoff values, enabling robust inter-basin comparisons while maintaining essential trend characteristics. Overall, the results demonstrate its superior utility for comparative assessment of hydrological changes across diverse climatic zones.

3.5.3. Transformation patterns of runoff evolution in the most recent decade

Zhang et al. [30] analyzed runoff characteristics at ten representative stations across seven major rivers in China using data collected prior to 2018 and reported declining annual runoff trends at all stations, except for Datong on the Yangtze River. Their findings revealed insignificant changes in the southern basins, while statistically significant decreases were observed in the northern river systems. Although our findings are generally consistent with these conclusions, novel hydrological patterns have emerged in the Songhua and Liaohe River basins in northeastern China. Zhang et al. [30] reported significant declines at Harbin (Songhua River, Z_s = –3.11) and Tieling (Liaohe River, Z_s = –2.89) stations based on the pre-2018 data series. However, after incorporating recent observations (2019–2024), we found the following: ① The trend at Harbin Station became non-significantly decreasing, and ② Tieling Station shifted to a non-significant increasing trend, reflecting substantial runoff increases after 2018 (Fig. 2). Statistical analysis showed that the mean annual runoff from 2019 to 2024 at Harbin (152.7 mm) and Tieling (40.2 mm) stations exceeded the historical averages by 45.4% and 75.6%, respectively. Fig. 6 further compares the runoff anomalies from 2000 to 2018 and 2019 to 2024 relative to the pre-2000 baselines, highlighting recent hydrological regime shifts.

Specifically, Fig. 7 identifies three distinct hydrological regimes across various temporal scales. The 2000–2018 period is characterized by a distinct "west-increase/south-stable/north-decrease" spatial pattern. Runoff in the upper Yangtze River and rivers in the northwest and southwest (excluding Yunjinghong) increased by 8%–55% relative to the pre-2000 baseline. In contrast, runoff decreased by 10%–83% in the Yellow, Haihe, Liaohe, and Songhua River basins, whereas relatively stable conditions were observed in the Yangtze, Huaihe, and Pearl River basins (within ±10%). From 2019 to 2024, the western basins maintained positive anomalies (2%–62%). Notably, remarkable hydrological reversals emerged north of the Yangtze River: the Yellow, Liaohe, and Songhua rivers shifted from previous deficits to surpluses of 4%–68%; the reduction rate in the Haihe River Basin moderated from 60%–83% to 14%–30%; and the Huaihe River Basin uniquely developed deficits of 5%–21%, accompanied by exceptional reduction surges of 9%–17% in the eastern regions. Importantly, the 65-year perspective (1960–2024) confirms the persistence of the fundamental "south-abundant/north-deficient" paradigm in China. Although the northern basins have experienced a recent runoff recovery of more than 30%, this finding underscores the resilience of the macro-scale hydrological organization to decadal fluctuations.

3.5.4. Drivers of runoff variations: Climate change and human activities

Changes in runoff and its intra-annual distribution are closely linked to global climate change and human activities [41–43]. Climate change alters precipitation regimes and enhances evaporation, thereby directly influencing the runoff volume and timing. Human activities, including dam construction, irrigation water withdrawal, and urbanization, can substantially modify natural river flow regimes. These combined effects threaten water availability and pose major challenges to water security and ecosystem sustainability. Therefore, understanding the drivers of runoff variations is critical for formulating adaptive strategies for water resource management.

China has experienced pronounced warming in recent decades. From 1961 to 2024, the national mean temperature increased at an accelerated rate of 0.3 °C per decade. Between 2015 and 2024, temperatures averaged 0.63 °C above the 1991–2020 mean and 1.54 °C higher than the 1961–1990 baseline. Spatially, warming occurred broadly, with more pronounced increases observed in the northern and western regions than in the southern and eastern regions. The Qinghai–Xizang Plateau experienced the most rapid warming (0.36 °C per decade), whereas South and Southwest China demonstrated comparatively moderate increases. The national annual precipitation has also shown a long-term upward trend since 1961, increasing by 6.0 mm per decade, despite substantial decadal variability. The 1990s were relatively wet, followed by a drier phase in the early 2000s. Since 2012, precipitation has generally remained above average for the 1991–2020 period. Regionally, significant wetting occurred over the Qinghai–Xizang Plateau, whereas a drying trend was evident in Southwest China. Since the early 21st century, northern river basins, including the Songhua, Liaohe, Haihe, and Yellow River basins, have generally experienced increased wetness, whereas southern basins have displayed greater interannual variability [38]. In recent years

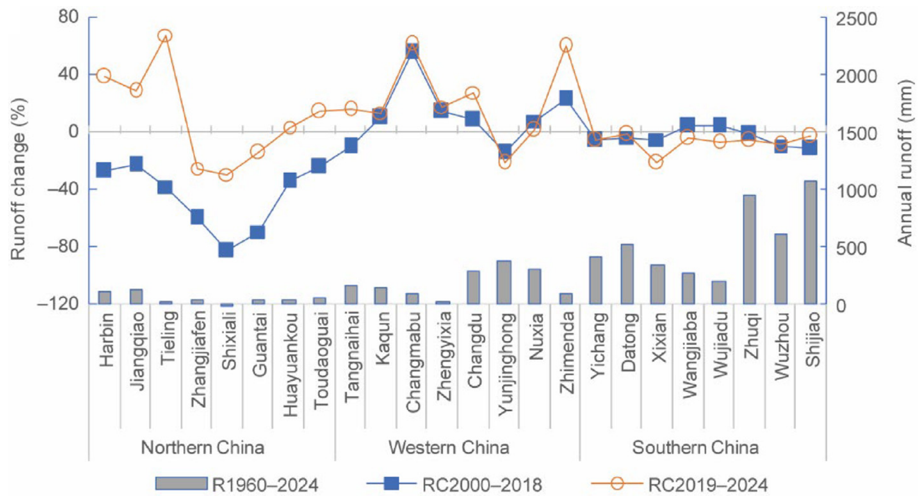


Fig. 7. Comparative analysis of mean annual runoff at representative hydrological stations across major water regions in China: runoff in 1960–2024 (gray bars, R1960–2024) versus relative runoff changes in 2000–2018 (blue solid line with solid squares, RC2000–2018) and 2019–2024 (yellow solid line with hollow circles, RC2019–2024) periods compared to the pre-2000 mean.

(2015–2024), against a backdrop of sustained warming, major river basins across China have undergone widespread temperature increases and divergent precipitation changes: Northern and western basins received more moisture, whereas southern and eastern regions experienced greater rainfall variability and more frequent extreme hydroclimatic events, thereby reflecting growing climate instability.

By 2024, China constructed 94 608 reservoirs with a total storage capacity of 1.0062×10^{12} m^3. This extensive infrastructure supports an irrigated area of 8.1743×10^5 km^2, including 7.2432×10^5 km^2 of cultivated land, accounting for 56.3% of the national total cultivated area [37]. Total water consumption in 2024 reached 5.9280×10^{11} m^3, indicating an increase of approximately 4.3×10^{10} m^3 since 2000. Agriculture remained the largest water user, accounting for 3.6484×10^{11} m^3, indicative of substantial irrigation demand. Industrial and domestic water uses followed at 9.710×10^{10} and 9.268×10^{10} m^3, respectively, while environmental and ecological water allocations totaled 3.818×10^{10} m^3. These data underscore a policy shift toward balancing human demand with ecosystem protection. Regional disparities in water consumption were also evident. Declines of 3%–7% occurred in the Songhua River, Liaohe River, Haihe River, Pearl River, and Southeast Rivers regions. In contrast, the Huaihe River, Yangtze River, Southwest Rivers, and Northwest Rivers regions exhibited increases exceeding 6%, with the Yangtze River Basin showing the largest increase at nearly 20% [39,44].

3.5.5. Attribution of runoff change for major river basins in China

Here, we revealed that the measured runoff predominantly increased in western China, whereas the Yellow, Haihe, Huaihe, and Pearl River basins experienced declining runoff trends. Seasonally, runoff decreased in summer and autumn but increased in winter and spring. Understanding the drivers of these changes is essential for formulating effective climate responses and improving water resource management in the context of global climate change and regional human activity [45].

Western China, characterized by its high elevations and low temperatures, featured extensive glaciers and snow cover [46]. The region experienced a notable increase in temperature and precipitation due to global warming. Over the past 60 years, the Qinghai–Xizang Plateau and northwestern China experienced temperature increases of 0.36 °C per decade and precipitation increases of 6.8 mm per decade [38]. Increased precipitation, along with accelerated ice and snowmelt driven by rising temperatures, represents the primary mechanism underlying runoff increases in these regions (e.g., Kaqun and Zhengyixia stations), especially during winter and spring [26,29,47].

In contrast to the overall increasing trend in western China, the measured runoff at the Yunjinghong Station on the Lancang River declined, particularly over the past two decades. A pronounced shift toward "reduced wet-season flow and increased dry-season flow" occurred in its intra-annual distribution. This pattern is consistent with the regional decline in precipitation in southwestern China (-10.7 $mm \cdot a^{-1}$) over recent decades. Moreover, major hydropower station construction in the Lancang River Basin, including Jinghong, Xiaowan, and Nuozhadu, substantially altered the natural flow regime.[‡] Previous studies indicated that from 2014 to 2020, reservoir operations reduced flood-season (June–November) runoff by 44.3% and increased non-flood-season (December–May of the following year) runoff by 134.3% [40]. These regulatory effects that attenuate flood peaks and supplement dry-season flows improved flood control and strengthened water supply security in the middle and lower Mekong River.

The Yellow and Haihe River basins are among the most densely populated and highly developed industrial and agricultural regions in China; however, these areas suffer from acute water scarcity. Their multiyear mean water resources were 5.84×10^{10} and 1.71×10^{10} m^3, respectively. Rapid socioeconomic development substantially increased the water demand. By 2024, water use in these basins reached 3.91×10^{10} and 3.81×10^{10} m^3, respectively [39]. Despite increased precipitation in North China over the past decade, intensive human activities remain the primary driver of significant runoff reductions in both basins. Human activities account for more than 60% of the runoff reduction in the Yellow River [21,48] and more than 70% in the Haihe River [19,43].

The Yangtze River, the largest river in China, has a basin area exceeding 1.8 million km^2, length of 6300 km, and longitudinal span of 28°, leading to pronounced climatic and hydrological diversity. Under changing environmental conditions, runoff at Zhimenda Station in the upper reaches increased significantly, whereas stations in the middle and lower reaches (Yichang and Datong) showed slightly decreasing trends. The area upstream of Zhimenda, situated on the Qinghai–Xizang Plateau, experienced

‡ https://opendevelopmentmekong.net/topics/hydropower/.

warmer and wetter conditions, similar to those in northwestern China, contributing to increased runoff. The Yangtze River Economic Belt, especially in its middle and lower reaches, constitutes a core region of economic development in China. In 2024, industrial and agricultural water use in the basin reached 20.32×10^{10} and 5.86×10^{10} m^3, respectively. Although socioeconomic development and agricultural water use influenced runoff at Yichang and Datong, the abundant water resources of the Yangtze Basin (multiyear mean surface water availability of 9.776×10^{11} m^3) mitigated the overall impacts of human activities. Therefore, the runoff variability in these reaches is primarily controlled by precipitation fluctuations [49,50].

The Huaihe River, Pearl River, and Southeast Rivers regions exhibited greater socioeconomic development and generally possess more abundant water resources than the Yellow and Haihe river basins. The multiyear mean surface water resources were 6.89×10^{10}, 4.740×10^{11}, and 2.683×10^{11} m^3, respectively. However, high water demand in these regions, with water use in 2025 reaching 5.99×10^{10}, 7.72×10^{10}, and 2.93×10^{10} m^3, respectively, contributed to varying degrees of runoff reduction. Similar to the Yangtze River Basin, climate change remains the dominant factor controlling runoff variability in these southern basins [17,23].

Since the beginning of the 21st century, winter and spring runoff has generally increased across most of the major rivers and regions in China, whereas flood-season runoff in the southern rivers has declined to some extent. Since the 1970s, China has implemented numerous water conservancy projects. Operating these infrastructures reduces flood peaks and enhances dry-season flows, resulting in decreased flood-season runoff (mainly in summer and autumn) and increased non-flood-season runoff (mainly in winter and spring). This accounts for the increased winter and spring runoff observed in most southern basins [51–53]. In western China, particularly in the northwest, increased ice and snowmelt due to rising temperatures are the major drivers of higher winter and spring runoff [29,47].

Global climate change and intensified human activities both exert significant influences on streamflow. This study systematically analyzes runoff trends and preliminarily identifies potential drivers of the observed changes. However, a key limitation of this study is that the relative contributions of climate change versus human activities to runoff alteration are not quantitatively disentangled, which constrains ability to support climate adaptation and evidence-based watershed management directly. Therefore, future research should prioritize the development of robust quantitative methods to attribute hydrological changes to their climatic and anthropogenic causes, thereby facilitating sustainable water resource management under changing environmental conditions.

4. Summary and conclusions

By thoroughly analyzing the spatiotemporal evolution of runoff across major river basins in China, several major conclusions can be drawn regarding runoff change trends and their spatial change patterns.

From 1960 to 2024, China exhibited a distinct east–west divergence in runoff patterns. Most western stations showed increasing annual runoff, with significant increases at Kaqun (Yarkant River), Changmabu (Changma River), Zhimenda (Yangtze River headwaters), and Changdu (Lancang River) stations. These increases may be attributed to elevated precipitation and enhanced snow and glacial melt driven by rising temperatures. Conversely, all monitored stations in the Yellow–Huaihe–Haihe and Pearl River basins showed decreasing trends, with significant reductions observed at the Toudaoguai and Huayuankou (Yellow River) stations; Zhangjiafen, Guantai, and Shixiali (Haihe River) stations; and Yunjinghong Station (Lancang River). These trends may be attributed to intensive human activities in these regions.

Annual runoff trend rates revealed extreme variations: larger decreases at Yunjinghong (-17.94 mm·$10a^{-1}$), Guantai (Haihe River), and Xixian (Huaihe River) stations, whereas Changmabu Station showed the sole major increase (> 10 mm·$10a^{-1}$). URIs indicated significant declines at Guantai (-30.5%·$10a^{-1}$) and Shixiali (-34.01%·$10a^{-1}$) stations. Notably, although Xixian (Huaihe River) and Wuzhou and Shijiao (Pearl River Basin) stations exhibited large absolute runoff trend rates, they lacked statistical significance. In contrast, Shixiali (-4.21 mm·$10a^{-1}$) and Huayuankou (-4.44 mm·$10a^{-1}$) demonstrated significant declines despite smaller magnitudes. This observation confirms that unit-normalized indices more effectively reflect variation intensity across basins.

The Northwest Rivers (Kaqun and Changmabu) and Qinghai–Xizang Plateau (Changdu and Zhimenda) demonstrated perennial increasing trends across all seasons, with Changmabu and Zhimenda reaching full significance. Conversely, all Haihe River Basin stations and the Huayuankou (Yellow River) Station showed consistent decreases. Seasonal patterns included the following: spring variations (-6.6 to 8.3 mm·$10a^{-1}$); predominant summer/autumn decreases (medians: -1.67/-1.44 mm·$10a^{-1}$); and widespread winter increases (median: 1.20 mm·$10a^{-1}$). Unit-normalized rates showed maximum summer decline at Guantai (-13.84%·$10a^{-1}$) and the most pronounced winter changes at Shixiali (-4.75%·$10a^{-1}$).

This spatial variation in long term runoff suggests that most western regions should capitalize on increased runoff to facilitate economic development and ecological restoration, whereas eastern regions require enhanced water resources management to alleviate the negative consequences of reduced runoff.

Since the early 21st century, runoff has substantially increased in northwestern and northeastern China, whereas chronic water scarcity has persisted across much of the northern region. Concurrently, historically stable southern China experienced a clear decrease in runoff. These shifts reflect a broader transformation in the runoff regime in China, transitioning from the earlier pattern of "northern depletion and southern stability" to a new phase characterized by "partial northern recovery and emerging southern desiccation." This spatial redistribution highlights a growing imbalance in water resources due to the combined effects of climate change and human activities, highlighting the urgent need for regionally differentiated adaptive management strategies.

CRediT authorship contribution statement

Yueyang Wang: Writing – original draft, Investigation, Formal analysis, Data curation. **Jianyun Zhang:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Zhenxin Bao:** Supervision, Software, Resources, Funding acquisition. **Junliang Jin:** Validation, Software, Investigation, Data curation. **Guoqing Wang:** Writing – review & editing, Visualization, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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