



# Research on Sequence Construction and Characteristics Diagnosis of Droughts and Floods in the Qinling Mountains of China From 1850 to 1959

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In recent years, under the background of the global climate, drought and flood disasters have occurred frequently in China. Historical climate research is an important part of the international Climate Variability and Predictability project. Based on the existing historical documents and literatures about counties and distributions in the Qinling Mountains from 1850 to 1959, we reconstructed a sequence of drought and flood grades. The characteristics of droughts and floods, including their phases, periodicity, and mutability in all regions from 1850 to 1959, were analyzed by employing the accumulative anomaly, wavelet analysis, and sliding *t*-test techniques. The results showed that there were 76 droughts and floods in the Qinling Mountains from 1850 to 1959, with droughts and floods occurred 29 and 47 times, respectively, accounting for 38.16% and 61.84% of the total events, respectively. The changes in drought and flood grade sequences in the Qinling Mountains had obvious phases, showing alternating dry and wet periods. A fluctuating climatic phase with both floods and droughts occurred from 1850 to 1879 and from 1949 to 1959; the climate was relatively wet from 1880 to 1912; the climate was relatively dry from 1913 to 1948. The seasonal variation in droughts in the Qinling mountains was concentrated on spring, summer, and back-to-back summer and autumn seasons; while the seasonal variation in floods was concentrated on summer and autumn, and back-to-back summer and autumn seasons. Moreover, there were two periods, 5~7 a and 11 a, that corresponded to the El Niño-Southern Oscillation (ENSO) activity cycle and were consistent with global climate change. Through the sliding *t*-test technique and comparison of the drought-flood change sequence, there were two common significant mutations on a decade scale and 20-year scale. The positive PSDI swings are conducive to increased flood occurrence and negative PSDI values to increased drought occurrence, and these changes have good consistency of changes in the two data sources, and also verify the good reliability of the reconstruction results in this paper.

**Keywords:** sequence of droughts and floods, wavelet analysis, climate change, the qinling mountains, historical climate

## INTRODUCTION

The current global climate system is the cumulative result of natural changes in the past environment. To understand the current characteristics and future trends of climate, it is necessary to understand how the climate has changed from ancient times to the present. Therefore, the historical climate is an important part of the international Climate Variability and Predictability (CLIVAR) project (Duplessy and Overpeck, 1994). It is of great significance to reconstruct the historical climate change sequence using continuous historical data. As an ancient civilization with a long history and cultural tradition, China has abundant historical documents and continuous historical climate information, which have unique advantages in the field of historical climate research. In other words, these data provide greater possibilities for the reconstruction of China's historical climate status and its evolutionary process (Zhu, 1973; Zheng et al., 1993; Bradley, 1993). Drought and flood are the two most frequent natural disasters in Chinese dynasties (Zhang et al., 2013; Zhang et al., 2014; Xiao et al., 2015) and had significant impacts on the regional social economy, agricultural production, and people's lives and property safety. With the global environmental change, extreme climate events have occurred more frequently (Easterling, 2000), the impact of global drought and flood had further expanded, and the frequency of occurrence of global drought and flood disasters has increased; drought and flood events have gradually become a popular topic in climate research (Zhou, 2003; Wang et al., 2007; Xiao et al., 2015; Konisky et al., 2016; Paulo et al., 2016; Wan et al., 2018).

In recent years, the study of climate change in historical periods has been reconstructed from historical materials, especially the Ming and Qing Dynasty archives, and there have been more achievements. For example, Ge et al. (2007), Zheng et al. (2014), Hao et al. (2008), Ding and Zheng (2020), and Zhang et al. (1997) made a breakthrough in the processing of higher resolution data, such as Yu-Xue-Fen-Cun (Yu-Xue-Fen-Cun is China's earliest, systematic historical archive of ancient weather conditions. To timely understand the agricultural affairs, the rulers of the Qing Dynasty required local officials to report to the Emperor in the form of official reports on the depth of rain (Yu) and snow (Xue) in the area under their jurisdiction, as well as the start and end date of rain and snow. Since "cun" and "fen" were the units of measurement in the Qing Dynasty, it was called "Yu-Xue-Fen-Cun".) and established a series of basic climate change sequences, such as plum rain activity in the lower reaches of the Yangtze River and precipitation in the middle and lower reaches of the Yellow River, over the past 300 years. However, the spatial resolution of Yu-Xue-Fen-Cun data varies greatly. On the whole, the quantity and continuity of data in North China and the middle and lower reaches of the Yangtze River are relatively good, while the data are generally poor in other regions of China. Therefore, it is difficult to reconstruct high-resolution precipitation through historical data, but instead, the changes in drought and flood grades are mainly documented (Zhang et al., 2018), such as in the Atlas of Drought and Flood Distribution in China in the Last 500 Years and its subsequent reconstruction research (Institute of Meteorological Science, Central

Meteorological Administration, 1981; Zhang and Liu, 1993; Zhang et al., 2003; Bai, 2010). For western China, which has a relatively special climate, it is relatively difficult to use historical materials to study its historical climate due to historical limitations and a lack of early data. However, a few scholars have collected a large amount of historical data, local chronicles, and some instrumental data, which make up for the lack of high spatial resolution data and have made great progress in reconstructing the sequences of droughts and floods. Bi et al. (2016) collected and classified drought and flood disaster data in eastern Northwest China from 1470 to 1912 and reconstructed the sequence of drought and flood grades. They found that the drought and flood grade sequence has a high degree of consistency with stalagmite oxygen isotope records during the same period and corresponds to another precipitation sequence, which can indirectly prove the reliability and feasibility of recovered historical flood and drought grade sequences based on historical documentary data. Based on the statistics and collation of the data of drought and flood disasters in the Baoji area from 1368 to 1911, Wan et al. (2018) believed that the successive occurrence of drought and flood events in the Baoji area during the Ming and Qing dynasties was a response to global climate change. Based on historical document records as proxy data, Han et al. (2019) reconstructed the sequence of extreme drought events in North China during 1000–2000 AD and then analyzed the characteristics and principles of these extreme drought events. Liu and Yang (2021) reconstructed the extreme drought and flood events in Southwest China over the past 600 years (1400–2000 AD). By using the drought and flood grade method and the percentile threshold method, they found that ENSO (El Niño-Southern Oscillation) and PDO (Pacific Decadal Oscillation) played an important role in extreme drought and flood events.

The Qinling Mountains are located in the ecological transition zone between warm temperate and subtropical zones in China and represent the most important ecological barrier and one of the richest areas of global biodiversity in central China. As an important geographic and climatic boundary between northern and southern China, this area represents a significant focus and hotspot for climate change research in China (Bai et al., 2019). In recent years, scholars have performed more research on the contemporary climate of the Qinling Mountains (Li et al., 2018; Zhang et al., 2018; Bai et al., 2019; Lu and Lu, 2019; Qi et al., 2020; Zhao et al., 2020; Zhang et al., 2021) but less research on the ancient climate of the Qinling Mountains. To understand the current characteristics and future trends of climate, it is necessary to understand how the climate has changed from ancient times to the present.

Based on the existing historical documents and literatures about counties in the Qinling Mountains, according to the criterion of droughts and floods grade, we reconstructed the sequence of droughts and floods grade from 1850 to 1959. To verify the reliability of the sequence, we performed a comparative analysis of the PDSI data and the sequence of the Qinling Mountains. This study is intended to provide theoretical support for climate refinement research, water resource protection, and regional ecological civilization in the Qinling Mountains.

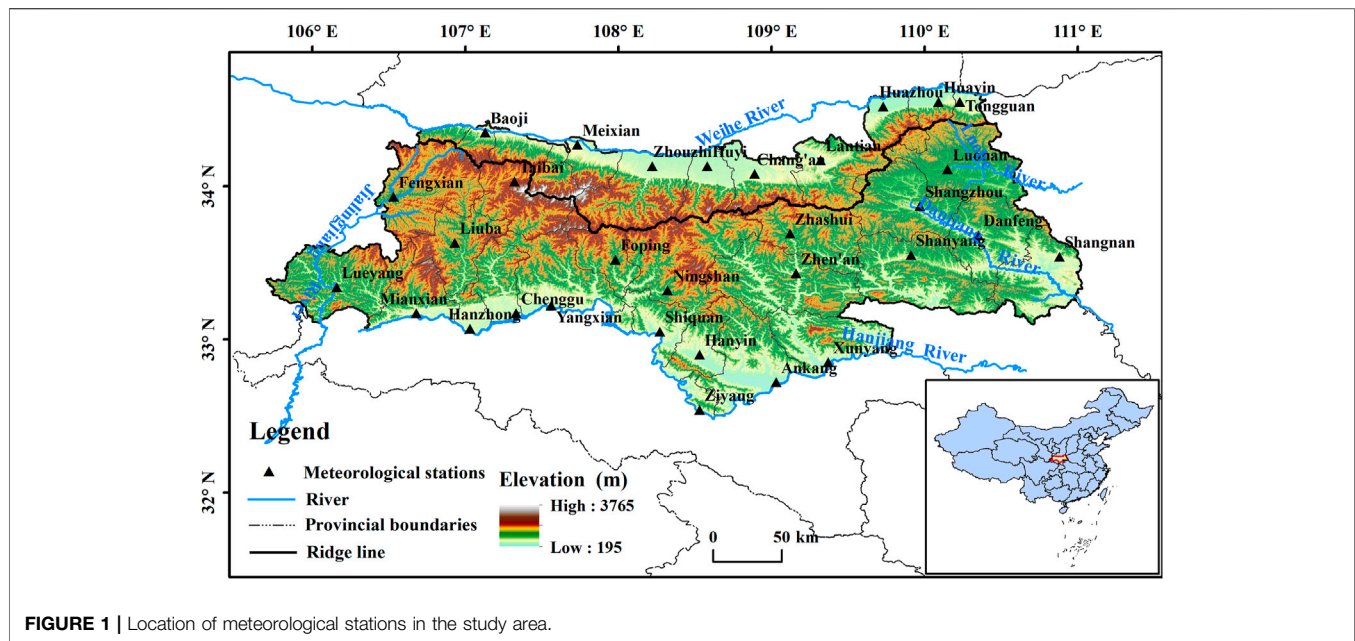


FIGURE 1 | Location of meteorological stations in the study area.

## DATA AND METHODS

### Overview of the Study Areas

The Qinling Mountains stretch across the middle of China and represent a large mountain range that runs from east to the west and generally coincides with the January 0°C isotherm and 800 mm equipluve in China (Bai et al., 2019). The Qinling Mountains are the boundary between the humid monsoon climate and the semihumid monsoon climate, as well as the dividing line between the mixed evergreen and deciduous broad-leaved forest in the northern subtropics and the warm-temperate deciduous broad-leaved forest (Lu and Lu, 2019). The alpine and mid-mountainous landforms of the Qinling Mountains are generally 1500–3000 m above sea level, with a diverse climate, diverse mountain distribution, and obvious vertical zoning characteristics (Bai et al., 2019). As the altitude rises, the warm temperate zone and the medium temperate zone appear in turn, and a cold temperate zone and other vertical climatic zones appear (the southern slope is below the warm temperate zone, and there is a northern subtropical zone). The vertical zonality of the climatic zones and the corresponding vegetation also presents obvious vertical zoning characteristics. This study utilizes the hinterland of the Qinling Mountains in Shaanxi Province as the study area (105°42′~111°06′E and 32°40′~34°35′N). The Weihe River is the boundary between the Qinling Mountains to the north and the Hanjiang River to the south, and it traverses southern Shaanxi from east to the west (Figure 1).

### Data and Preprocessing

The selection of historical documents took into account the influence of climate on a large scale and local climate change and selected historical books, local chronicles, and historical monographs were utilized as data sources. Data sources in this study were based on “A Compendium of Chinese Meteorological Records of the Last 3000 Years” (Zhang, 2000), “Brief Records on

Historical Natural Disasters in Shaanxi” (Wang, 2002), “Encyclopedia of Meteorological Disasters in China; Shaanxi Volume” (Wen and Zhai, 2005), “Disaster History in Northwest China” (Yuan, 1994), and “A collection of historical materials on natural disasters in China’s agriculture” (Zhang, 1994). Shaanxi provincial chronicles and county and city chronicles of each administrative region in the Qinling mountains were also utilized.

For the classification of drought and flood levels in the Qinling mountains, we referred to past classifications of drought and flood levels from the Distribution of Droughts and Floods in the Last 500 Years in China (CMA, 1981), Atlas of the Distribution of Droughts and Floods in the Last 500 Years in Northwest China (Bai, 2010), and the national standard of Classification of Meteorological Droughts (GB/T20481-2006). According to the descriptions of droughts and floods in limited historical data sources, following the duration, intensity, extent of damage, and degree of damage of the disasters, while taking into account the approximate proportion of various records, we classified droughts and floods into five levels based on the standards described in Table 1, including severe drought, mild drought, normal, mild flood, and severe flood. In our reconstructed series, we have validated the records using different sources for the same event. In our reconstructed series, we validated the records using different sources for the same event. We used the drought and flood events in Huaxian County in 1852 as an example. According to the classification standard, the key drought and flood phenomena can be found to discern the drought and flood levels.

It is important to note that when there were multiple records for a given year, the descriptions that were longer in duration, more widespread in impact, or had caused more damage or loss were selected for grading. If there were records of both drought and flooding in a given year and a review of the literature revealed

**TABLE 1** | Classification standards of drought and flood events.

Event level	Event type	Classification standard	Main phenomena
1	Severe drought	A drought of long duration and severe impact occurring over a larger area. In the case of drought, the impact of the drought was severe and the crop yields were reduced or extinguished on a large scale	"In the spring and summer drought, people ate grassroots and bark for thousands of miles on the bare ground"; "in the summer and autumn drought, the harvest was exhausted"; "in the summer hyper drought, famine"; "no rain from april to august, no cereal harvest"; "the river dried up"; "the pond dried up"; "the wellspring was exhausted"; "no rain from april to august"; "rivers dried up"; "ponds dried up"; "wellsprings were exhausted"
2	Mild drought	A drought that occurred on a local scale and was less severe in individual months	"spring drought"; "autumn drought"; "drought"; "drought in a certain month"; "late season crops get less rain"; "drought locust"
3	Normal	A period of good wind and rainfall and abundant crops in a larger area, with no recorded floods or droughts	"big ripening"; "a harvest, a good year"; "bountiful harvest", etc.
4	Mild flood	A single season of continuous precipitation in a small area, with less severe floods	"spring rain hurts the harvest"; "autumn rain harms the crops"; "april floods, famine"; "august floods"; in a certain county, "the water were so steep that the fields were destroyed", etc.
5	Severe flood	A period of high-intensity precipitation in a larger area where precipitation occurred with high intensity and for a long period or caused casualties and property damage	"heavy rain in spring and summer for several days"; "heavy rain for 10 days, the river overflowed"; "spring and summer floods drowned many people and animals"; "the rain was so heavy that the land was flooded with boats for days"; "the floods in several counties" and "the hurricanes and heavy rains drifted over the fields and huts"

**TABLE 2** | Criterion of drought and flood events of huaxian county in 1852.

different sources	Drought and flood phenomenon in huaxian county (1852)	level
local chronicles of huaxian	In the summer drought, the weihe river was cut off and people can wade in vain	1
Shaanxi provincial chronicles	In may and june, Xianning, Chang'an, Weinan, Huaxian, Xiaoyi Hall, and other counties suffered a severe drought, weihe river dried up, people can wade in vain, Xiaoyi Hall's crops and trees were withered	1
Brief records on historical natural disasters in shaanxi	In shaanxi summer in May, the weihe river dried up and can be waded in vain, and hua county was drought in summer	1

that there was a record of "rain" in 1 month but drier records in two adjacent months, then it was classified as "mild drought." According to the records of historical data, we can see that the drought in our paper is a combination of hydrological drought and agricultural drought (Tables 1, 2).

## MATERIAL AND METHODS

### Wavelet Analysis

Based on the Fourier transform, wavelet analysis is a time-frequency analysis method that reflects the local abruptness of time series and better analyses the characteristics of the series over time compared with the Fourier transform. In this paper, the wavelet coefficients are calculated by the wavelet transform method; the periodicity of the sequence is calculated by the real part distribution of the wavelet coefficients, and the wavelet variance reflects the change in the fluctuation energy of the time series with the time scale. Since the evolution of the time series of droughts and floods is continuous and has multiple time scales, this paper adopts the continuous complex wavelet transform based on the Morlet function for analysis. The continuous wavelet transform of the drought and flood hazard class function  $f(t)$  can be expressed as

$$\varphi(t) = e^{ict} e^{\frac{t^2}{2}} \quad (1)$$

$$W_f(a, b) = |a|^{-\frac{1}{2}} \int_{\mathbb{R}} f(t) \varphi\left(\frac{t-b}{a}\right) dt = [f(t), \varphi_{a,b}(t)] \quad (2)$$

where,  $i$  is an imaginary number;  $c$  is a constant;  $W_f(a, b)$  is the wavelet transform coefficient,  $f(t)$  is a time series function,  $a$  is the scaling parameter;  $b$  is the time translation parameter;  $\varphi_{a,b}(t)$  is a series of functions formed by expansion and translation of  $\varphi(t)$ , called continuous wavelet.

The wavelet transform form is:

$$\varphi_{a,b} = |a|^{-\frac{1}{2}} \varphi\left(\frac{t-b}{a}\right) \quad (3)$$

### Sliding $t$ -test

The basic principle of the sliding  $t$ -test (Sheng et al., 2001) is to test for abrupt changes in a climate series by examining the significance of the difference between the means of two sample groups. The basic idea is to test whether there is a significant difference between the means of two subseries in a climate series as a question of whether there is a significant difference between the means from the two overall series. If the difference between the means of the two subseries exceeds a certain significance level,



it is assumed that a qualitative change in the mean value has occurred and that a sudden change in the type and intensity of the hazard has occurred. Let us suppose the two contrastive sequences respectively are  $X_1$  and  $X_2$ , while  $\bar{x}_1$  and  $\bar{x}_2$  are the mean values, and  $H: \bar{x}_1 - \bar{x}_2 = 0$ , as shown in Eqs 4, 5.

$$t = \frac{\bar{x}_1 - \bar{x}_2}{s\left(\frac{1}{n_1} + \frac{1}{n_2}\right)^{-\frac{1}{2}}} \quad (4)$$

$$s = \sqrt{\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}} \quad (5)$$

where  $s_1$  and  $s_2$  respectively are the variances of  $X_1$  and  $X_2$ ;  $n_1$  and  $n_2$  are the lengths of the two sequences;  $t$  meets the distribution of  $t(n_1 + n_2 - 2)$ ; and  $\alpha$  is the given significance level. If  $|t| < t_\alpha$ , then  $H$  is false; on the condition that  $|t| > t_\alpha$ , the higher the value of  $|t|$ , the higher the significance level (Du et al., 2019).

## The Cross Wavelet Transform

The cross wavelet transform (XWT) was used to analyze the relationship between drought and flood sequence and ENSO and sunspots in the Qinling Mountains. The cross wavelet transform (XWT) of two time series  $x_n$  and  $y_n$  is defined as  $W^{XY} = W^X W^{Y*}$ , where  $*$  denotes complex conjugation (Grinsted et al., 2004).

The cross-wavelet power spectrum can be defined as  $|W_n^{XY}(s)|$ , which contains the time-frequency-amplitude information. The larger the value is, the higher the correlation between the two time series is. For two smooth stochastic processes, the normalized form of the cross wavelet transform can be written as the wavelet interrelation number (Du et al., 2019):

$$r(X, Y) = \frac{\sum_{i=1}^n \left( W_i^X(s) - \overline{W_i^X(s)} \right) \left( W_i^Y(s) - \overline{W_i^Y(s)} \right)}{\sqrt{\sum_{i=1}^n \left( W_i^X(s) - \overline{W_i^X(s)} \right)^2} \sqrt{\sum_{i=1}^n \left( W_i^Y(s) - \overline{W_i^Y(s)} \right)^2}} \quad (6)$$

This technique can study the interrelationship between two time series in the time-domain frequency from multiple time scales. The method can reveal the correlation and consistency at two different time scales and can reproduce the phase relationship in the time-frequency space.

## RESULTS

### Characteristics of the Change in Drought and Flood Levels

According to Figure 2, there were 76 drought and flood events in the Qinling Mountains from 1850 to 1959. There were 29 droughts and 47 floods, which accounted for 38.16% and 61.84% of the total events, respectively. According to the statistics of drought and flood levels, there were 7 severe droughts, 22 mild droughts, 34 normal years, 36 mild floods, and 11 severe floods. From 1850 to 1959, floods occurred more frequently than droughts, indicating a relatively humid climate in

the Qinling mountains. There was a continuous distribution of droughts and floods in the level of droughts and floods, with alternating drought and flood events. In terms of the levels of droughts and floods, the Qinling Mountains were characterized by a continuous distribution between droughts and floods, with alternating patterns continuously existing in the drought and flood events.

### Interannual Variation in Drought and Flood Characteristics

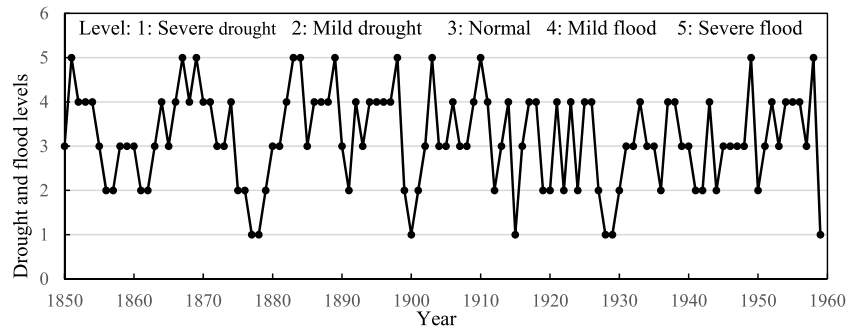
We statistically analyzed the drought and flood characteristics in the Qinling Mountains based on a period of every 10 years (Table 3). We found that a total of 76 drought and flood events occurred in Qinling from 1850 to 1959, and the average frequency was 1.45 years. Overall, the higher frequency of floods than droughts indicates a relatively wet climate in the Qinling mountains from 1850 to 1959. These drought and flood events occurred more frequently from 1870 to 1929, and the frequency showed an increasing trend. However, the frequency of drought and flooding varied in different periods as follows: droughts dominated from 1870 to 1879 and from 1920 to 1929; floods dominated from 1850 to 1869 and from 1950 to 1959; and there were few drought and flood events in 1930–1949.

The cumulative anomaly and 5-year sliding processing of the grade index of drought and flooding from 1850 to 1959 in the Qinling Mountains are shown in Figure 3, where the upward curve indicates a wet trend and the downward curve indicates a dry trend. The drought and flood series in the Qinling Mountains have obvious stage characteristics, which are mainly divided into a rising stage and a falling stage. The period of rising from 1880 to 1912 can be divided into a rising stage from 1880 to 1898, rising stage from 1904 to 1912, and decreasing stage from 1899 to 1904, indicating that flooding occurred more frequently than drought during this phase, while a drought lasting for approximately 5 years occurred between 1899 and 1904. After consulting the data, it was found that there was a large-scale drought with a long duration in approximately 1900. The declining stage from 1913 to 1948 indicates that droughts occurred more frequently than floods during this period.

Generally, the droughts and floods in the Qinling Mountains fluctuated significantly from 1850 to 1959, showing alternating dry and wet periods. Floods were concentrated on the years 1850–1869 and from 1880 to 1899, and droughts in the years 1910–1929. Fluctuations were relatively smooth for the first 30 years of the second half of the 19th century, followed by a trend of increased flooding, and then, as the 20th century progressed, drought events occurred more frequently than flooding events throughout the Qinling Mountains.

### Seasonal Variation in the Characteristics of Droughts and Floods

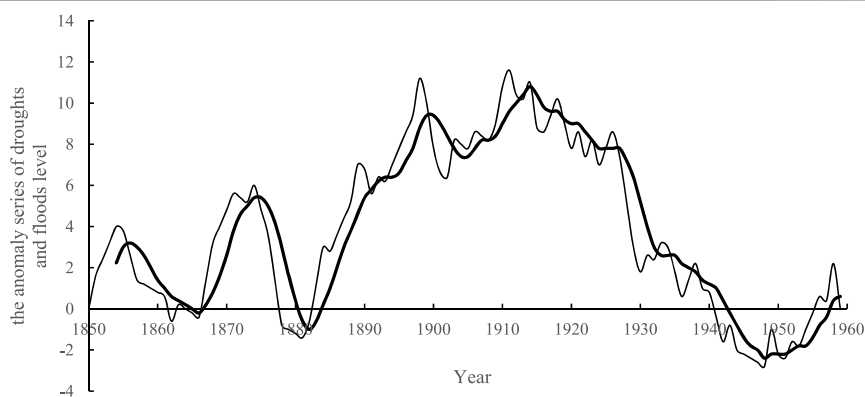
The Chinese lunar calendar is used to divide the seasons, namely, spring from January to March, summer from April to June, fall from July to September, and winter from October to December. Among the disasters with obvious seasonal records in the existing literature data, drought and flooding in the Qinling Mountains



**FIGURE 2 |** Annual grade sequence of droughts and floods in the Qinling mountains from 1850 to 1959.

**TABLE 3 |** The drought and flood level frequency in the Qinling Mountains from 1850 to 1959.

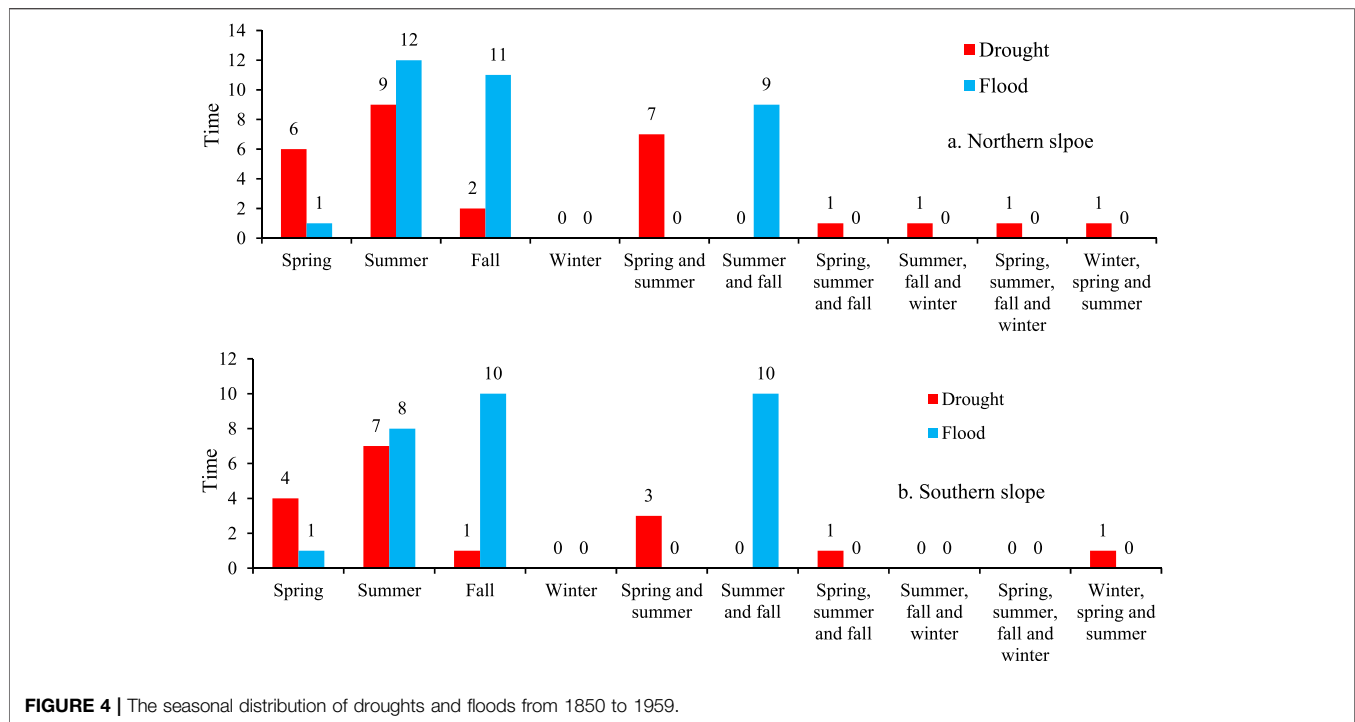
Year	Frequency (%)	Level				
		Level 1	Level 2	Level 3	Level 4	Level 5
		Frequency/%	Frequency/%	Frequency/%	Frequency/%	Frequency/%
1850–1859	6 (7.89)	0 (0)	2 (20)	4 (40)	3 (30)	1 (10)
1860–1869	7 (9.21)	0 (0)	2 (20)	3 (30)	3 (30)	2 (20)
1870–1879	8 (10.53)	2 (20)	3 (30)	2 (20)	3 (30)	0 (0)
1880–1889	7 (9.21)	0 (0)	0 (0)	3 (30)	4 (40)	3 (30)
1890–1899	8 (10.53)	0 (0)	2 (20)	2 (20)	5 (50)	1 (10)
1900–1909	5 (6.58)	1 (10)	1 (10)	5 (50)	2 (20)	1 (10)
1910–1919	8 (10.53)	1 (10)	2 (20)	2 (20)	4 (40)	1 (10)
1920–1929	10 (13.16)	2 (20)	4 (40)	0 (0)	4 (40)	0 (0)
1930–1939	5 (6.58)	0 (0)	2 (20)	5 (50)	3 (30)	0 (0)
1940–1949	5 (6.58)	0 (0)	3 (30)	5 (50)	1 (10)	1 (10)
1950–1959	7 (9.21)	1 (10)	1 (10)	3 (30)	4 (40)	1 (10)
A total of 110 a	76 (100)	7 (6.36)	22 (20)	34 (30.91)	36 (32.73)	11 (10)



**FIGURE 3 |** The anomaly series of drought and flood levels in the Qinling Mountains from 1850 to 1959 (the thin line is the anomaly series of drought and flood levels, and the thick line is the movable sequence for 5 years)

occurred mainly in a single season but also occurred in two, three, or even four seasons (Figure 4). Among them, a single season was the most frequent period of drought and the most frequent in summer, and drought occurred 16 times in a single season, 9 times on the northern slope, and 7 times on the southern

slope. Among the double season droughts, spring and summer droughts were predominant. Among the double season droughts, spring and summer droughts were predominant, with 10 occurrences, while triple and all-season droughts also occurred. Floods were also predominantly single-season floods,



with summer and autumn being the most frequent periods of flooding, occurring 20 and 21 times, respectively, and flooding on the northern slopes was higher in summer than on the southern slopes, while on the southern slopes, it was higher in autumn than in summer; double-season floods were mostly consecutive floods in summer and autumn, occurring 19 times in total. There were no historical records of three or four seasons of flooding.

In conclusion, the seasonal variation in droughts in the Qinling mountains was concentrated on spring, summer, and back-to-back summer and fall seasons, while the seasonal variation in floods was concentrated on summer and fall, and back-to-back summer and autumn seasons. These seasonal characteristics of droughts and floods may have been related to monsoonal activity in the Qinling mountains.

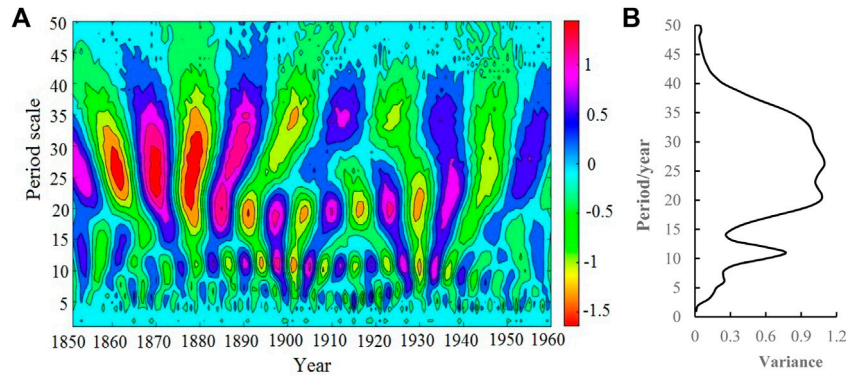
## The Periodical Characteristics of Droughts and Floods

Morlet wavelets were used to diagnose the characteristics of drought and flood cycles in the Qinling Mountains (Figure 5). The horizontal coordinates of the figure are time series, the vertical coordinates are time scales, and the contour curves are the real part values of wavelet coefficients for drought and flood levels (Figure 5A). The central closure of the contour corresponds to the center of precipitation abundance and deficit (center of drought and flood), with positive values indicating flood and negative values indicating drought and the size of the central value reflecting the intensity of fluctuating oscillations. Wavelet variance difference can reflect the change of signal wave energy, so as to determine the main period in a time series (Figure 5B). From the real part of the

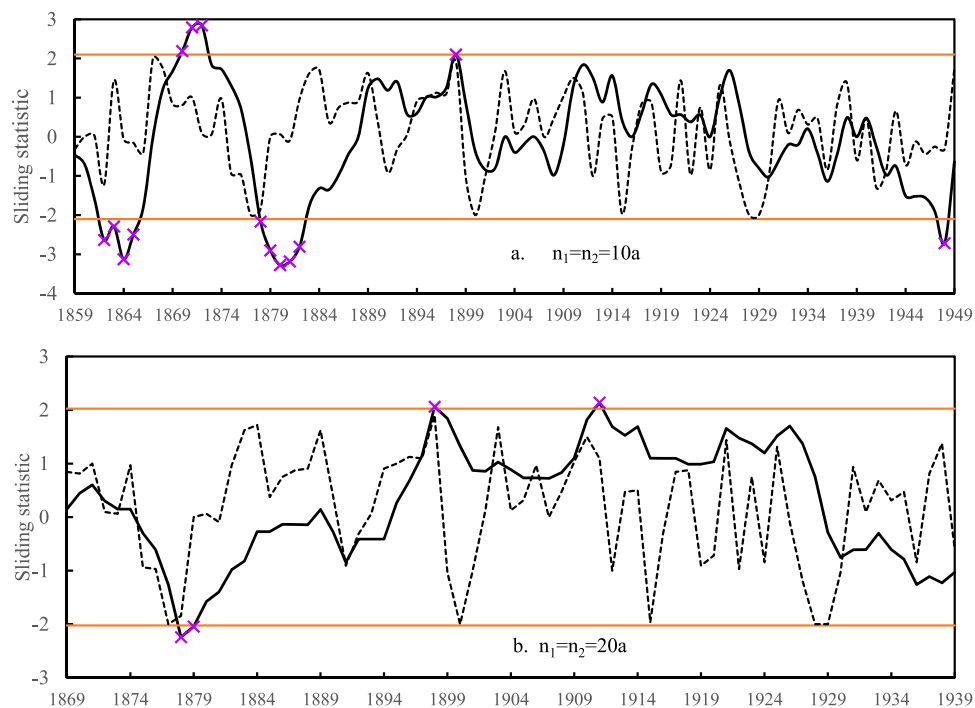
wavelet analysis (Figure 5A), we found obvious alternating characteristics in the Qinling mountains on the time scale, where a drought followed a flood and equally a flood followed a drought. However, overall, we demonstrated that flood events were still dominant in this period, which may have been related to the inherent frequency of climate change in the Qinling mountains. The wavelet variance analysis showed that there were three oscillation cycles at approximately 5~7 a, 11 a, and 20~32 a (Figure 5B). Among them, the 20~32 periodic oscillation was at a maximum peak, which was the first cycle of drought/flood sequence change in the Qinling Mountains. What is clear from Figure 3 is that this is simply a result of one prolonged period of positive values of the drought-flood metric for 40 years (1890–1930). This is clearly a distortion effect of the wavelet analysis working with only 110 years of data. With this in mind, we removed all the results from the timescales of 20 years and longer. So, the 11 a periodic oscillation was the first cycle, and the 5~7 a periodic oscillation was the second cycle. These significant cycles were consistent with sunspot activity and the El Nino activity cycle, indicating that the periods of drought and flood change in the Qinling Mountains were closely linked to the cycles of sunspot and sea-air movements.

## The Mutation Characteristics of Droughts and Floods

The sliding  $t$ -test method was used to determine drought/flood mutation by examining whether the difference between the means of the two groups of samples was significant. To avoid the drift of mutation points caused by arbitrarily selected subsequence length, we used variable subsequence lengths for



**FIGURE 5 |** Wavelet analysis of real parts and variance plots of drought and flood hazard class indices in the Qinling mountains.



**FIGURE 6 |** The sliding *t*-test statistic curve of drought and flood levels in the Qinling mountains from 1850 to 1959 (orange line is the threshold value line of the 95% *t*-distribution; thin black dashed line is the change line of the drought and flood sequence; thick black line is the statistic curve of the *t*-test; *x* is a mutation point).

experimental comparisons and determined the subsequent lengths to be 10 and 20 years. Under the given significance level  $\alpha = 0.05$ , when  $n_1 = n_2 = 10$ , by *t*-distribution degrees of freedom  $f = n_1 + n_2 - 2 = 18$  ( $t_{0.05} = \pm 2.101$ ), the statistical values were above the significance level of 0.05 in 5 places (Figure 6A); when  $n_1 = n_2 = 20$ ,  $f = n_1 + n_2 - 2 = 38$  ( $t_{0.05} = \pm 2.024$ ), there were 3 more places above the 0.05 significance level (Figure 6B).

Through the test and comparison of the two different subsequences, there were two significant mutations in common, which occurred in 1878–1882 and 1898. One of the two mutations was from the beginning of the drought period to the flood period, and the other was from the flood period to the

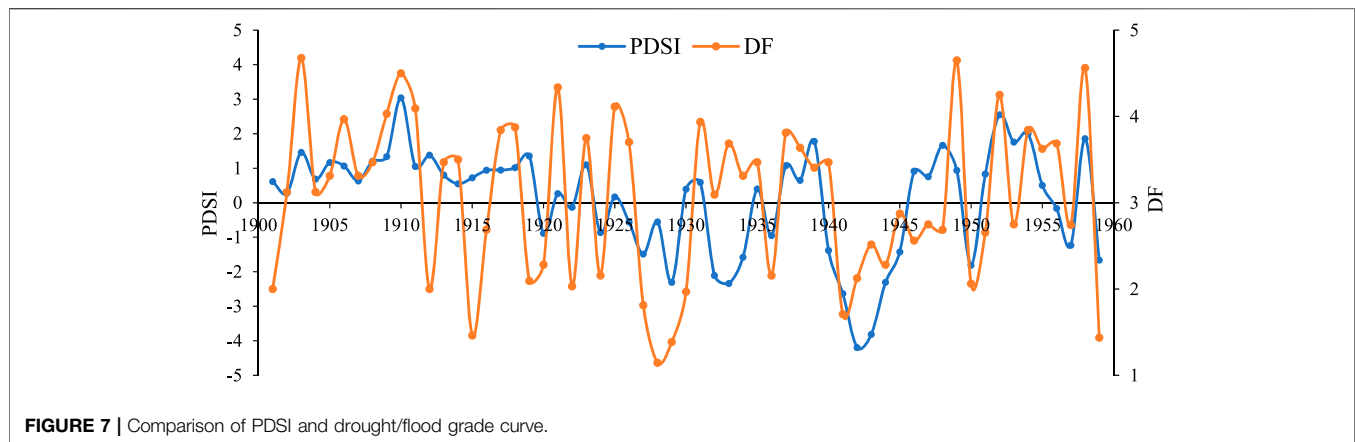
drought period. From the perspective of the overall change, the climatic evolutionary features of drought period-flood period alternation are presented.

## DISCUSSION

### Reliability Validation of Drought and Flood Grade Sequences

In the study area, the long-term trend of the drought and flood grade series and the PDSI for the Qinling Mountains from 1901 to 1959 were analyzed and compared to further investigate drought





**FIGURE 7** | Comparison of PDSI and drought/flood grade curve.

and flood conditions and test the reliability of the drought and flood grade series in the Qinling Mountains from 1850 to 1959 that was recovered from historical records. The PDSI data were obtained from the deglobalized  $0.5^\circ \times 0.5^\circ$  monthly scale self-corrected PDSI database constructed by the Climate Research Unit (CRU) of East Anglia University, United Kingdom. We downloaded the PDSI data of nine grids in the Qinling Mountains and took the average of all the grids as the PDSI values of the Qinling area. In order to satisfy the conditions for comparative analysis, the reconstruction period after 1901 was selected. In general, by breaking down the DF metric to consider the occurrence of floods and droughts separately, we found the positive PSDI swings are conducive to increased flood occurrence and negative PSDI values to increased drought occurrence (**Figure 7**). These changes have good consistency of changes in the two data sources, and also verify the good reliability of the reconstruction results in this paper.

However, there are periods when droughts and floods do not coincide with the change of negative and positive PSDI values, such as the early 1930s and from 1946 to 1948. These differences in drought and flood changes may be due to the two indices have different classification criteria, and PDSI is a state-based metric with positive values denoting a wet extremes (i.e., floods) and negative values denoting dry extremes (i.e., droughts), and the DF metric is an occurrence-based metric—that includes both floods and droughts in the accounting; or due to different sampling points, different spatial scales of the reconstructed data, or human factors; or due to the reconstructed data were mainly based on the most significant drought and flood event per year, ignoring other less severe droughts and floods. While in general, the positive PSDI swings are conducive to increased flood occurrence and negative PSDI values to increased drought occurrence.

## The Mechanisms of Floods and Droughts

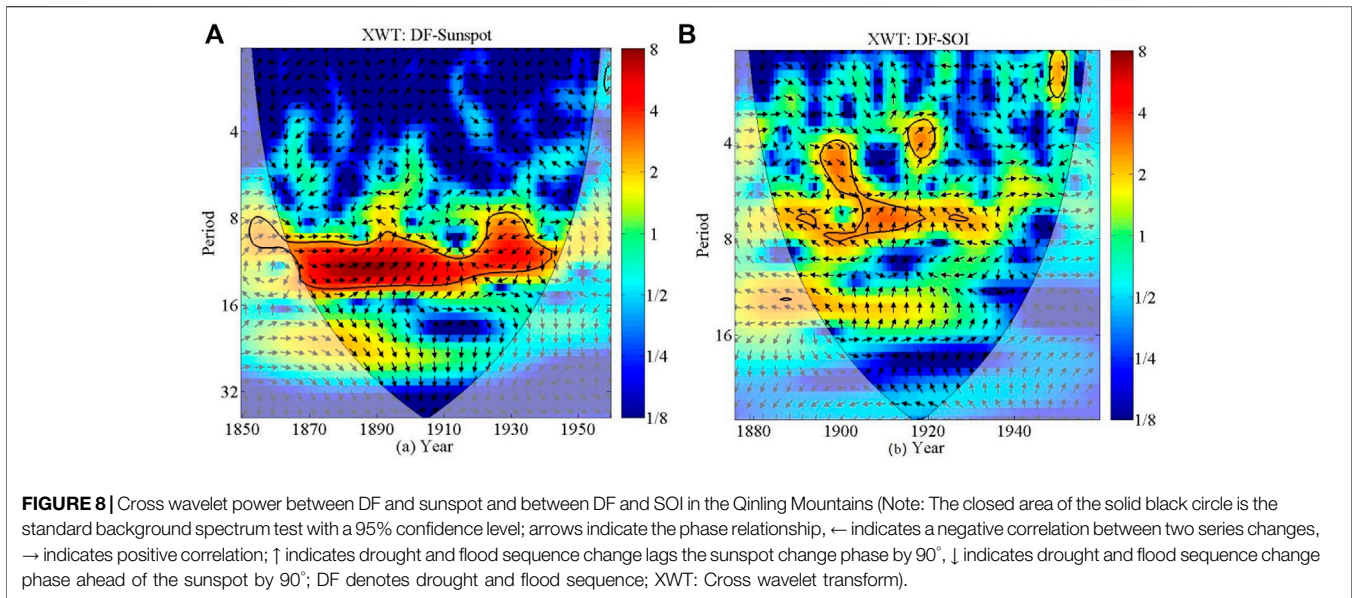
The Qinling Mountains are located in the eastern monsoon region of China, which is the boundary between the northern subtropical zone and the warm temperate zone, and the mechanisms affecting Qinling Mountain drought and flood evolution are complex. It has been shown that precipitation in northern China is negatively correlated with SST in the eastern equatorial Pacific, and that ENSO is closely related to Asian

monsoon variability and influences precipitation over most of China (Zhu and chen, 2002; Lu, 2005); when ENSO was in the cold phase, the Walker and Hadley circulations were strengthened by the higher SST over the equatorial Western Pacific, and the descending branch broke the subtropical high northward, presenting a humid climate in northern China (Yang and Lau, 2004). The periodic changes of 5~7a in the drought-flood reconstruction sequence data further prove this relationship. Therefore, in order to further explore the relationship between drought and flood changes in the Qinling Mountains and the large-scale circulation, the reconstructed drought and flood data are analyzed with the Pacific Southern Oscillation index.

It has been shown that, during the very low solar activity period, the eastern part of China shows a “flood-drought-flood” pattern from south to north, i.e., the Yangtze River basin is drought-prone, and southern and northern China are flooded; the opposite is true for the very high period (Ge et al., 2016). There are negative correlations between precipitation and sunspots and they are most obvious in 9-year time scale in the Yellow River Basin in China (Li and Yang, 2006); the sunspot number and drought and flood of Guanzhong Plain in China showed negative relationship through 1960s, since the 1970s to the present, the two factors showed the positive relationship (Dou and Yan, 2013).

These studies demonstrate that there is a relationship between sunspots and changes in the drought and flood index series. In addition, since the cycles of drought and flood data in the Qinling Mountains are similar to those of sunspots, the relationship between drought and flood data and sunspots is analyzed in the paper. We chose sunspot number (1850–1959) and the Southern Oscillation Index (SOI, 1876–1959) to analyze the causes of drought and flood variability in the Qinling Mountains.

Through cross wavelet analysis (**Figure 8**), we found that there was a significant resonant periodic oscillation of approximately 9~12 a between sunspot and Qinling drought/flood sequence values from 1850 to 1940. There was a significant positive correlation before 1910 and a significant negative correlation after 1910. That is, before 1910, when sunspots reached a peak year, the Qinling Mountains were prone to flooding events, and after 1910, when sunspots reached a valley year, the Qinling



Mountains were prone to flooding events. During 1892–1920, the Southern Oscillation Index (SOI) and the drought/flood series in the Qinling Mountains had a significant resonant periodic oscillation of 4~8 a, and the two were mostly positively correlated. The factors affecting Qinling Mountain drought and flood evolution are complex. Future studies should identify more influencing factors, conduct in-depth mechanistic exploration, and provide suggestions for the production of forestry and agriculture in this region. Nevertheless, the presented analysis suggests that there are periods where the occurrence of droughts and floods vary distinctly with sunspot activity and SOI.

The factors affecting Qinling Mountain drought and flood evolution are complex. Future studies should identify more influencing factors, conduct in-depth mechanistic exploration, and provide suggestions for the production of forestry and agriculture in this region.

## Study Limitations

In this paper, the grade sequences of droughts and floods in the Qinling Mountains from 1850 to 1959 were reconstructed using historical data, but the droughts and floods can reflect only the trend of abnormal climate change, which is mainly determined by the nature of historical data itself. From the classification criteria of drought and flood grade, we can see that our reconstructed data were mainly based on the most significant drought and flood event per year, ignoring other less severe droughts and floods. However, the study of historical droughts and floods can be regarded as an effective method of research. Given the limitations of historical documents and literature, although the collected historical materials have been compared and verified, the years with no records or conflicting records have not been verified one by one, and the obscure language of historical materials leads to some subjectivity and uncertainty in the classification of classes. According to the definitions of meteorological drought,

hydrological drought, agricultural drought, and socioeconomic drought, as well as the records of historical data and the classification criteria of drought and flood grade, we can see that the drought in our paper is quite difficult to distinguish properly between the different types of drought.

Wavelet analysis is a powerful tool for observing the periodic nature of timeseries, but we must be very careful in judging and interpreting the periodicity of time series between the timespan of the raw data and the periodic timescales of the wavelet decomposition. It is clear that wavelet timescales of 20 years or longer are compromised in the 100-year timespan of droughts and floods reconstruction. With this in mind, we removed all the results from the timescales of 20 years and longer. In addition, drought and flood occurrences are not only affected by ENSO and solar activity but also may be closely related to air-sea interaction influences and large-scale human activities, which will be the direction of future research.

## CONCLUSION

In this paper, the grade sequences of drought and flood in the Qinling mountains from 1850 to 1959 were reconstructed by using historical data, and we used various mathematical methods to study the characteristics of drought and flood disasters in this region. Our conclusions are as follows:

A total of 76 drought and flood events occurred in the Qinling area from 1850 to 1959. Among these events, droughts and floods occurred 29 and 47 times, respectively, which accounted for 38.16% and 61.84% of the total events, respectively. From 1850 to 1959, floods occurred more frequently than droughts, indicating a relatively humid climate in the Qinling mountains. There was a continuous distribution of droughts and floods in the hierarchy of droughts and floods, with alternating drought and flood events.

The changes in drought and flood grade sequences in the Qinling Mountains had obvious phases. A fluctuating climatic phase with both floods and droughts occurred from 1850 to 1879 and from 1949 to 1959; the climate was relatively wet from 1880 to 1912, and the climate was relatively dry from 1913 to 1948. The seasonal variation in droughts in the Qinling mountains was concentrated on spring, summer, and back-to-back summer and autumn seasons, while the seasonal variation in floods was concentrated on summer and autumn, and back-to-back summer and autumn seasons.

Through the sliding *t*-test method and comparison of the drought-flood change sequence, there were two significant mutations in common, which occurred in 1878–1882 and 1898. One of the two mutations was from the beginning of the drought period to the flood period, and the other was from the flood period to the drought period. From the perspective of the overall change, the climatic evolutionary features of drought period-flood period alternation were presented.

Wavelet variance analysis showed that there were 2 oscillation cycles at approximately 5~7 a, and 11 a. Sunspots and the Southern Oscillation Index (SOI) were closely related to the changes in drought and flooding in the Qinling Mountains.

The positive PSDI swings are conducive to increased flood occurrence and negative PSDI values to increased drought occurrence, which indirectly proved that the sequence recovered from historical documents has good reliability.

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## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

## AUTHOR CONTRIBUTIONS

SZ: Investigation, Methodology, Writing—Original draft preparation. GQ: Conceptualization, Data curation, Software. KS: Visualization, Writing—Review and Editing. LZ: Data Curation, Formal analysis. HB: Supervision, Conceptualization, Project administration, Funding acquisition.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/feart.2022.860750/full#supplementary-material>

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