

Article

Identification and Analysis of Compound Extreme Climate Events in the Huangshui River Basin, 1960–2022

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Abstract

With the increasing volatility and extremity of global climate change, the frequency, intensity, and associated impacts of compound extreme climate events have escalated substantially. To investigate the temporal trends and characteristics of such events, we identified compound extreme climate events in the Huangshui River Basin, located in the northeastern Qinghai–Tibet Plateau, using daily mean temperature and precipitation records from eight meteorological stations. Compound warm–wet, warm–dry, cold–wet, and cold–dry events from 1960 to 2022 were detected based on cumulative distribution functions, and their long-term trends and intensity structures were examined. The results show that: (1) Warm–dry events dominate the basin, with an average annual frequency of 32.84 days per year, occurring frequently across all seasons; cold–dry events rank second (22.38 days per year) and are particularly frequent in winter. (2) Warm–dry events are highly concentrated in the river valley region (e.g., Minhe station), whereas cold–dry and warm–wet events mainly occur in the low-mountain areas (e.g., Huangyuan and Datong). (3) From 1960 to 2022, warm–dry and warm–wet events exhibit a highly significant increasing trend ($p < 0.001$), cold–dry events show a significant decreasing trend, and cold–wet events display no statistically significant trend. (4) In terms of intensity, all four types of compound events—warm–wet, warm–dry, cold–wet, and cold–dry—are dominated by weak to moderate grades. Overall, the basin is undergoing a compound-risk transition from historically “cold–dry dominated” conditions toward a regime characterized by “warm–dry predominance with emerging warm–wet events.” By identifying compound extreme climate events and analyzing their spatiotemporal variability and intensity characteristics, this study provides scientific support for disaster prevention, daily management, and risk mitigation in climate-sensitive regions. It also offers a useful reference for developing strategies to address compound extreme events induced by climate change and for implementing regional risk-prevention measures.

Keywords: compound extreme weather events; climate change; Huangshui River basin; trend of change; intensity



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1. Introduction

Compound extreme climate events refer to extreme events arising from the intertwined occurrence of multiple climatic drivers and associated hazards. Owing to their complexity

and high risk, they have received special attention in the IPCC Sixth Assessment Report (AR6). Analyses in the Working Group I contribution to AR6 explicitly point out that, compared with single-factor extreme events, compound extreme climate events can cause much greater impacts on both the environment and human society [1–4]. In this study, compound extreme climate events are classified according to combinations of meteorological and hydrological variables into four categories: warm–wet (WW), warm–dry (WD), cold–wet (CW), and cold–dry (CD) events [5,6].

Compound extreme climate events arise from complex formation mechanisms and are jointly influenced by large-scale atmospheric circulation, multi-scale climate variability, and human activities. This complexity has motivated extensive research on multivariate compound events by scholars worldwide. In terms of linking compound extremes with system-level impacts, previous studies have shown that extreme events may trigger critical transitions in Earth system components, such as rainforest degradation and marine heatwaves [7], thereby providing a valuable perspective for developing identification metrics for compound extreme events from an Earth system viewpoint. Other studies have assessed the spatiotemporal characteristics of lethal heat stress and extreme cold events in the north-central United States, as well as their disproportionate impacts on socially vulnerable populations, revealing the high degree of complexity with which compound extreme events operate across both climatic and social systems [8].

In the identification and characterization of compound extreme climate events, previous studies have systematically examined the historical evolution and future projections of compound drought–heatwave and heatwave–extreme precipitation events across China [9] and have further explored the spatiotemporal characteristics and driving mechanisms of compound temperature–precipitation extremes in northwestern China [10]. These efforts provide essential methodological support for identifying compound extremes and analyzing their trends at regional scales. Related review studies have synthesized the variability and physical mechanisms of high-temperature, drought, and associated compound events [11] and have mapped the national-scale spatiotemporal distribution patterns of extreme climate events [12], thereby enhancing the systematic understanding of compound extreme climate event identification and analysis. Further research has emphasized that compound events arise from the concurrent influence of multiple climatic drivers and hazard-inducing factors and that their impacts often far exceed those of single-factor extremes. As such, they represent a frontier scientific issue and a major security challenge under ongoing climate change. Elucidating their occurrence patterns is thus critical for improving adaptation strategies and risk management [13].

With the intensification of the “warming–wetting” trend over the Tibetan Plateau, regional extreme weather events and natural disasters have become increasingly pronounced. In particular, the rising frequency of compound extreme climate events poses severe challenges to local production, livelihoods, and ecosystem stability. The Huangshui River Basin, situated at the transitional margin between the Tibetan Plateau and the arid region of northwestern China and at the western boundary of the East Asian monsoon, features highly heterogeneous and complex topography that gives rise to strong variability in both temperature and precipitation. As a primary tributary basin of the Yellow River, the Huangshui River Basin forms a critical ecological barrier safeguarding water and ecological security in the upper Yellow River. The region is also densely populated and economically developed, hosting nearly 60% of Qinghai Province’s population and more than 70% of its industrial and mining enterprises [14,15]. Consequently, investigating the spatial heterogeneity of compound extreme climate events under the plateau-wide warming–wetting background is of substantial scientific and practical importance.

Studies evaluating the warming–wetting process in this basin using multiple analytical methods have indicated that no significant wetting trend was observed prior to 1996; wetting signals began to emerge after 1996, and the variability of wetting intensity increased notably after 2002, albeit with considerable regional differences [16]. Additional research has examined extreme runoff responses, the ecological impacts of extreme precipitation and warming on the Tibetan Plateau [17,18], as well as the historical evolution and projections of individual or compound extreme events [19–26]. However, substantial research gaps remain regarding compound extreme events that arise from the combination of meteorological and hydrological variables [27–29].

Based on daily records from eight meteorological stations in the Huangshui River Basin from 1960 to 2022, this study identifies temperature–precipitation compound extreme climate events and analyzes their spatiotemporal differentiation, temporal trends, intensity characteristics, and influencing factors, with the aim of supporting disaster risk prevention and agricultural production and livelihood security in the basin.

2. Materials and Methods

2.1. Study Area

The Huangshui River Basin is located in the northeastern Tibetan Plateau ($100^{\circ}40'–103^{\circ}03'$ E, $36^{\circ}02'–37^{\circ}25'$ N). Known as the “mother river” of Qinghai Province, the Huangshui River originates in the Baohutu Mountains and flows through Haibei Tibetan Autonomous Prefecture, Xining City and Haidong City before ultimately discharging into the Yellow River. The basin covers an area of approximately 32,000 km². Topographically, it is high in the northwest and low in the southeast, with a feather-shaped drainage network. The region is characterized by an arid to semi-arid plateau continental climate. Strong plateau topographic effects (with elevations ranging from 1689 to 4860 m) lead to annual and diurnal temperature ranges that are markedly larger than those in low-elevation areas at similar latitudes.

Precipitation in the Huangshui River Basin is relatively scarce, with annual totals between 300 and 500 mm [30,31], and shows pronounced spatial and temporal heterogeneity. More than 70% of the annual precipitation occurs in summer [32], often in the form of short-duration, high-intensity rainfall. These events are closely associated with localized strong convective activity driven jointly by dynamic uplift over the plateau and thermal forcing linked to valley topography. The pronounced variability in temperature and precipitation, together with the basin’s unique geographical setting, provides favorable climatic and topographic conditions for the occurrence of compound extreme climate events involving combinations of high/low temperature and drought/wetness. (An overview of the study area is shown in Figure 1).

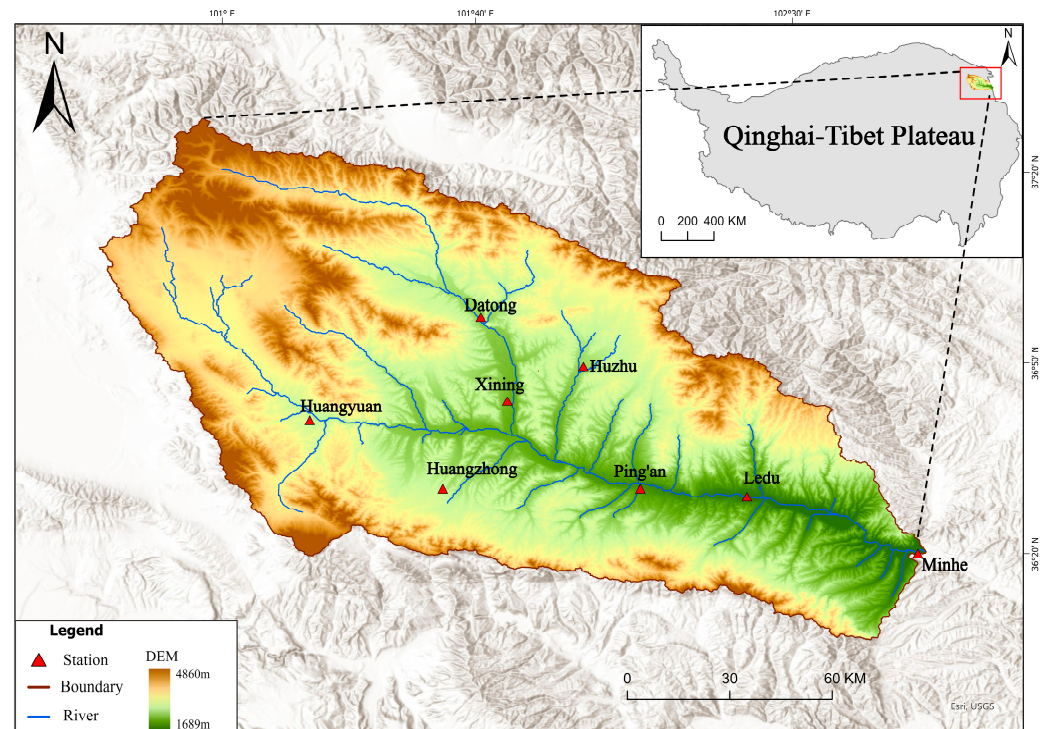


Figure 1. Regional Overview Map of the Huangshui River Basin Study Area. (As the study area is located on the Tibetan Plateau in China, the boundary of the Plateau is used as the background in this figure to show its geographical position within the country).

2.2. Data and Methods

2.2.1. Data Sources and Preprocessing

The meteorological data used in this study were obtained from the China National Meteorological Science Data Center (<http://data.cma.cn>, accessed on 13 November 2025), and the China National Tibetan Plateau Data Center, and consist of daily mean temperature and daily precipitation records from eight national basic meteorological stations in the Huangshui River Basin for the period from January 1960 to December 2022. Because temperature and precipitation exhibit pronounced spatial and temporal heterogeneity across the basin, the Huangshui River Basin was subdivided into four subregions according to the structure of the drainage network: the Beichuan River Basin, Xichuan River Basin, Nanchuan River Basin, and the middle-lower Huangshui River Basin. All meteorological series were subjected to homogeneity testing and treatment of isolated missing values, and outliers were corrected where necessary to ensure the completeness and reliability of the dataset.

2.2.2. Methodology

The Theil-Sen slope estimator is a non-parametric trend estimation method that calculates the slopes between all pairs of data points in a time series and takes the median of these slopes to obtain a robust estimate of the interannual trend rate (e.g., “change in event frequency per decade”). This method is highly robust to outliers and non-normal distributions, making it suitable for the analysis of meteorological indices [33].

The Mann-Kendall (MK) trend test is used to assess the statistical significance of the trends in the four types of extreme events. One of its advantages is that it does not require assumptions about the underlying data distribution and is insensitive to outliers, making it widely applied in climate and hydrological time-series analysis [34–36]. A trend is considered statistically significant at the 95% confidence level when the p -value is less than 0.05.

2.3. Extraction of Compound Extreme Climate Events

In this study, compound extreme climate events are identified using a percentile-based method derived from the cumulative distribution function (CDF), based on daily observations from all stations in the Huangshui River Basin during 1960–2022 (daily mean temperature and daily total precipitation). For each station and calendar month (“station-month” basis), fixed thresholds over the full period are calculated independently. The 10th ($T_{10\%}$) and 90th ($T_{90\%}$) percentiles of temperature are computed from all daily temperature samples at that station in that month, representing extreme low-temperature and extreme high-temperature conditions, respectively.

For precipitation, percentiles are likewise used to characterize dry and wet extremes. The threshold $P_{90\%}$ for defining extreme strong precipitation is estimated from rainy-day samples only ($P > 0$ mm), where days with $P \geq 0.1$ mm are defined as precipitation days, after excluding dry days ($P = 0$ mm). By contrast, the threshold $P_{10\%}$ for identifying dry conditions (dry extremes) is estimated from the complete set of daily precipitation records, including days with $P = 0$ mm, so that the dry threshold reflects both the long-term arid background of the study area and the dominance of no-precipitation days in the regional precipitation regime [37,38]. This asymmetric treatment is adopted because $P_{90\%}$ aims to capture the intensity of wet extremes (which would be underestimated if zero values were included), whereas $P_{10\%}$ must include dry days to meaningfully represent overall dry conditions.

Notably, due to the high frequency of zero-precipitation days in this arid basin, the $P_{10\%}$ threshold is uniformly 0 mm across all stations and all months; consequently, days classified as ‘dry extremes’ ($P \leq P_{10\%}$) correspond exclusively to rainless days ($P = 0$ mm).

Based on the joint exceedance or non-exceedance of these temperature and precipitation thresholds, four types of compound extreme climate events are defined: if daily temperature $\geq T_{90\%}$ and precipitation $\geq P_{90\%}$, the day is classified as a warm–wet (WW) event; if temperature $\geq T_{90\%}$ and precipitation $\leq P_{10\%}$, it is classified as a warm–dry (WD) event; if temperature $\leq T_{10\%}$ and precipitation $\geq P_{90\%}$, it is classified as a cold–wet (CW) event; and if temperature $\leq T_{10\%}$ and precipitation $\leq P_{10\%}$, it is classified as a cold–dry (CD) event. The detailed classification scheme is summarized in Table 1.

Table 1. Extraction of Compound Extreme Climate Events.

Event Type	Event Definition
Warm-Wet (WW)	$T \geq T_{90\%}$ and $P \geq P_{90\%}$
Warm-Dry (WD)	$T \geq T_{90\%}$ and $P \leq P_{10\%}$
Cold-Wet (CW)	$T \leq T_{10\%}$ and $P \geq P_{90\%}$
Cold-Dry (CD)	$T \leq T_{10\%}$ and $P \leq P_{10\%}$

T denotes daily mean temperature, P denotes daily precipitation, and the statistical unit is the number of days (d).

2.4. Intensity Classification of Compound Extreme Climate Events

To enable a quantitative assessment of compound extreme climate events, this study classifies the intensity of the four event types into three levels—strong, moderate, and weak—based on daily mean temperature and daily precipitation, following the principle of “synchronous enhancement of temperature and precipitation extremeness.” The specific classification criteria are summarized in Table 2. For temperature, the intensity thresholds are defined using a percentile gradient of $T_{90\%}/T_{10\%} \rightarrow T_{95\%}/T_{5\%} \rightarrow T_{99\%}/T_{1\%}$, while for precipitation, the corresponding thresholds follow $P_{90\%}/P_{10\%} \rightarrow P_{95\%}/P_{5\%} \rightarrow P_{99\%}/P_{1\%}$ [39].

Table 2. Classification standards for the intensity levels of four types of compound extreme weather events.

Event Type	Strength Grade	Classification Criteria
Warm-Wet (WW)	Strong grade	$T \geq T_{99\%}$ and $P \geq P_{99\%}$
	Moderate grade	$T \geq T_{95\%}$ and $P \geq P_{95\%}$
	Weak grade	$T \geq T_{90\%}$ and $P \geq P_{90\%}$
Warm-Dry (WD)	Strong grade	$T \geq T_{99\%}$ and $P \leq P_{1\%}$
	Moderate grade	$T \geq T_{95\%}$ and $P \leq P_{5\%}$
	Weak grade	$T \geq T_{90\%}$ and $P \leq P_{10\%}$
Cold-Wet (CW)	Strong grade	$T \leq T_{1\%}$ and $P \geq P_{99\%}$
	Moderate grade	$T \leq T_{5\%}$ and $P \geq P_{95\%}$
	Weak grade	$T \leq T_{10\%}$ and $P \geq P_{90\%}$
Cold-Dry (CD)	Strong grade	$T \leq T_{1\%}$ and $P \leq P_{1\%}$
	Moderate grade	$T \leq T_{5\%}$ and $P \leq P_{5\%}$
	Weak grade	$T \leq T_{10\%}$ and $P \leq P_{10\%}$

T denotes daily mean temperature, P denotes daily precipitation, and the statistical unit is the number of days (d).

3. Results

3.1. Interannual Trends of Temperature and Precipitation

Figure 2 shows the temporal evolution of temperature and precipitation in the Huangshui River Basin from 1960 to 2022. Based on daily mean temperature and precipitation records from eight meteorological stations (daily data points, totaling approximately 173,495 observations over 62 years), a linear regression model combined with the Mann–Kendall trend test reveals a statistically significant “warming and wetting” trend at the basin scale. The annual mean temperature exhibits a highly significant increasing trend (Mann–Kendall test: $p < 0.001$, $r = 0.91$), with relatively modest warming before 1980 followed by an accelerated increase thereafter. The shape of this trend is consistent with NOAA global surface temperature records, and the warming rate ($0.45\text{ }^{\circ}\text{C}$ per decade) is more than twice the global average [40,41], in line with the “amplifier” effect of warming over the Tibetan Plateau. The annual mean precipitation exhibits a statistically significant increasing trend from 1960 to 2022 (Mann–Kendall test: $p < 0.01$; Sen’s slope = 0.036 mm day^{-1} per decade), although the relatively low correlation coefficient ($r = 0.35$) indicates considerable interannual variability superimposed on this trend [42].

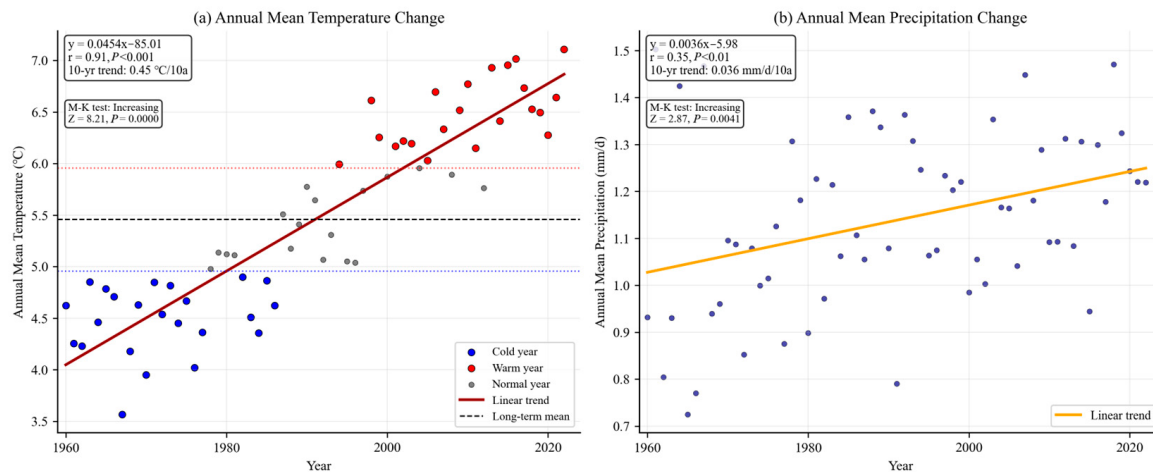


Figure 2. Temporal trends of annual mean temperature and precipitation in the Huangshui River Basin from 1960 to 2022. In panel (a), blue, red, and gray scatter points represent cold years (< -0.5 °C), warm years ($> +0.5$ °C), and normal years relative to the long-term mean temperature, respectively. The black dashed line represents the long-term mean value, while the blue and red dashed lines indicate the ± 0.5 °C thresholds. The solid dark red line shows the linear trend. The text box in the upper left corner includes the regression equation, the correlation coefficient (r), significance (p -value), and the 10-year rate of change, along with the Mann–Kendall test results. Panel (b) displays the annual mean precipitation (units: mm/d) in a similar layout, with the orange solid line representing the linear trend.

3.2. Analysis of the Annual Distribution Frequency of Compound Extreme Climate Events

3.2.1. Regional Analysis

Based on the long-term averages of compound extreme events from 1960 to 2022, the four event types exhibit pronounced regional spatial differentiation across the Huangshui River Basin.

As shown in Figure 3, at the individual-station scale, warm–wet (WW) events occur most frequently at Huangyuan and Datong; warm–dry (WD) events are most common at Ledu and Minhe; cold–wet (CW) events show high frequencies at Xining, Huangzhong, Ping’an, and Minhe; while cold–dry (CD) events occur most frequently at Huangyuan and Huzhu. Among these stations, Ledu (1980 m) and Minhe (1819 m) are the only two valley stations in the basin, whereas all other stations are located in the low-mountain zone at elevations ranging from 2315 m to 2677 m.

Figure 4 presents the annual mean frequency of compound extreme climate events for each sub-basin and for the entire Huangshui River Basin. These values are calculated as the ratio of the total number of event days recorded at all stations within the region to the number of valid observation years, following the same statistical logic used for individual-station frequencies. As shown in Figure 4, warm–dry (WD) events (32.84 d a^{-1}) dominate the entire basin, followed by cold–dry (CD) events (22.38 d a^{-1}), whereas cold–wet (CW, 2.08 d a^{-1}) and warm–wet (WW, 0.38 d a^{-1}) events are extremely rare.

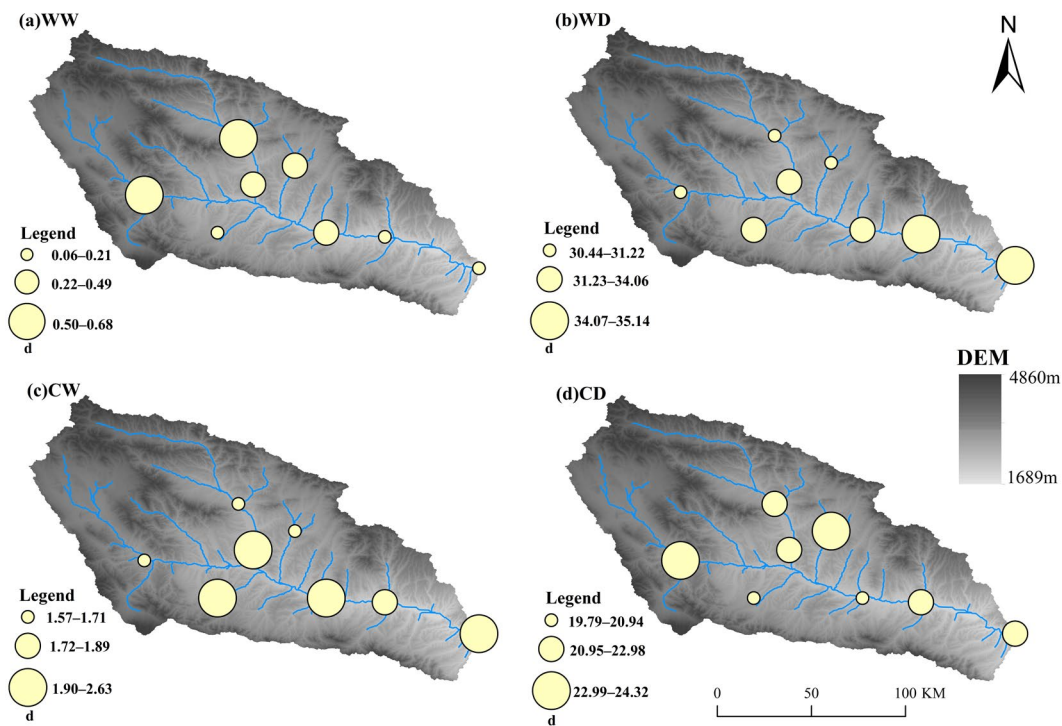


Figure 3. Annual mean frequency distribution of the four types of compound extreme climate events at individual stations in the Huangshui River Basin from 1960 to 2022 (units: days per year), classified using Jenks natural breaks. Class counts (2 or 3) and boundaries reflect actual data distribution; single-value classes are shown as “a–a”, and gaps indicate ranges with no observations.

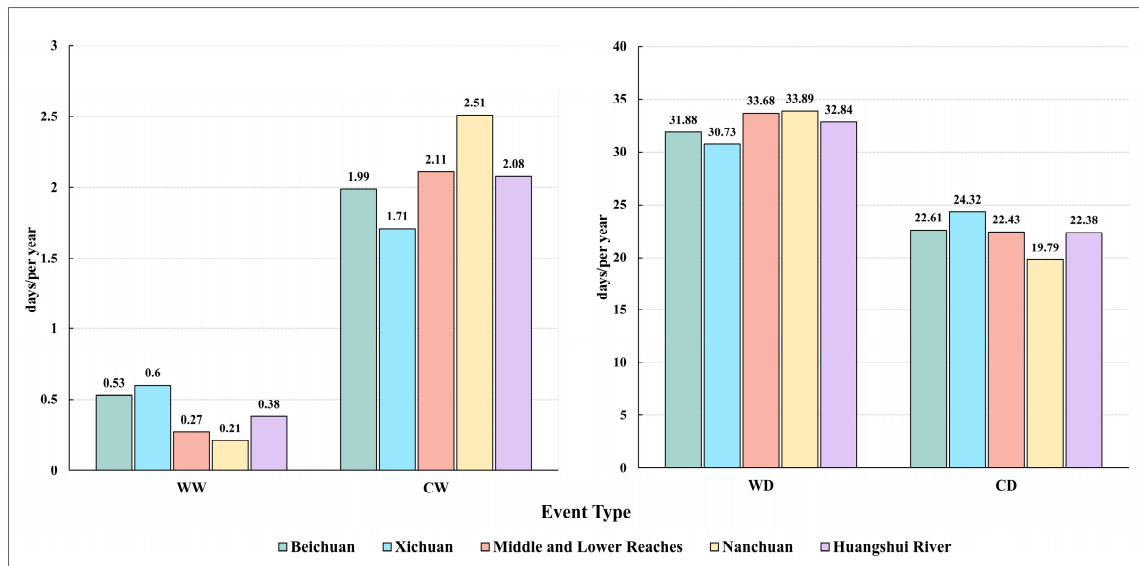


Figure 4. Summary of the annual mean frequencies of the four types of compound extreme climate events for the Huangshui River Basin and its subregions from 1960 to 2022 (units: days per year).

The low frequency of wet-type events partly reflects the methodological definition, wet extremes are identified based only on days with measurable precipitation ($P \geq 0.1$ mm), whereas dry extremes include all days (with $P_{10\%} = 0$ mm in this arid region). Nevertheless, the marked contrast between warm and cold extremes—where 90% of extremely warm days are dry but only 60% of extremely cold days are dry—reveals a genuine climatic asymmetry, likely linked to the frequent occurrence of cloud cover and weak precipitation during cold episodes.

At the sub-basin scale, cold–dry events reach 24.32 d a^{-1} in the Xichuan River sub-basin. Cold–wet events are relatively more prominent in the Nanchuan River sub-basin. In the middle–lower sub-basin—which includes both valley and low-mountain stations—the annual mean frequencies of warm–dry (33.68 d a^{-1}) and cold–dry (22.43 d a^{-1}) events are the highest or second highest among all sub-basins.

3.2.2. Seasonal Analysis

From the seasonal distribution patterns shown in Figures 5–9, all four types of compound extreme climate events—warm–wet (WW), warm–dry (WD), cold–wet (CW), and cold–dry (CD)—occur in every season in the Huangshui River Basin, but their frequencies exhibit pronounced seasonal and spatial variability.

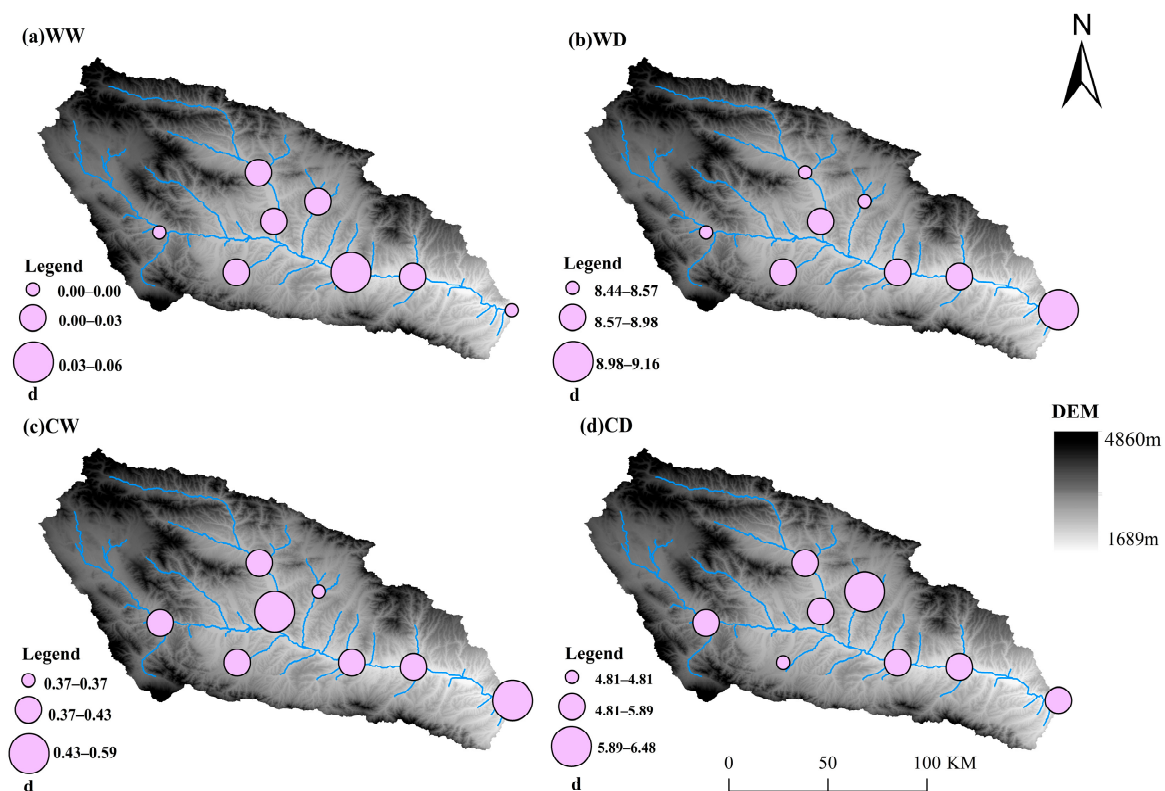


Figure 5. Spatial distribution of mean spring frequency of the four types of compound extreme climate events at individual stations in the Huangshui River Basin (1960–2022) (units: days per year), classified using Jenks natural breaks. Class counts (2 or 3) and boundaries reflect actual data distribution; single-value classes are shown as “a–a”, and gaps indicate ranges with no observations.

Figure 5 illustrates the spring pattern (March–May). Based on the mean frequency during spring at each station, warm–wet (WW) events occur relatively frequently at Ping’an; warm–dry (WD) events are concentrated mainly at Minhe; cold–wet (CW) events are most prominent at Xining; and cold–dry (CD) events occur most frequently at Huzhu.

It is evident from Figure 9 that, at the basin scale, the springtime mean frequencies show that warm–wet events are extremely rare across the Huangshui River Basin (0.02 d a^{-1}), with slightly higher values in the Nanchuan River sub-basin than in the other regions. Cold–wet events have a mean frequency of 0.45 d a^{-1} and are mainly concentrated in the Beichuan River sub-basin. Warm–dry (WD) events (8.79 d a^{-1}) are the dominant type in spring, with high-value areas located in the Nanchuan River and middle–lower sub-basins, followed by the Beichuan and Xichuan River sub-basins. Cold–dry events have an annual mean frequency of 5.65 d a^{-1} and also occur predominantly in the middle–lower sub-basin.

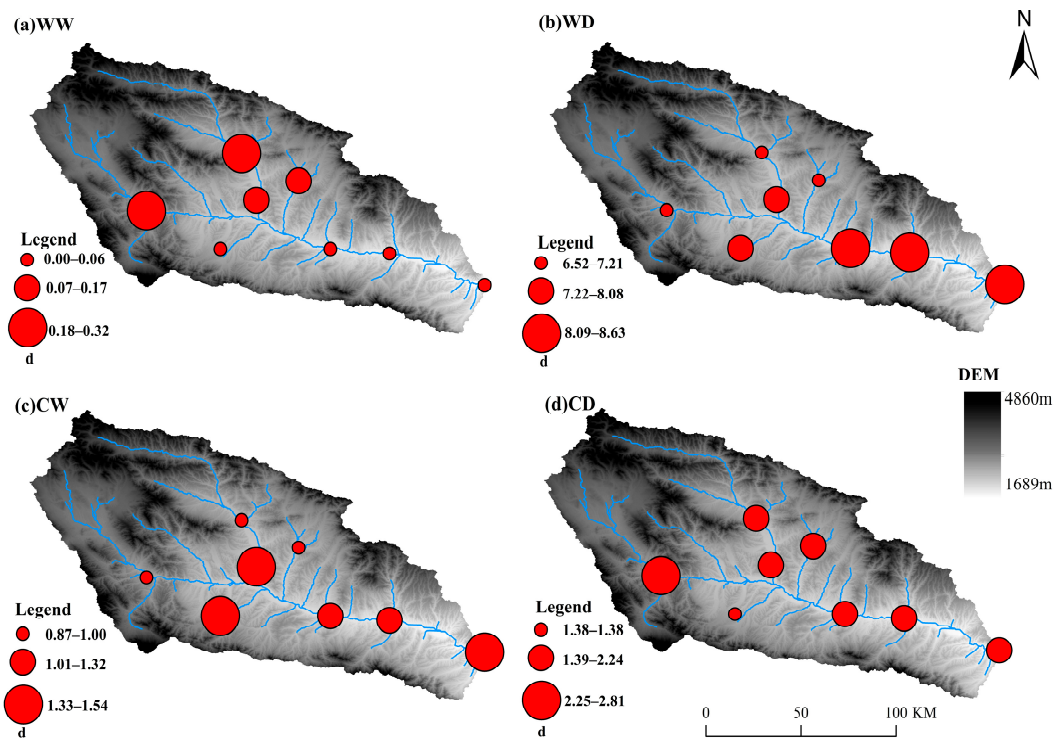


Figure 6. Spatial distribution of mean summer frequency of the four types of compound extreme climate events at individual stations in the Huangshui River Basin (1960–2022) (units: days per year), classified using Jenks natural breaks. Class counts (2 or 3) and boundaries reflect actual data distribution; single-value classes are shown as “a–a”, and gaps indicate ranges with no observations.

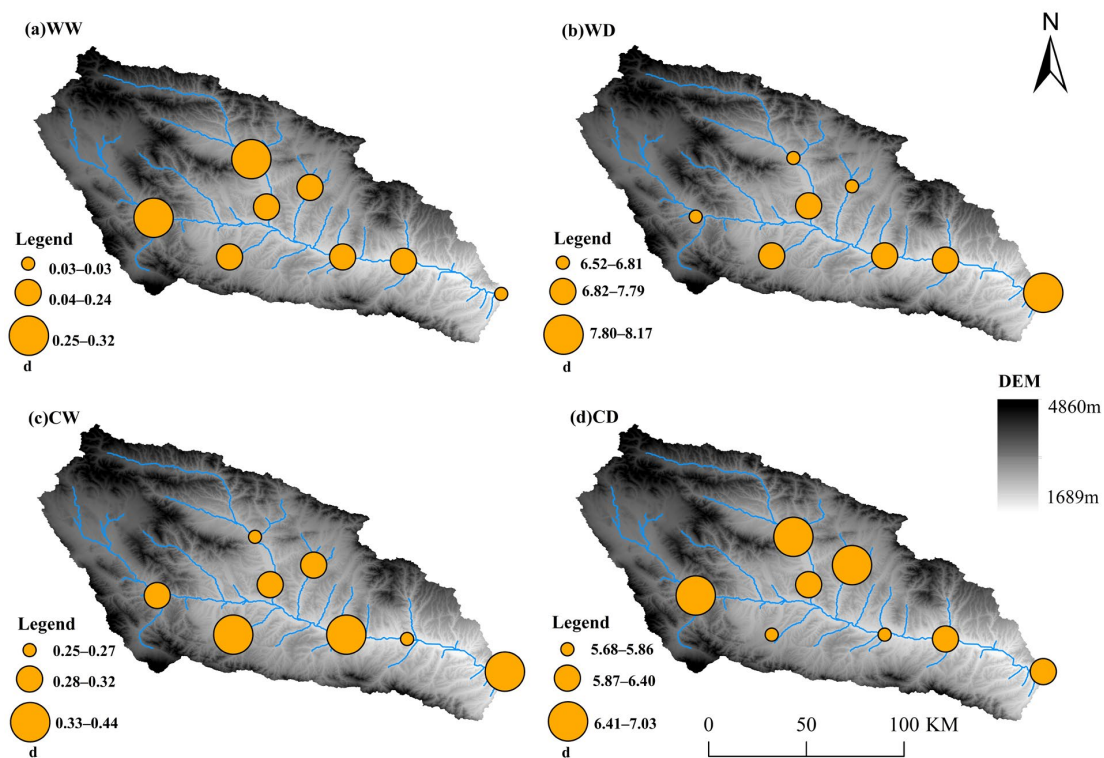


Figure 7. Spatial distribution of mean autumn frequency of the four types of compound extreme climate events at individual stations in the Huangshui River Basin (1960–2022) (units: days per year), classified using Jenks natural breaks. Class counts (2 or 3) and boundaries reflect actual data distribution; single-value classes are shown as “a–a”, and gaps indicate ranges with no observations.

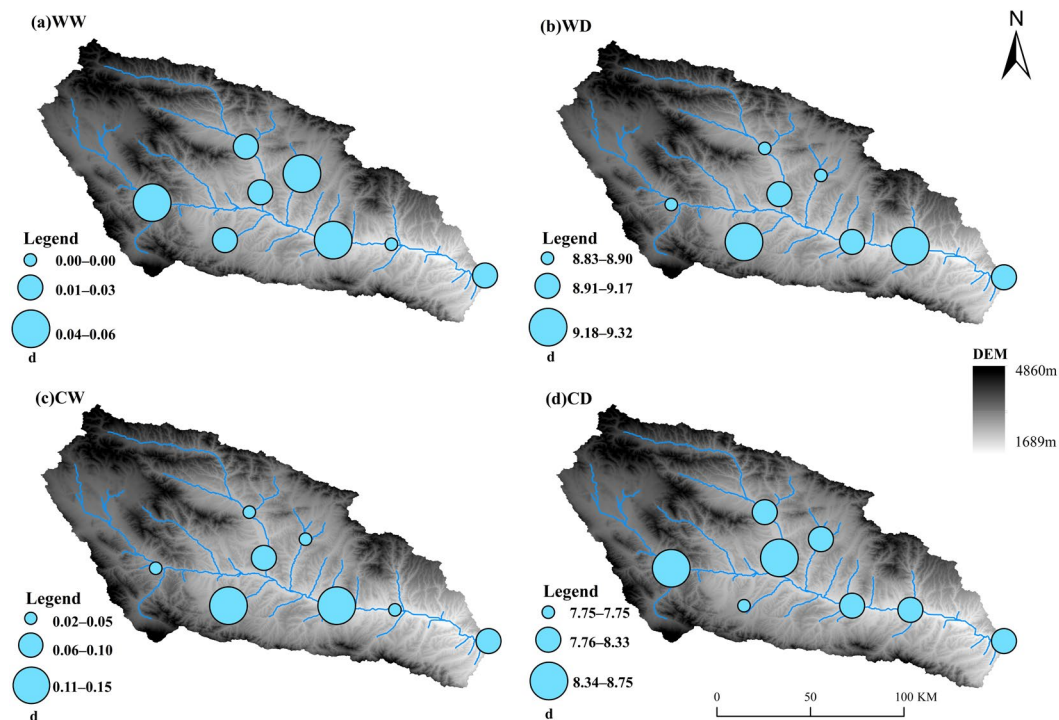


Figure 8. Spatial distribution of mean winter frequency of the four types of compound extreme climate events at individual stations in the Huangshui River Basin (1960–2022) (units: days per year), classified using Jenks natural breaks. Class counts (2 or 3) and boundaries reflect actual data distribution; single-value classes are shown as “a–a”, and gaps indicate ranges with no observations.

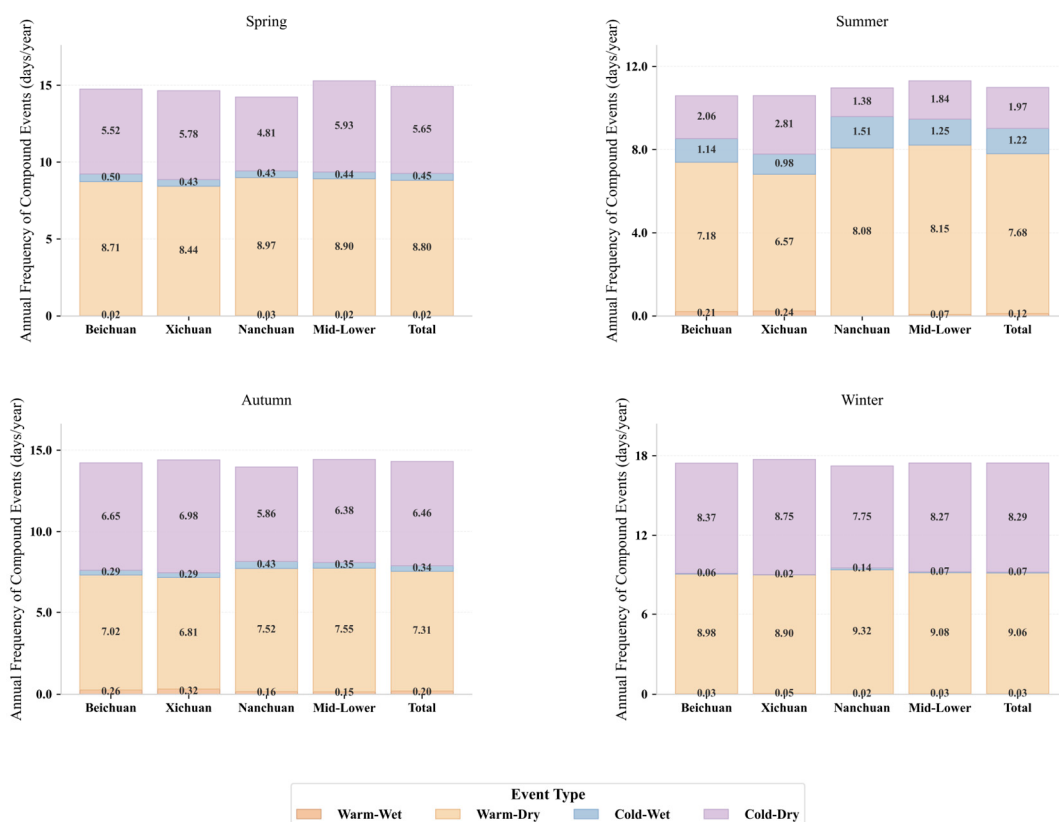


Figure 9. Summary of the seasonal annual mean frequencies of the four types of compound extreme climate events in the Huangshui River Basin and its subregions during 1960–2022 (units: days per year).

In summer, precipitation in the Huangshui River Basin is highly concentrated, consistent with the typical characteristics of a plateau continental climate in which most rainfall occurs during the warm season. The overall distribution pattern of the four types of compound extreme climate events largely follows the ranking observed in spring, but their frequencies and spatial configurations show notable adjustments (Figure 6).

At the individual-station scale, warm–wet (WW) events reach their highest annual mean frequency at Datong (0.32 d a^{-1}). Warm–dry (WD) events are most prominent at Minhe. Cold–wet (CW) events are mainly concentrated at Minhe, Xining, and Huangzhong, whereas cold–dry (CD) events occur most frequently at Huangyuan.

At the basin scale, the mean summer frequencies exhibit a clear hierarchical structure: warm–dry (WD) events occur most frequently (7.68 d a^{-1}), followed by cold–dry (CD) events (1.97 d a^{-1}) and cold–wet (CW) events (1.22 d a^{-1}), while warm–wet (WW) events are the least common (0.12 d a^{-1}). Overall, the event ranking in summer is $\text{WD} > \text{CD} > \text{CW} > \text{WW}$.

At the sub-basin scale, the middle–lower sub-basin records the highest frequency of warm–dry events, reaching 8.15 d a^{-1} . Warm–wet events are concentrated primarily in the Xichuan River sub-basin and are almost absent in the Nanchuan River sub-basin. High-frequency zones of both warm–dry and cold–wet events jointly cover the middle–lower and Nanchuan River sub-basins. Cold–dry events are widely distributed across the Xichuan and Beichuan River sub-basins, with the lowest frequencies observed in the Nanchuan River sub-basin.

As shown in Figures 7 and 9, the autumn frequencies of the four types of compound extreme climate events in the Huangshui River Basin follow the order: warm–dry (WD, 7.31 d a^{-1}) > cold–dry (CD, 6.46 d a^{-1}) > cold–wet (CW, 0.34 d a^{-1}) > warm–wet (WW, 0.20 d a^{-1}), indicating that dry-type events remain dominant overall.

At the individual-station scale, warm–wet (WW) events reach their highest annual mean frequency at Huangyuan, warm–dry (WD) events are most prominent at Minhe, cold–wet (CW) events are mainly concentrated at Ping'an, and cold–dry (CD) events occur most frequently at Datong.

At the sub-basin scale, warm–wet (WW) events exhibit high-frequency zones in the Xichuan and Beichuan River sub-basins, with the lowest frequencies in the middle–lower and Nanchuan River sub-basins. Warm–dry (WD) events show the opposite pattern, with high values in the middle–lower and Nanchuan River sub-basins and the lowest frequencies in the Xichuan River sub-basin. Cold–wet (CW) events are most frequent in the Nanchuan River sub-basin, whereas cold–dry (CD) events are mainly distributed in the Xichuan and Beichuan River sub-basins and occur least frequently in the Nanchuan River sub-basin.

Figure 9 shows that, in winter, the mean frequencies of the four compound extreme climate event types in the Huangshui River Basin follow the order: warm–dry (WD, 9.06 d a^{-1}) > cold–dry (CD, 8.29 d a^{-1}) > cold–wet (CW, 0.07 d a^{-1}) > warm–wet (WW, 0.03 d a^{-1}), indicating that wet-type events are nearly absent.

At the individual-station scale (Figure 8), warm–wet (WW) events occur relatively frequently at Huzhu and Ping'an; warm–dry (WD) events are most prominent at Huangzhong; cold–wet (CW) events are concentrated at Ping'an; and cold–dry (CD) events occur most frequently at Huangyuan.

At the sub-basin scale, warm–wet (WW) events show high frequencies in the Xichuan River, middle–lower, and Beichuan River sub-basins, with the lowest values in the Nanchuan River sub-basin. Both warm–dry and cold–wet events reach their highest frequencies in the Nanchuan River sub-basin. Cold–dry (CD) events, in contrast, are concentrated in the Xichuan River sub-basin.

3.3. Analysis of Trends and Patterns

According to Figure 10 and Table 3, the four types of compound extreme climate events in the Huangshui River Basin exhibit distinct trend behaviors during 1960–2022.

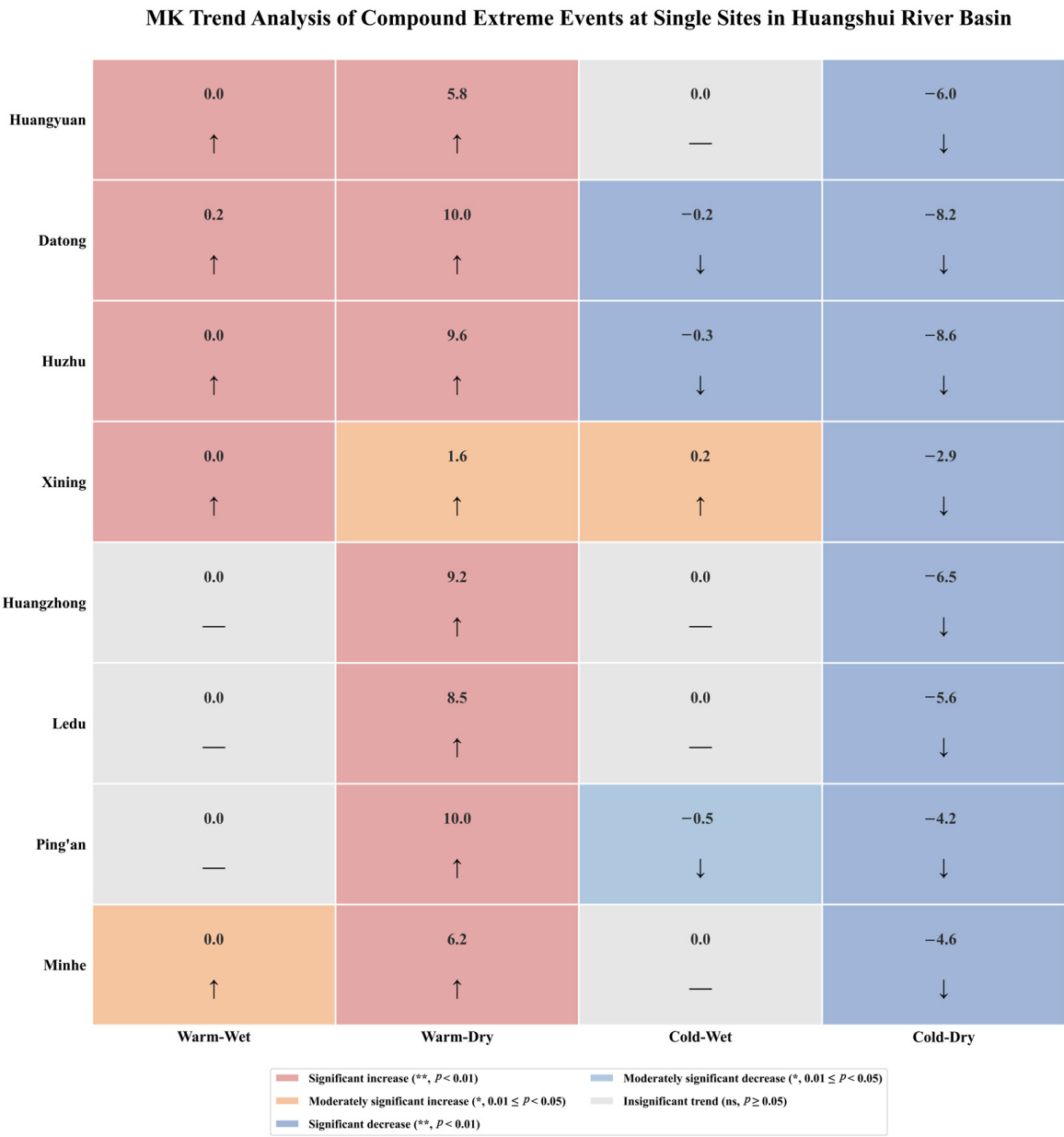


Figure 10. Trends and statistical significance of the four types of compound extreme climate events at individual stations in the Huangshui River Basin from 1960 to 2022 (unit: days per decade). ** indicates a significant trend ($p < 0.01$) and * indicates a moderately significant trend ($0.01 \leq p < 0.05$); the symbols “↑” and “↓” indicate statistically significant increasing and decreasing trends at the 95% confidence level, respectively, while the absence of a symbol denotes a non-significant trend.

Table 3. Trends (days per decade) of the four types of compound extreme climate events in the Huangshui River Basin and its subregions.

Event Type	Beichuan	Xichuan	Nanchuan	Middle and Lower Reaches	Huangshui River Basin	Unit
Warm-Wet (WW)	0.1 ↑	0 ↑	0	0 ↑	0.1 ↑	days per decade
Warm-Dry (WD)	6.1 ↑	5.8 ↑	9.2 ↑	7.1 ↑	6.9 ↑	days per decade
Cold-Wet (CW)	0	0	0	−0.1	0	days per decade
Cold-Dry (CD)	−5.4 ↓	−6.0 ↓	−6.5 ↓	−6.3 ↓	−6.0 ↓	days per decade

The values in the table represent the linear trend rates of the four types of compound extreme climate events (unit: days per decade). The symbols “↑” and “↓” indicate statistically significant increasing and decreasing trends at the 95% confidence level, respectively, while the absence of a symbol denotes a non-significant trend.

Warm–wet (WW) events display a significant increasing trend across the basin, with a regional trend rate of 0.10 d per decade. Among the eight stations, five show a significant increase ($p < 0.05$), while the remaining three exhibit no significant change. Stations Huangyuan, Datong, Huzhu, and Xining all pass the significance test, and station Minhe shows a moderately significant upward trend ($0.01 \leq p < 0.05$). Notably, at some stations the Sen’s slope estimate is close to or equal to zero, whereas the Mann–Kendall test still indicates a significant upward trend. This suggests that warm–wet events do not increase in a steady linear fashion, but rather through step-like increments or episodes of concentrated occurrence in the later period. In fact, such events were almost absent in the early part of the record and only begin to appear sporadically in recent years, resulting in an overall monotonic “from none to some” enhancement. However, because their annual mean frequency is very low ($<0.4 \text{ d a}^{-1}$) and interannual variability is strong, a distinct linear trend in the slope is not captured.

The basin-wide trend is not a simple average of the subregional trends; instead, it is independently estimated from an annually aggregated time series constructed using all available stations, and thus more faithfully represents the overall evolution of the region. Warm–dry (WD) events exhibit a significant increasing trend across the entire basin. With the exception of one station, which shows a moderately significant increase with a trend rate of 1.6 d per decade, the remaining seven stations all display significant increases, yielding a basin-wide mean trend rate of 6.9 d per decade. At the sub-basin scale, the largest increase in WD events occurs in the Nanchuan River sub-basin (9.2 d per decade), followed by the middle–lower sub-basin (7.1 d per decade), the Beichuan River sub-basin (6.1 d per decade), and the Xichuan River sub-basin (5.8 d per decade). Given the dense human activities and wide river valleys in the middle–lower reaches, the pronounced warming and drying there has particularly important socio-ecological implications.

Cold–wet (CW) events show no significant trend at the basin scale. Only station Xining exhibits a moderately significant increasing trend ($p < 0.1$), while stations Huangyuan, Huangzhong, Ledu, and Minhe show no significant change. The remaining three stations display significant decreasing trends, indicating a pronounced spatial heterogeneity in CW event evolution.

By contrast, cold–dry (CD) events exhibit a significant decreasing trend at all stations, with a basin-wide trend rate of -6.0 d per decade. Among the sub-basins, the fastest decline occurs in the Nanchuan River sub-basin (-6.5 d per decade), followed by the middle–lower sub-basin (-6.3 d per decade), the Xichuan River sub-basin (-6.0 d per decade), and the Beichuan River sub-basin (-5.4 d per decade). These results suggest that low-temperature, drought-type events are weakening systematically across the region, especially in the densely populated middle–lower reaches where warming is most pronounced.

3.4. Intensity Characteristics of Compound Extreme Events

Figure 11 illustrates the station-level annual mean frequency distribution across intensity classes, highlighting distinct differences in the intensity structure of the four types of compound extreme climate events, warm-wet (WW), warm-dry (WD), cold-wet (CW), and cold-dry (CD), in the Huangshui River Basin from 1960 to 2022.

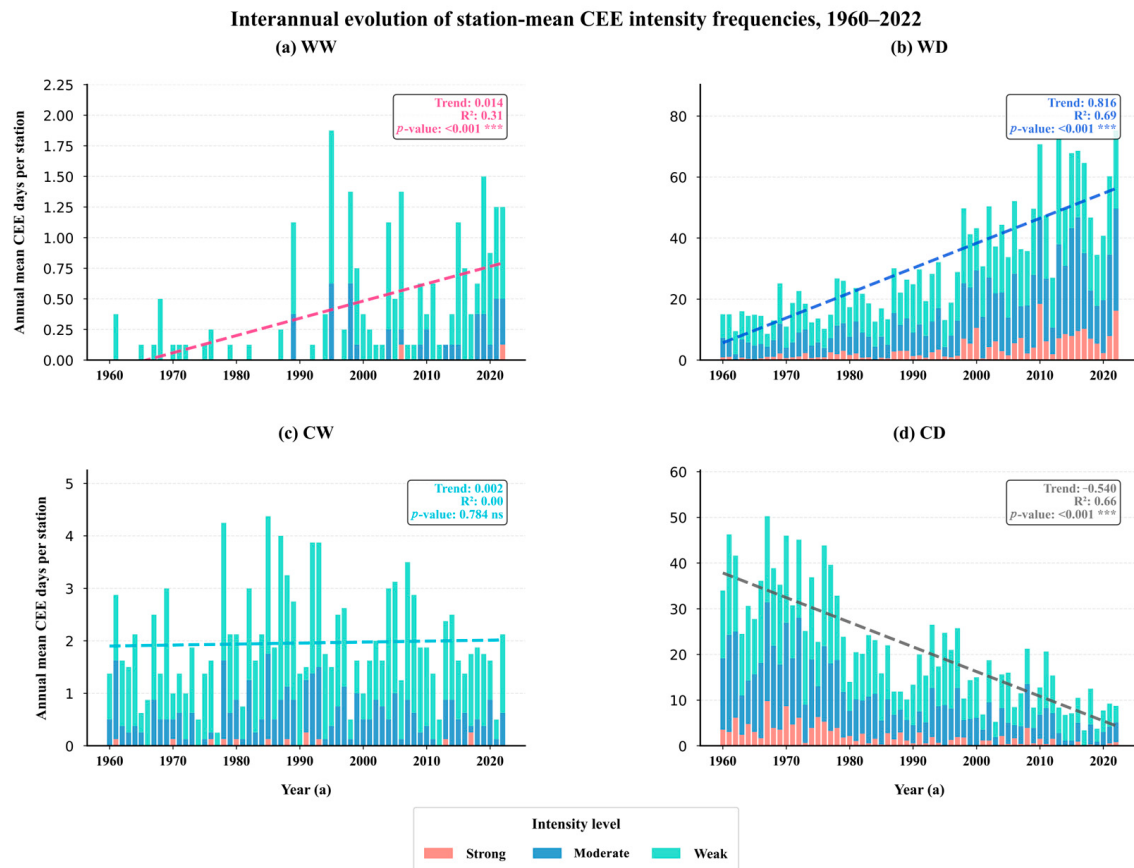


Figure 11. Interannual evolution of intensity-class-resolved compound extreme event frequencies averaged across stations in the Huangshui River Basin (1960–2022). Stacked bar charts represent the annual mean number of days per station for each event type (WW: warm-wet; WD: warm-dry; CW: cold-wet; CD: cold-dry), partitioned into weak, moderate, and strong intensity classes. Dashed lines show linear trends fitted to the total annual frequency (sum of all intensity classes). The slope, coefficient of determination (R^2), and p -value of the total trend are displayed in the upper-right corner of each panel (** $p < 0.001$; ns, not significant).

For all four event types, weak and moderate intensity events predominate, whereas strong-intensity events occur infrequently. This suggests that changes in compound extremes are primarily driven by shifts in the frequency of weak and moderate events, rather than an increase in strong-intensity occurrences.

Trend analysis of annual frequencies reveals persistent increases in both WW and WD events over 1960–2022. Linear regression yields positive slopes for both ($p < 0.001$), confirming statistically significant upward trends. Specifically, WW events were extremely rare between 1960 and 1980, with some years recording no occurrences; their increase is concentrated after the 1980s and is dominated by rises in weak (slope = $0.0100 \text{ d} \cdot \text{station}^{-1} \cdot \text{year}^{-1}$, $p < 0.001$) and moderate (slope = 0.0038 , $p < 0.001$) intensity classes. Notably, strong-intensity WW events remained exceptionally rare throughout the period and showed no significant trend (slope = 0.0003 , $p = 0.071$).

WD events were the most frequent among the four types. Both weak (slope = 0.3000, $p < 0.001$) and moderate (slope = 0.3774, $p < 0.001$) intensity classes exhibited continuous increases over the entire period. Importantly, strong-intensity WD events also increased significantly (slope = 0.1389, $p < 0.001$), indicating not only a rise in overall frequency but also a clear intensification in high-severity occurrences.

In contrast, CW events showed no significant trend in annual frequency ($p = 0.784$). Although the OLS fit yields a slight positive slope, interannual variability is low and the time series remains stable overall. Weak and moderate events continue to dominate, with strong-intensity events occurring only sporadically.

CD events, however, exhibited a consistent and significant decline over the study period ($p < 0.001$), with pronounced decreases in weak (slope = -0.2210 , $p < 0.001$), moderate (slope = -0.2410 , $p < 0.001$), and strong (slope = -0.0778 , $p < 0.001$) intensity classes. Strong-intensity CD events have become particularly rare in recent decades.

To complement the temporal trends presented in Figure 11, Figure 12 illustrates the spatial differentiation of intensity classes for the four types of compound extreme climate events across all stations. It highlights how different intensities of these events are distributed spatially within the entire basin and its sub-basins.

Warm–wet (WW) events have the lowest overall frequencies. Strong-intensity WW events are extremely rare, with only two stations recording non-zero values (maximum, 0.02 d a^{-1}). The annual mean frequencies are 0.08 d a^{-1} and 0.29 d a^{-1} for moderate and weak classes, respectively. WW events have mainly occurred in the Beichuan River sub-basin, followed by the Xichuan River sub-basin.

Warm–dry (WD) events exhibit substantially higher frequencies than the other types, with annual mean frequencies of 15.97 d a^{-1} , 13.23 d a^{-1} , and 3.64 d a^{-1} for weak, moderate, and strong classes, respectively. High frequencies of all three classes are concentrated in the middle–lower sub-basin (including Ledu and Minhe stations) and the Nanchuan River sub-basin.

Cold–wet (CW) events are dominated by the weak class (1.44 d a^{-1}), with annual mean frequencies of 0.61 d a^{-1} and 0.03 d a^{-1} for the moderate and strong classes, respectively. Strong CW events reach their highest frequencies in the Xichuan River sub-basin, whereas high frequencies of weak and moderate CW events extend from the Nanchuan River sub-basin into the middle–lower sub-basin.

For cold–dry (CD) events, the annual mean frequencies of weak, moderate, and strong classes are 11.28 d a^{-1} , 8.91 d a^{-1} , and 2.19 d a^{-1} , respectively. Spatially, CD events are most common in the Xichuan and Beichuan River sub-basins, where frequencies are markedly higher than in the Nanchuan River and middle–lower sub-basins.

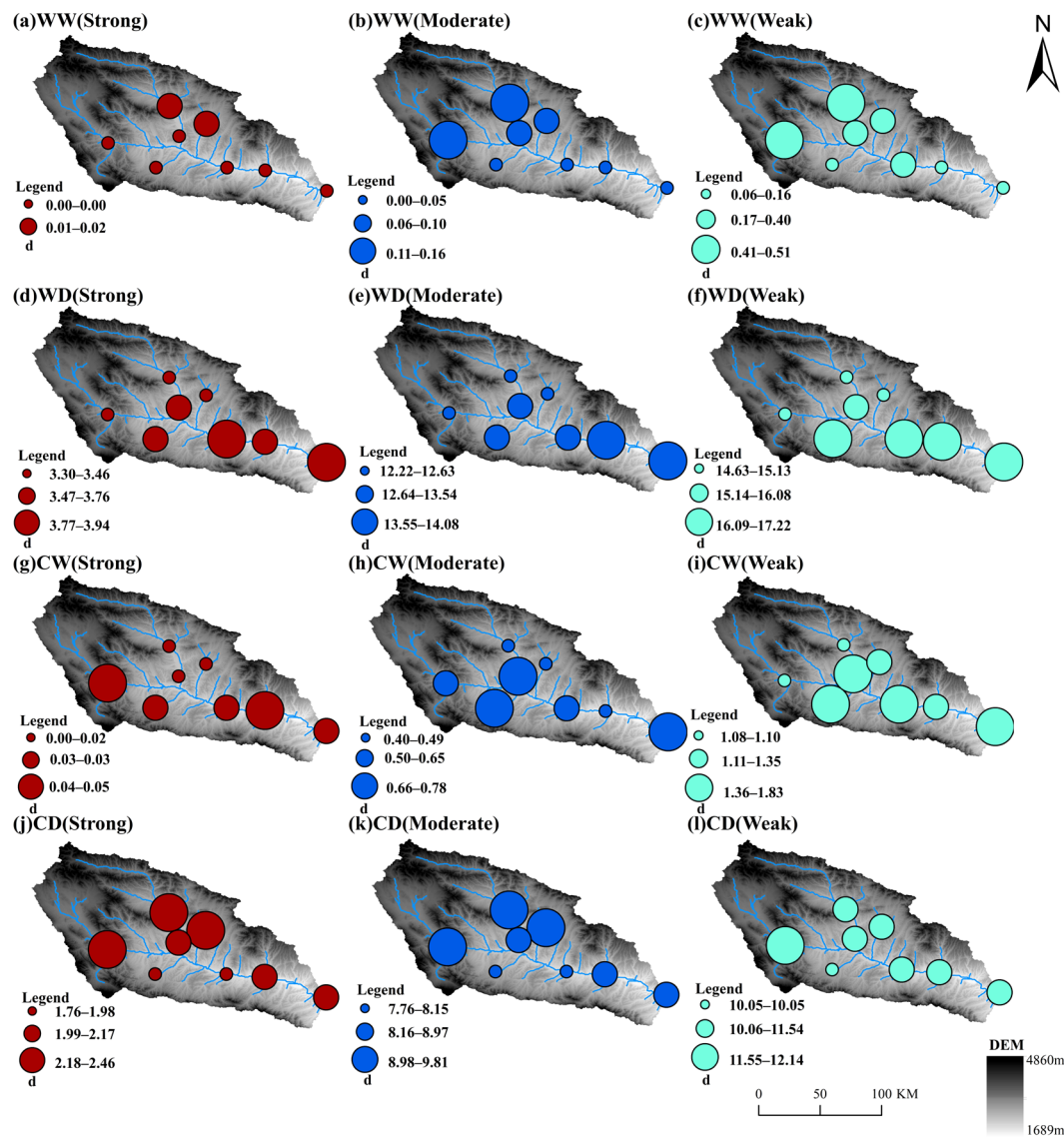


Figure 12. Spatial distribution of the intensity of the four types of compound extreme climate events at individual stations in the Huangshui River Basin (units: days per year), classified using Jenks natural breaks. Class counts (2 or 3) and boundaries reflect actual data distribution; single-value classes are shown as “a–a”, and gaps indicate ranges with no observations.

4. Discussion

4.1. Main Findings

Based on observational data from 1960 to 2022, this study systematically reveals that compound extreme climate events in the Huangshui River Basin are characterized by three core features: drought-type dominance, pronounced regional differentiation, and stable seasonal variability. Overall, over the past six decades, compound extreme events in the basin have been dominated by warm–dry conditions, while warm–wet events remain relatively infrequent but show an increasing tendency, and cold–dry events, though still frequent, exhibit a persistent decline. These findings are consistent with previous studies showing a significant warming trend and increasing precipitation over the main body of the Tibetan Plateau, with warming being more pronounced along its margins than in the interior [43–45].

Under the background of global warming, the Tibetan Plateau—owing to its unique geographical position and underlying surface conditions—acts as both a “driver” and an

“amplifier” of global climate change [46]. The climatic evolution of the Huangshui River Basin represents a typical manifestation of the active response of the eastern margin of the Tibetan Plateau to this broader climate signal. Our results show a significant increase in the frequency of warm–dry events across the entire basin, with the most pronounced intensification occurring in the low-elevation valley areas. In these zones, warming rates are substantially higher than in the high-elevation regions, and enhanced evaporation further amplifies the moisture deficit associated with warm–dry events. The combined effect of warmer and drier conditions is particularly evident in winter and spring, ultimately leading to a persistently high frequency of warm–dry events throughout the year in low-elevation areas.

Previous studies have shown that, since 1960, extreme precipitation events over the Tibetan Plateau have become more frequent and the wetting trend has intensified, with particularly pronounced changes in the eastern Plateau [47]. This understanding is highly consistent with our finding of a significant increase in warm–wet events in the Huangshui River Basin. Notably, the frequency of warm–wet events has risen rapidly since the 1980s and occurs predominantly in the low-mountain areas. On the one hand, annual precipitation over the Tibetan Plateau has increased significantly during 1981–2020 (at a rate > 10 mm per decade), and the combined influence of the mid-latitude westerlies and the East Asian summer monsoon has enhanced moisture transport into the region. On the other hand, sub-basins such as the Beichuan and Xichuan Rivers are located in low-mountain terrain, where orographic uplift favors condensation and thus increases the occurrence of warm–wet events [48–50]. However, because the Huangshui River Basin as a whole remains within an arid to semi-arid climatic regime with limited moisture supply, strong warm–wet events are still relatively rare. Under these dry background conditions, wintertime warming is insufficient to offset the moisture deficit, and warm–wet events therefore occur mainly during the relatively warm seasons.

Cold–dry (CD) events exhibit a significant decreasing trend across the entire basin, with the largest decline occurring in the middle–lower reaches. Although CD events remain the second most frequent type after warm–dry events in the Huangshui River Basin, the persistent background warming makes it increasingly difficult to meet the “cold” temperature thresholds, thereby substantially suppressing the formation of cold–dry conditions—particularly in winter, when the decline is most pronounced. This highlights the pervasive and robust impact of regional warming. The sustained decrease in both the intensity and frequency of CD events is highly consistent with the broader pattern of systematic weakening of low-temperature, drought-type extremes under the warming–wetting regime of the Tibetan Plateau, further corroborating the long-term shift in the regional climate toward a warmer and wetter state.

At the scale of the entire basin, cold-wet (CW) events exhibit no statistically significant long-term trend over 1960–2022, a pattern consistent with the topographic setting of the Huangshui River Basin, which is situated between the Daban and Laji mountains on the northeastern margin of the Tibetan Plateau. This setting is characterized by the long-term coexistence of high-elevation cold conditions and monsoon-borne moisture, providing a relatively stable climatic basis for a “low temperature and precipitation” cold-wet regime [51].

On the interannual timescale, CW frequency is primarily modulated by ENSO-related anomalies in large-scale circulation and moisture transport. During the decay phase of El Niño, the western North Pacific subtropical high tends to be displaced westward and strengthened, and the associated anomalous southwesterly warm–moist flow transports moisture from source regions such as the Bay of Bengal and the South China Sea to the northeastern margin of the Tibetan Plateau. Although this circulation pattern favors above-

normal precipitation, the accompanying subsidence warming and warm advection raise near-surface air temperature, causing more wet years to manifest as warm-wet (WW) rather than cold-wet (CW) events [52,53].

Conversely, during La Niña events, the East Asian trough deepens, and both the East Asian winter monsoon and cold-air activity intensify. If, at the same time, the South Asian and/or East Asian monsoon is anomalously strong and moisture transport from low-latitude oceans is enhanced, low temperatures and abundant precipitation are more likely to occur simultaneously, thereby favoring the occurrence of CW events that satisfy the dual thresholds of “low temperature and precipitation” [54].

Therefore, El Niño generally tends to strengthen a warm–wet background over the basin, whereas La Niña more readily produces a cold–wet background. Their alternating dominance on decadal timescales both enhances the interannual and quasi-periodic variability of CW events and, to some extent, offsets potential unidirectional long-term changes, leading to a CW frequency that is statistically characterized by pronounced fluctuations but no significant long-term trend [55,56].

At the seasonal scale, the Huangshui River Basin in summer is mainly controlled by the East Asian summer monsoon, leading to highly concentrated rainfall, and the mean summer occurrence of cold–dry (CD) events is only 1.97 d a^{-1} . The scarcity of CD events in summer stems from the fact that dry days, common during breaks in monsoon rainfall, are usually accompanied by intense solar insolation, which elevates temperatures and favors warm–dry rather than cold–dry conditions. Since the 1980s, the strengthening of the summer monsoon and the marked increase in precipitation over the eastern Tibetan Plateau have led to a pronounced rise in the frequency of warm–wet (WW) events in summer and autumn [57]. This trend is further amplified by rising temperatures, which increase the likelihood that wet days also meet the “warm” criterion. However, due to the “more in the east, less in the west” pattern of moisture transport by the summer monsoon, WW events reach only limited high values in the Beichuan and Xichuan River sub-basins, where orographic uplift is pronounced. In some years, when the western North Pacific subtropical high is anomalously strong and extends westward, with its ridge axis displaced southward, the East Asian summer monsoon tends to weaken, and the frequency of warm–dry (WD) events correspondingly increases [58].

During the non-summer seasons, the basin is primarily influenced by the mid-latitude westerlies, and the background climate is generally cold and dry. Under continued warming, the low-elevation valley areas maintain a relatively warm–dry state overall, whereas the high-elevation mountain areas remain dominated by CD events. This spatial contrast arises not from lower mean temperatures (since “cold” events are defined based on local percentiles) but from a higher co-occurrence frequency of cold and dry conditions at high elevations. Nonetheless, the frequency of CD events in these high-elevation regions has already begun to decline, with persistently high occurrence only in the Xichuan River sub-basin.

In addition to natural drivers, anthropogenic factors also play a non-negligible role in the occurrence of compound extreme events in the Huangshui River Basin. Although human activities do not alter the fundamental characteristics of these events, they amplify both the rate of increase and the intensity contrast of events in low-elevation valley areas through land-surface modification and altered energy and water balances. In these low-elevation regions, high population density and intensive industrial development mean that urbanization significantly affects local climatic conditions. Urban expansion and the associated urban heat-island effect can increase air temperature by an additional $0.3\text{--}2 \text{ }^{\circ}\text{C}$ [59,60], which, superimposed on background climatic warming, further strengthens the upward trend in warm–dry (WD) events. Agricultural activities, such as the widespread use of

plastic greenhouses, also enhance local “warm” conditions. The intensity-class distribution of WD events shows that their overall frequency around 2022 is considerably higher than in earlier periods, indicating that human activities have likely contributed to the increased occurrence of compound hot–dry extremes [61]. Although measures such as reforestation of former cropland and reservoir impoundment may, to some extent, modify local hydrological conditions and regulate moisture availability, the basin as a whole remains in an arid to semi-arid climatic regime, and any increase in humidity is inherently limited [62].

In summary, the compound extreme event regime in the Huangshui River Basin is undergoing a transition from being dominated by cold–dry conditions to a compound risk pattern characterized by predominantly warm–dry events with emerging warm–wet events, driven jointly by plateau warming, enhanced monsoon activity, and intensified human influences.

4.2. Limitations and Prospects

The analytical framework proposed in this study can provide a useful reference for investigating compound extreme events in other river–valley basins of the Tibetan Plateau, as well as in mountain basins across arid and semi-arid regions worldwide. The revealed differential response pattern between river valleys and mountainous areas helps deepen our understanding of the evolution mechanisms of extreme events under a transforming climate.

However, this study has several limitations. First, the use of percentile thresholds (90th/10th percentiles) to classify event intensity may not fully capture the characteristics of regional extremes in complex terrain. Second, when applying the weighted-averaging method to account for differences in station record length, the sparse and uneven spatial distribution of early stations may limit the ability to robustly detect local signals. Finally, the analysis of influencing factors has not quantified the relative contributions of natural versus anthropogenic drivers.

In future work, satellite-based indicators such as NDVI and datasets on the degree of urbanization should be incorporated to quantitatively assess the relative contributions of natural and anthropogenic factors. Reanalysis products and climate models can be used to further elucidate the spatiotemporal coupling mechanisms of compound extreme events, while projections under different emission scenarios would allow their future trends and intensity changes to be assessed with greater scientific rigor and accuracy. Moreover, as the Huangshui River Basin represents only a river–valley sector on the northeastern margin of the Tibetan Plateau, a focus limited to this basin alone is insufficient to meet the practical needs of managing compound extreme events across the entire Plateau. Future studies should therefore expand the spatial scope of analysis and, drawing on the Plateau’s unique geographical setting and climatic background, promote systematic investigations of compound extremes at the full-plateau scale. This would help raise awareness of, and research attention to, compound extreme events in the region and provide a more robust scientific basis for the Tibetan Plateau as a whole to respond to such complex hazards.

Accordingly, this study provides an initial exploration of the mechanisms and risk characteristics of compound extreme events, offering a useful reference for optimizing regional disaster early-warning systems, adjusting climate adaptation strategies, and improving ecological security and public well-being. The results also lay a foundation for more in-depth analyses of the evolution of extreme events in plateau mountain basins and can support policy-making and scientific practice in related fields.

5. Conclusions

This study systematically analyzes the evolution of compound extreme climate events in the Huangshui River Basin during 1960–2022 and leads to the following key conclusions:

(1) Among the four types of compound extreme events in the Huangshui River Basin, warm–dry (WD) events have the highest annual mean number of occurrence days (32.84 d a^{-1}), far exceeding the other types. Cold–dry (CD) events rank second (22.38 d a^{-1}), followed by cold–wet (CW) events (2.08 d a^{-1}), while warm–wet (WW) events are the least frequent (only 0.38 d a^{-1}). The annual mean number of WD days is approximately 86.4 times that of WW events and 15.8 times that of CW events, indicating that drought-type events (WD and CD) overwhelmingly dominate the compound extreme event regime in the basin. This strong disparity is partly attributable to the asymmetric definition of dry and wet extremes: dry thresholds are based on the full daily record (including zero precipitation days), whereas wet thresholds are defined only on precipitation days ($P \geq 0.1 \text{ mm}$), which inherently limits the frequency of wet-type events.

(2) In terms of seasonal distribution, WD events maintain a high frequency of occurrence in all four seasons (spring, summer, autumn and winter), whereas CD events are concentrated mainly in winter. WW events exhibit the lowest occurrence frequencies in every season, reflecting the scarcity of humid conditions in the basin.

(3) Based on the 1960–2022 time series, the four types of compound extreme events show clearly differentiated trends. WW and WD events exhibit significant increasing trends ($p < 0.05$), with the fastest increase in WW events occurring in the Beichuan River sub-basin. CD events show a significant decreasing trend across the entire basin ($p < 0.05$), whereas CW events do not display a statistically significant trend ($p \geq 0.05$). Spatially, the middle–lower reaches experience the most pronounced changes, with the highest rates of increase in WD events and the largest decreases in CD events, indicating an ongoing transition in the extreme-event structure from cold–dry dominance to warm–dry dominance in this region.

(4) All four compound event types exhibit a “weak-class dominance” in their intensity structure. Over 1960–2022, only warm–dry (WD) events show a significant increase in strong-intensity frequency; warm–wet (WW) events increase only in weak and moderate classes; cold–dry (CD) events decline across all intensities; and cold–wet (CW) events show no significant trends.

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