J. Geogr. Sci. 2018, 28(3): 337-350
DOI: https://doi.org/10.1007/s11442-018-1476-y

Spatio-temporal evolution of drought and flood disaster chains in Baoji area from 1368 to 1911

WAN Honglian[1,2], SONG Hailong[1,3], ZHU Chanchan[1], ZHANG Beibei[1,2], ZHANG Mi[1]

1. College of Geography and Environment, Baoji University of Arts and Sciences, Baoji 721013, Shaanxi, China;
2. Key Laboratory of Disaster Monitoring and Mechanism Simulation of Shaanxi Province, Baoji University of Arts and Sciences, Baoji 721013, Shaanxi, China;
3. Suide Middle School, Suide 718000, Shaanxi, China

Abstract: Based on the collation and statistical analysis of flood and drought information in Baoji area from 1368 to 1911, and in the context of climate change, we investigated the spatio-temporal evolution characteristics of drought and flood disaster chains in this area during the Ming and Qing dynasties using the methods of moving average, cumulative anomaly and wavelet analysis. The results are as follows: (1) We found a total of 297 drought and flood events from 1368 to 1911 in Baoji. Among these events, droughts and floods occurred separately 191 and 106 times, which accounted for 64.31% and 35.69% of the total events, respectively. (2) We observed distinct characteristics of flood and drought events in Baoji in different phases. The climate was relatively dry from 1368 to 1644. A fluctuant climate phase with both floods and droughts occurred from 1645 to 1804. The climate was relatively wet from 1805 to 1911. Moreover, we observed a pattern of alternating dry and wet periods from 1368 to 1911. In addition, 3 oscillation periods of drought and flood events occurred around 70 a, 110 a and 170 a, which corresponded to sunspot cycles. (3) We also observed an obvious spatial difference in drought and flood events in Baoji. The northern and eastern parts of Weihe River basin were regions with both frequent droughts and floods. (4) The sequential appearance of drought and flood disaster chains in Baoji from 1368 to 1911 was in response to global climate change. Since the 1760s, global climatic deterioration has frequently led to extreme drought and flood events.

Keywords: Baoji area; drought and flood disaster chain; climate change; spatio-temporal distribution; wavelet analysis

1 Introduction

Drought and flood are common meteorological events, which have severe regional impacts on production, daily life and socioeconomic development. China is located in eastern Asia.

Received: 2017-03-22 **Accepted:** 2017-05-04
Foundation: National Natural Science Foundation of China, No.41601016; Philosophy and Social Science Research Fund in Shaanxi, No.2017E003; Fundamental Research Funds for Key Subject Physical Geography of Baoji University of Arts and Sciences
Author: Wan Honglian (1969–), PhD and Professor, specialized in resource development and environmental change, the disaster in history and other works of research and teaching. E-mail: hyhm2006@163.com

The droughts and floods exhibit regionally distinct patterns of distribution, which are affected by both monsoon intensity and global climate change. Droughts and floods were collectively the worst natural disasters during the span of successive dynasties of China (Wang and Zhao, 1979; Ge *et al*., 2013; Xiao *et al*., 2015). In the context of global warming, extreme weather events have increased the frequency of droughts and floods in recent years. Therefore, a number of research areas, including identifying climate change patterns, reducing the influence of drought and flood disasters on regional development, and studying the human response to global climate change, have gradually become the hotspots and focus of academic research (Zhou, 2003; Wang *et al*., 2007; Xiao *et al*., 2014; Li and Li, 2016).

The occurrence of droughts and floods is closely linked to climate change. According to the study of Zhu (1973), at the end of the Yuan Dynasty and the beginning of the Ming Dynasty, the method of documenting climatic events shifted from “documental period” to “gazetteer period”, and the records of various disasters became more elaborate. In the same time span, China entered a cold period of 500 years called “the little ice age (LIA) of Ming and Qing dynasties”. The frequency of various natural disasters in this period also reached a historic high (Wang *et al*., 1998; Wang *et al*., 2006; Zhu, 2012), which has become a focus of research in recent years (Ye *et al*., 2012; Wan *et al*., 2017). Additionally, the sequential and adequate historical records provide us the opportunity to study the regional history of droughts and floods, and reconstruct the process of climate evolution (Bradley, 1993; Zheng *et al*., 1993; Shi *et al*., 2012). Moreover, drought and flood disasters have become important factors that impede economic development. As such, drought and flood related research has become the focus of regional disaster prediction and mitigation.

Currently, researchers have obtained fruitful results from their studies of drought and flood events in different historical periods (Lee and Zhang, 2010; Yuan *et al*., 2015; Pei *et al*., 2015; Ge *et al*., 2016). Zhou analyzed the spatio-temporal distribution characteristics and patterns of drought and flood events in Baoji area in the past 1500 years (Zhou, 2003a, 2003b). He found that the occurrence of droughts and floods in Baoji corresponded to global climate change, and these disasters were the regional responses to environmental changes. Wan *et al*. found that the occurrence of drought and flood events in Baoji in the past 1400 years primarily resulted from the combination of geographic location, abnormal climatic fluctuations and human activities, which greatly impacted the regional socioeconomic development (Wan, 2014; Wan *et al*., 2013, 2017). The research outcomes described above are consistent with the conclusions of drought and flood studies at larger spatial scales (Zheng *et al*., 1993; Lee and Zhang, 2010; Yuan *et al*., 2015; Pei *et al*., 2015), which analyzed both the disasters and their impacts. However, the relationship between regional drought and flood disaster chain and global climate change remains largely unexplored.

In this study, based on historical records of droughts and floods in Baoji from 1368 to 1911, and also in reference to the recent domestic studies of the relationship between drought and flood disasters and global climate change in 100 to 1000 year timescales (Ge *et al*., 2013; Zheng *et al*., 2014), we studied the spatio-temporal distribution and periodical change pattern of droughts and floods in Baoji during the climatic fluctuation period of the LIA of Ming and Qing dynasties using “disaster chain” as the entry point. In addition, we also discussed the relationship between regional drought and flood disaster chains and global climate change. The results of this study will provide a reference basis for the early prediction, preparedness and mitigation of drought and flood disasters in Baoji.

2 Overview of the study area

Baoji area is located in western Guanzhong region (106°18'–108°03'E and 33°35'–35°06'N). The west-to-east length is 156.6 km and the north-to-south width is 160.6 km. The 2015 total population estimate of Baoji, comprising 3 districts and 9 counties, was 3.76 million. Baoji lies in the Guanzhong Plain and is located in the upstream and midstream of Weihe River basin with the Qinling Mountains to the south, the Beishan Mountains to the north and the Guanshan Mountain to the west, belonging to the southwest Loess Plateau. The Qinling Mountains to the south of Baoji are the dividing line of southern and northern China. Northern Baoji faces the hinterland of the Loess tablelands. The interior of Baoji has intricate geological formations, and distinct topographic and geomorphologic features. Mountains, rivers and plains co-exist with mountainous and hilly landforms in predomination. In terms of climate, Baoji is located in the warm temperate and semi-humid climate zone. Local climate change is blocked by the Qinghai-Tibet Plateau, Qilian Mountains and Qinling Mountains. The spatio-temporal distribution of local precipitation varies significantly with the influence of the East Asian monsoon, Qinghai-Tibet high and western Pacific Subtropical High. The average annual precipitation is between 590 and 900 mm (BLCCC, 1998). Consequently, natural disasters have occurred frequently due to the influence of climatic conditions, topographic features and geological formations, and droughts and floods are the major form of natural disasters in this area.

3 Data sources and method

Data sources of this study are based on “The Historical Inundation and Drought of Baoji” (WCN, 1985) and “Encyclopaedia of China’s Meteorological Disasters; Shaanxi Volume” (Wen and Zhai, 2005), from which we collated the flood and drought information of Baoji using lunar calendar. Moreover, we further analyzed and verified these collected data with references, including “A Compendium of Chinese Meteorological Records of the Last 3000 Years” (Zhang, 2000), “Disaster History in Northwest China” (Yuan, 1994), “Brief Records on Historical Natural Disasters in Shaanxi” (Wang, 2002), and local chronicles of Baoji and the counties of Fengxiang, Qishan, Meixian, Fufeng, Longxian, Qianyang, Linyou, Fengxian and Taibai (CLCSSP, 1991; Baoji CCCC, 1998; Fufeng CCCC, 1993; Linyou CCCC, 1993; Longxian CCCC, 1993; Meixian CCCC, 2000; Qishan CCCC, 1992; Taibai CCCC, 1998). By this means, we removed incomplete data and improved the creditability of historical data. Additionally, for the classification of drought and flood levels in Baoji, we referred to past classifications of drought and flood levels in Baoji from *Yearly Charts of Dryness/Wetness in China for the Last 500 Years Period* (CMA, 1981), *The Atlas of Drought and Flood Distribution over Northwest China in Past 500 Years*: *1470–2008* (Bai *et al*., 2010; Xu *et al*., 2015), the national standard of *Classification of Meteorological Droughts* (*GB*/*T20481-2006*) and the national hydraulic industry standard of *Flood Disaster Assessment* (*SL 579-2012*). According to the descriptions of droughts and floods in our data sources, we classified droughts and floods into 7 levels based on the standards described in Table 1, including catastrophic flood, severe flood, mild flood, normal, mild drought, severe drought and catastrophic drought (Bai *et al*., 2010; Xu *et al*., 2015). Furthermore, we processed and analyzed the drought and flood levels using statistical analysis software, ArcGIS and MATLAB, and we also investigated the drought and flood disaster chains in Baoji and the response to climate change during the Ming and Qing dynasties.

Table 1 The classification standard of drought and flood events

Event level	Event type	Classification standard
1	Catastrophic flood	The flood lasted for a long time and affected most of the area. Had a remarkable effect on local production activities and living conditions, and caused casualties.
2	Severe flood	The flood affected a large portion of the area, resulting in submerged agricultural lands, damaged crops, reduced production, destroyed housing, and prompted tax exemption.
3	Mild flood	The flood slightly affected local living conditions, crop production and socioeconomic development.
4	Normal	No droughts or floods were recorded.
5	Mild drought	The drought affected sowing and reduced crop production, and resulted in food shortages and high food prices.
6	Severe drought	The drought caused starvation, locust infestation and severe pandemic, forced people to consume wood bark and grass, and led to extremely high food prices, relocation of people and even casualties.
7	Catastrophic drought	The drought affected most of the area, resulting in nearly no harvest, extreme poverty, severe food shortages, cannibalism, frequent sightings of starved corpses and numerous casualties.

4 Results and analysis

4.1 The inter-annual variation in drought and flood characteristics

We statistically analyzed the drought and flood characteristics in Baoji based on a period of every 50 years. The results showed that in the Ming and Qing dynasties, drought and flood events occurred 297 times in Baoji, and the average frequency was 1.83 years. These events occurred more frequently in the middle and late stages of the study period, and the frequency showed an upward trend. Moreover, we conducted cumulative anomaly analysis of the drought and flood levels in Baoji from 1368 to 1911. The moving average of 11 years was selected to match the periodic fluctuations in solar activity that follows the approximate 11-year cycle (Figure 1). The characteristics of drought and flood events in Baoji in different phases are presented in Figure 1. In the years between 1368 and 1644, the curve of the anomalies slopes upward. We observed two sharp rises spanning 1368–1530 and 1581–1644, and one gradual rise in 1531–1580, which indicates that droughts occurred more frequently than floods. From 1645 to 1804 was a phase marked by fluctuant climate with both floods and droughts, indicating unstable climate and abnormal patterns of droughts and floods. From 1805 to 1911, the curve slopes downward. We observed a sharp drop from 1868 to 1911, and a relatively flat curve from 1854 to 1867, which indicate that floods occurred more frequently than droughts in this phase. Overall, from 1368 to 1911 in Baoji, drought and flood events showed considerable fluctuations, and we observed a pattern of alternating dry and wet periods. In the whole study period, droughts occurred more frequently in the early and middle stages, and floods occurred more frequently in the late stage.

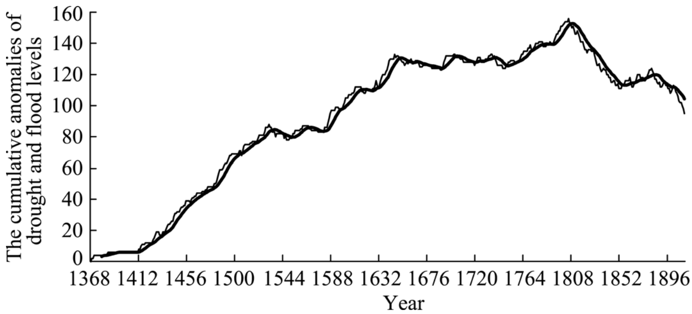

Figure 1 The anomalies of drought and flood levels in Baoji area from 1368 to 1911

4.2 The seasonal characteristics of drought and flood changes

We divided the four seasons according to the lunar calendar as follows: spring from January to March (March to May in Georgian calendar), summer from April to June (June to August in Georgian calendar), fall from July to September (September to November in Georgian calendar) and winter from October to December (December to following February in Georgian calendar). Based on our data sources, 87 drought and flood events were recorded without seasonal information, and with seasonal information there were 210 drought and flood events recorded, which included 128 droughts and 82 floods.

In Baoji, drought and flood events usually spanned a single season. However, we also found instances where continuous droughts and floods spanned two to four seasons in total (Figure 2). In terms of drought and flood disasters in Baoji, droughts were dominant and typically occurred within a single season. In particular, droughts occurred most frequently in summer with a total of 41 events. The two-season droughts mainly continued from summer into fall with a total of 20 events. We also observed that some droughts continued for three or four seasons. Meanwhile, the majority of floods occurred within a single season. Fall had the highest frequency of floods with a total of 35 events. The two-season floods mainly continued from summer into fall with a total of 9 events. We did not find historical records of floods that lasted three or four seasons. From the above analysis, the droughts and floods in Baoji from 1368 to 1911 mainly occurred during summer or fall months or lasted from summer into fall, and the seasonal distributions of droughts and floods were associated with summer monsoon activities. Baoji is located in the inland monsoon boundary zone. Under the influences of the East Asian monsoon, Indian Low and Western Pacific Subtropical High, warm and rainy weather alternates with hot and dry weather in summer. Under the influences of the Qinghai-Xizang high and Siberian high, the weather is cold and dry in winter. Because spring and fall are the transition periods between winter and summer monsoons, precipitation in these two seasons is highly unstable, which also primarily accounts for the high frequency of droughts and floods in summer and fall seasons, and causes the average annual precipitation to fluctuate between 590 and 900 mm.

4.3 The spatial characteristics of changes in droughts and floods

The Baoji area includes 3 districts and 9 counties (Wan *et al*., 2013, 2014, 2016, 2017). The drought and flood information of Taibai County was not included because the county was

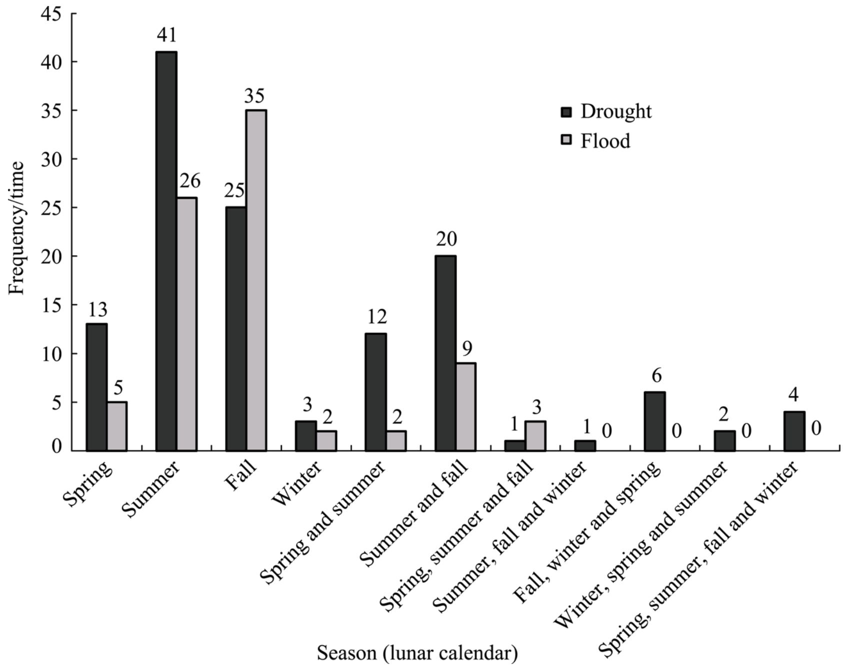

Figure 2 The seasonal distribution of droughts and floods in Baoji area from 1368 to 1911

established in 1961. Through collating all drought and flood events based on where the disasters occurred, we found that the distribution of drought or flood varies in different counties of Baoji from 1368 to 1911 (Figure 3).

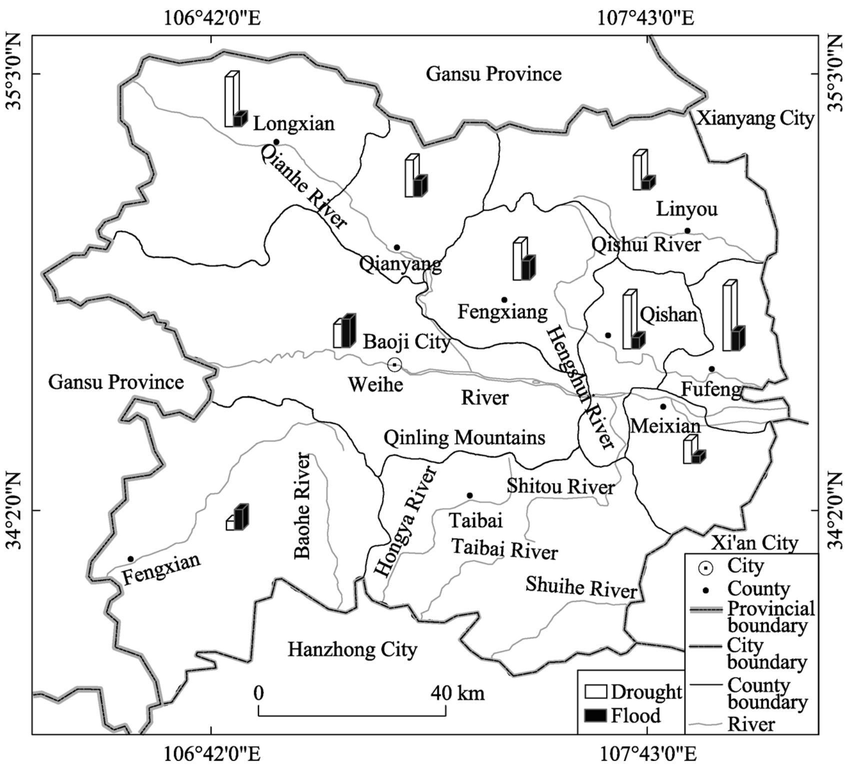

Figure 3 The spatial distribution of droughts and floods in Baoji area from 1368 to 1911

From the distribution of droughts and floods in every county, Fufeng County had the most droughts with 51 events. Qishan and Longxian counties had the 2nd and 3rd most droughts, with 42 and 39 events, respectively. On the contrary, Fengxian County located to the south of Qinling Mountains had the least droughts with only 7 events. Meanwhile, Baoji City had the most floods with 22 events and Fengxian County had the 2nd most floods with 16 events. With only 6 floods, the least number of floods occurred in Meixian County. In terms of the entire Baoji area, droughts were mainly distributed in the region to the north of the Qinling Mountains with the distinction that more droughts occurred in the north than in the south. Droughts occurred frequently in the 6 counties located in the Qianhe and Qishui river basins in the northern Weihe River basin, which accounted for 86.91% of the total number of droughts in the entire Baoji. Meanwhile, floods mainly occurred in the southern Weihe River basin and eastern Baoji area, including Baoji City, and Fengxian, Fufeng and Fengxiang counties and accounted for 64.15% of the total number of floods in Baoji. As such, the northern and eastern parts of the Weihe River basin (the midstream and downstream of Weihe River), and the midstreams and downstreams of Qian and Qishui river basins, had frequent occurrences of both droughts and floods in Baoji from 1368 to 1911.

4.4 The periodical characteristics of droughts and floods

We performed wavelet analysis of the series of drought and flood levels in Baoji during the 544-year period in the Ming and Qing dynasties using MATLAB (Figure 4), and we also conducted correlation analysis of drought and flood cycles. From the real wavelet analysis (Figure 4a), we found an obvious pattern of alternating droughts and floods in Baoji from 1368 to 1911, where a flood followed a drought, and vice versa. Meanwhile, we demonstrated that the drought events were still dominant in this period, which is consistent with the conclusions from studies of Zhu (1973) and Zhu *et al*. (1998). They also posited that the climate in China was dry during the Ming and Qing dynasties, and during the LIA of Ming and Qing dynasties. The wavelet variance analysis (Figure 4b) showed that there were 3 oscillation periods around 60–80 a, 95–115 a, and 160–180 a, and the oscillation period around 160–180 a was most intense. Our findings match well with the research of Li and Zhao (2008), which demonstrated that there was a period around 168 a for the drought and flood disasters in northwestern China. In addition, our findings also corresponded with Xu and Jiang's research (1990), which showed that the sunspot cycles were around 5.5 a, 11 a, 17 a, 80 a, and 178 a, indicating that the drought and flood disasters in Baoji were very closely associated with sunspot cycles.

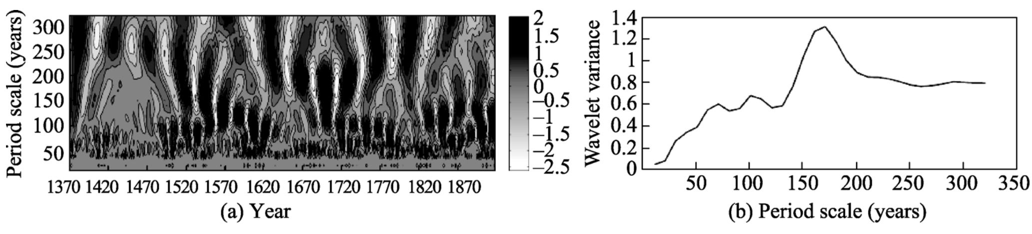

Figure 4 Real wavelet and wavelet variance analyses of droughts and floods in Baoji area from 1368 to 1911

4.5 The characteristics of the change in drought and flood levels

According to the classification standard of droughts and floods in Table 1, we found that a total of 297 drought and flood events occurred in Baoji from 1368 to 1911. There were 191 droughts and 106 floods, which accounted for 64.31% and 35.69% of the total events, respectively. Droughts occurred more frequently than floods. There were 31 catastrophic floods, 39 severe floods, 36 mild floods, 247 normal weather conditions, 68 mild droughts, 101 severe droughts and 22 catastrophic droughts, which respectively corresponded to 5.7%, 7.17%, 6.62%, 45.4%, 12.5%, 18.57% and 4.04% of the total events (Table 2). Overall, the higher frequency of droughts than floods indicates a relatively dry climate in Baoji from 1368 to 1911. In addition, we noted a pattern of continuity between droughts and floods. Namely, an extreme flood event was always followed by an extreme drought event, and vice versa. This alternating pattern continuously existed in the flood and drought disaster chains in Baoji from 1368 to 1911.

Table 2 The numbers and percentages of drought and flood events in Baoji area in 544 years

Year	Frequency (%)	Level						
		Level 1 Catastrophic flood	Level 2 Severe flood	Level 3 Mild flood	Level 4 Normal	Level 5 Mild drought	Level 6 Severe drought	Level 7 Catastrophic drought
		Frequency (%)	Frequency (%)	Frequency (%)	Frequency (%)	Frequency (%)	Frequency (%)	Frequency (%)
1368–1420	8 (2.69)	0 (0)	0 (0)	0 (0)	45 (84.91)	4 (7.55)	4 (7.55)	0 (0)
1421–1470	29 (9.76)	0 (0)	3 (6)	3 (6)	21 (42)	11 (22)	10 (20)	2 (4)
1471–1520	25 (8.42)	1 (2)	2 (4)	0 (0)	25 (50)	10 (20)	8 (16)	4 (8)
1521–1570	22 (7.41)	4 (8)	2 (4)	1 (2)	28 (56)	2 (4)	11 (22)	2 (4)
1571–1620	23 (7.71)	1 (2)	1 (2)	4 (2)	27 (54)	1 (2)	9 (18)	7 (14)
1621–1670	40 (13.47)	1 (2)	5 (10)	9 (18)	10 (20)	5 (10)	16 (32)	4 (8)
1671–1720	16 (5.39)	0 (0)	5 (10)	2 (4)	34 (68)	2 (4)	6 (12)	1 (2)
1721–1770	23 (7.74)	2 (4)	4 (8)	1 (2)	27 (54)	7 (14)	9 (18)	0 (0)
1771–1820	35 (11.78)	7 (14)	5 (10)	1 (2)	15 (30)	9 (18)	13 (26)	0 (0)
1821–1870	36 (12.12)	7 (14)	3 (6)	7 (14)	14 (28)	10 (20)	8 (16)	1 (2)
1870–1911	40 (13.47)	8 (19.51)	9 (21.95)	8 (19.51)	1 (2.44)	7 (17.07)	7 (17.07)	1 (2.44)
A total of 544 a	297 (100)	31 (5.7)	39 (7.17)	36 (6.62)	247 (45.4)	68 (12.5)	101 (18.57)	22 (4.04)

5 Discussion

5.1 The causes of floods and droughts

Baoji area is located in western Guanzhong Plain and has distinct climate, temperature and precipitation characteristics due to the influences of intricate topographic and geomorphologic features, and monsoons. Temperature and precipitation changes in this area are uneven at both spatial and temporal scales. Ren (1986) reported that the periodic climate change in China was not only related to the gravitation generated by the exceptional alignment of planets in our solar system, but it was also consistent with the periodic temperature oscillations of the Northern Hemisphere, which are induced by the Pacific Decadal Oscillation (PDO) phenomenon. PDO, which presents above the Pacific Ocean with alternating warm and cool phases, can potentially aggravate natural disasters when it meets El Niño and La Niña. The PDO has greatly impacted the periodic climate change in China and particularly in Baoji, resulting in the uneven distribution of flood and drought events in this area. This uneven distribution is basically constant with monsoon activities, which indicates a good correspondence between floods and droughts in Baoji and global climate change.

According to previous studies at a regional scale, the temperature change and the variation in dryness and wetness greatly affected precipitation during the last 2000 years (Ge *et al*., 2012, 2014, 2015; Zheng *et al*., 2005, 2010; Fang *et al*., 2014). Notably, although the Northern Hemisphere entered the cold stage during the Ming and Qing dynasties, climate change in China exhibited instability under the joint influences of location, geographic environment and monsoon, which consequently resulted in the alternating pattern of flood and drought events during this period. Moreover, the climate fluctuated from wetness to dryness during the Ming Dynasty, and the worst droughts since the Qin and Han dynasties had occurred in the late Ming Dynasty (Ge *et al*., 2012, 2014, 2015; Zheng *et al*., 2005, 2010; Fang *et al*., 2014). In the Qing Dynasty, climate was generally wet but with significant fluctuation. The uneven climate change induced flood and drought events profoundly impacted the socioeconomic development in China. In Baoji, drought and flood events occurred alternately from 1368 to 1911, which was linked to the regional terrain and the factors affecting monsoon activities in this period. The general circulation of the atmosphere, sunspot activities and regional centralization of human activities aggravated the frequency of drought and flood events in this period. Since the 1760s, under the influence of industrial revolution, human activities have led to the deterioration of the global climatic environment. Global temperature has risen continuously, climatic environment change has become unpredictable, and extreme flood and drought events have occurred frequently.

5.2 The changes in drought and flood disaster chains from 1368 to 1911

In 1987, Chinese seismologist Guo Zengjian firstly proposed the concept of “disaster chain”, which describes the phenomenon that a series of disasters occur successively (Guo *et al*., 2007). Since then, this concept has been gradually introduced and applied to other disasters. Drought and flood disaster chain refers to the alternating occurrence of droughts and floods, which results from the interactions among regional disaster-prone environment, disaster-inducing factors, and regional society and economy. Drought and flood disaster chains can not only lead to regional agricultural production loss, but also greatly impact regional socioeconomic development, and even cause social instability and casualties. Baoji is located in the monsoon boundary zone, and the climate instability of this area may cause variations in temperature and precipitation, and further change regional climate (Fang *et al*., 2015). The cold-dry and warm-wet change in water-heat regime is mainly affected by monsoon. Regional precipitation exhibits remarkable increases in the years with relatively strong summer monsoon activities, and conversely, decreases with weaker summer monsoon activities. In the Ming and Qing dynasties, the drought and flood disaster chains in Baoji exhibited an obvious alternating pattern. Drought was the dominant type of disaster before 1644, the frequencies of droughts and floods were balanced from 1645 to 1804, and flood became dominant from 1805 to 1911. Although the occurrence of droughts and floods in Baoji had distinct characteristics in each phase, a common phenomenon we observed was that a flood event usually preceded or followed a drought event, and vice versa. One such example is the extreme drought events that occurred from 1632 to 1635 and from 1638 to 1642, and the widespread starvation and cannibalism during these droughts were historically recorded. Furthermore, we found that extreme flood events occurred from 1630 to 1631 and from 1647 to 1655, which respectively preceded and followed the extreme drought events, and the crop loss and cannibalism during these floods were also historically recorded. In general, the drought and flood disaster chain is a real and subjective phenomenon, and the primary reason underlying this particular disaster chain is the conservation, conversion and transmission, and redistribution of energy in drought and flood disasters (Guo *et al*., 2007; Yang, 2008).

5.3 The relationship between the drought and flood disaster chain and climate change

Under the influence of the little ice age of Ming and Qing dynasties, the climate obviously became cold in eastern China, but the climate in western China did not change significantly (Zheng *et al*., 2010). Moreover, the climate change in various small areas exhibited various characteristics (Zhang *et al*., 2007; Zhang *et al*., 2008; Yang *et al*., 2014; Ge *et al*., 2014). In the region from the eastern part of the Qilian Mountains and the eastern edge of the Qaidam Basin to the western side of the Qinling Mountains, the climate was wet in the 14th century, from the second half of the 16th century to the beginning of the 17th century, and in the second half of the 18th century. On the contrary, the climate in the above area was dry in other periods, and the driest periods appeared in the 15th century and from the late 17th century to the beginning of the 18th century (Ge *et al*., 2012, 2014, 2015). Zhu *et al*. (1998) studied the historical climate change in Guanzhong region, and they reported that the climate was relatively warm in the second half of the 14th century, from the 1500s to the 1570s, in the 18th century and the first half of the 19th century. However, the climate was very cold in the second half of the 15th century, from the 1580s to the 1630s, in the second half of the 17th century and the second half of the 19th century. From the second half of the 14th century to the beginning of the 20th century, the global climate was in a little ice age, and accordingly, the climate in China was relatively dry and cold (Zhu, 1973; Zhu *et al*., 1998). Although the climate change exhibited some differences at small spatial scales, abundant precipitation usually occurred regionally in the warm period, and less precipitation occurred regionally in the cold period. In the period with abnormal climate fluctuations, extreme climate disasters occurred frequently (Yuan *et al*., 2015; Zhu *et al*., 1998; Zheng *et al*., 2005, 2010; Fang *et al*., 2014). Since the 1470s, the changes in flood and drought levels in China and Guanzhong region that were reported in the above studies are consistent with those recorded in *Yearly Charts of Dryness/Wetness in China for the Last 500 Years Period* (CMA, 1981) and *The Atlas of Drought and Flood Distribution over Northwest China in Past 500 Years*: *1470–2008* (Bai *et al*., 2010).

In the aforementioned climate change scenario, the flood and drought levels in Baoji during the Ming and Qing dynasties were smoothed using an 11-year moving average filter (Figure 5), which showed a good correspondence with the flood and drought level changes in Guanzhong region. In Figure 5, an upward curve indicates that more droughts occurred compared to floods, and conversely, a downward curve indicates that more floods occurred. The curve above the normal level line indicates a relatively dry climate, while the curve be-low the normal level line indicates a relatively wet climate. More droughts occurred in Baoji and the overall climate was relatively dry before the 16th century, from the end of the 16th century to the first half of the 17th century, and in the second half of the 18th century, indicating a relatively cold and dry climate in Baoji during these periods. Meanwhile, more floods occurred in Baoji and the overall climate was relatively wet in the 16th century, from the second half of the 17th century to the first half of the 18th century, and after the 19th century, indicating a relatively warm and wet climate in Baoji during these periods. The above results are consistent with the spatio-temporal distribution characteristics of flood and drought events in Baoji. The occurrence of flood and drought disaster chains in Baoji was basically constant with the overall climate change in Guanzhong region. However, the flood and drought disaster chains in Baoji moved in the same direction, yet not completely simultaneously, with global climate change during the Ming and Qing dynasties, which was linked to the location and geographic environment of this area. In Baoji, under the combined influences of the western Pacific subtropical high, Qinghai-Xizang high, Siberian high and monsoons, the regional droughts and floods exhibited unstable changes and occurred in chains. In each period described above, some fluctuations existed in the regional drought and flood events and temperature at smaller scales. Droughts and floods were dependent on regional precipitation and its intensity, while precipitation was highly influenced by the regional temperature (Zhu *et al*., 1998). If the weather is warm and wet and influenced by regional climate fluctuations, regional droughts and floods will also occur with intensive precipitation.

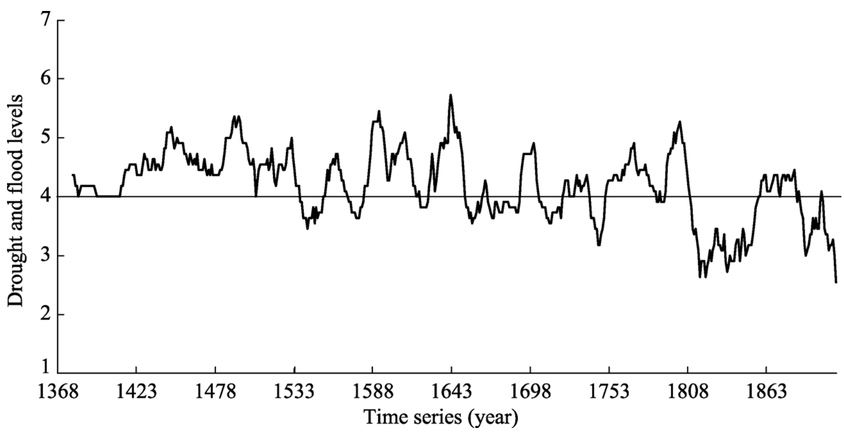

Figure 5 The 11-year moving average of drought and flood levels in Baoji area from 1368 to 1911

6 Conclusions

(1) From 1368 to 1911, a total of 297 drought and flood events occurred in Baoji area. Among these events, droughts and floods occurred separately 191 and 106 times, which accounted for 64.31% and 35.69% of the total events, respectively. The number of droughts outnumbered floods during the Ming and Qing dynasties, and the climate was relatively dry. We observed a pattern of continuity between droughts and floods, which exhibited the alternating occurrence of drought and flood disaster chains.

(2) We observed distinct characteristics of flood and drought events in Baoji in different phases. The climate was relatively dry from 1368 to 1644. A fluctuant climate phase with

both floods and droughts occurred from 1645 to 1804. The climate was relatively wet from 1805 to 1911. Moreover, we observed a pattern of alternating dry and wet periods from 1368 to 1911. In addition, 3 oscillation periods of drought and flood events occurred around 70 a, 110 a, and 170 a, which corresponded to sunspot cycles and moved in the same direction as global climate change. In Baoji, drought and flood events usually spanned a single season. However, we also found instances where continuous droughts and floods spanned two to four seasons.

(3) We observed an obvious spatial difference in drought and flood events in Baoji from 1368 to 1911. In terms of the entire Baoji area, droughts were concentrated in the region to the north of Qinling Mountains with the distinction that more droughts occurred in the north than in the south. Meanwhile, floods mainly occurred in the southern Weihe River basin and in eastern Baoji. Moreover, the northern and eastern parts of the Weihe River basin, and the midstreams and downstreams of Qianhe and Qishui river basins had frequent occurrences of both droughts and floods from 1368 to 1911.

(4) From 1368 to 1911, the drought and flood disaster chains in Baoji corresponded well with global climate change and served as a response process to global climate change. Since the 1760s, under the influence of human activities, global climatic deterioration has frequently led to extreme drought and flood events.

References

Bai Huzhi, Dong Anxiang, Zheng Guangfen *et al*., 2010. The Atlas of Drought and Flood Distribution over Northwest China in Past 500 Years: 1470–2008. Beijing: China Meteorological Press. (in Chinese)

Baoji Local Chronicles Compilation Committee (BLCCC), 1998. Baojizhi (First Volume). Xi'an: Sanqin Press. (in Chinese)

Bradley R S, 1993. High Resolution Record of Past Climate from Monsoon Asia, the Last 2000 Years and Beyond, Recommendations for Research. PAGES Workshop Report, Series 93–1, 1–24.

Central Meteorological Administration (CMA), 1981. Yearly Charts of Dryness/Wetness in China for the Last 500 Years Period. Beijing: Cartographic Publishing House. (in Chinese)

Chinese Local Chronicles Series in Shaanxi Province (CLCSSP), 1991. Qianyang County Annals. Xi'an: Shaanxi People's Education Publishing House. (in Chinese)

Fang Xiuqi, Su Yun, Yin Jun *et al*., 2015. Transmission of climate change impacts from temperature change to grain harvests, famines and peasant uprisings in the historical China. *Scientia Sinica* (*Terrae*), 45(6): 831–842. (in Chinese)

Fang Xiuqi, Zheng Jingyun, Ge Quansheng, 2014. Historical climate change impact-response processes under the framework of food security in China. *Scientia Geographica Sinica*, 34(11): 1291–1298. (in Chinese)

Fufeng County Chronicles Compilation Committee (Fufeng CCCC), 1993. Fufeng County Annals. Xi'an: Shaanxi People's Publishing House. (in Chinese)

Ge Quansheng, Fang Xiuqi, Zheng Jingyun, 2014. Learning from the historical impacts of climatic change in China. *Advances in Earth Science*, 29(1): 23–29. (in Chinese)

Ge Quansheng, Liu Jian, Fang Xiuqi *et al*., 2013. General characteristics of temperature change and centennial warm periods during the past 2000 years. *Acta Geographica Sinica*, 68(5): 579–592. (in Chinese)

Ge Quansheng, Liu Lulu, Zheng Jingyun *et al*., 2016. Spatial patterns of drought/flood over eastern China in the periods of anomalous solar activity during the past millennium. *Acta Geographica Sinica*, 71(5): 707–717. (in Chinese)

Ge Quansheng, Zheng Jingyun, Hao Zhixin *et al*., 2012. General characteristics of climate changes during the past 2000 years in China. *Scientia Sinica* (*Terrae*), 42(6): 934–942. (in Chinese)

Ge Q S, Zheng J Y, Hao Z X *et al*., 2013. General characteristics of climate changes during the past 2000 years in China. *Science China*: *Earth Sciences*, 56(2): 321–329.

Ge Quansheng, Zheng Jingyun, Hao Zhixin *et al*., 2014. State-of-the-arts in the study of climate change over China for the past 2000 years. *Acta Geographica Sinica*, 69(9): 1248–1258. (in Chinese)

Ge Quansheng, Zheng Jingyun, Hao Zhixin, 2015. PAGES synthesis study on climate change in Asia over the last 2000 years: Progresses and perspectives. *Acta Geographica Sinica*, 70(3): 355–363. (in Chinese)

Guo Zengjian, Guo Anning, Zhou Kexing, 2007. Geophysical Disaster Chain. Xi'an: Xi'an Map Publishing House. (in Chinese)

Lee HF, Zhang DD, 2010. Changes in climate and secular population cycles in China, 1000 CE to 1911. *Climate Research*, 42: 235–246.

Li Xiaogang, Li Min, 2016. Analysis of change law of drought and flood disasters from 1430 to 2000 in Shangluo. *Acta Agriculturae Jiangxi*, 28(2): 101–105, 111. (in Chinese)

Li Yanfang, Zhao Jingbo, 2008. The research on the flooding disaster in Guanzhong in recent 200 years. *Journal of Arid Land Resources and Environment*, 22(4): 96–99. (in Chinese)

Linyou County Chronicles Compilation Committee (Linyou CCCC), 1993. Linyou County Annals. Xi'an: Shaanxi People's Publishing House. (in Chinese)

Longxian County Chronicles Compilation Committee (Longxian CCCC), 1993. Longxian County Annals. Xi'an: Shaanxi People's Publishing House. (in Chinese)

Meixian County Chronicles Compilation Committee (Meixian CCCC), 2000. Meixian County Annals. Xi'an: Shaanxi People's Publishing House. (in Chinese)

Pei Lin, Yan Zhong Wei, Yang Hui, 2015. Multidecadal variability of dry/wet patterns in eastern China and their relationship with the Pacific Decadal Oscillation in the last 413 years. *Chinese Science Bulletin*, 60(1): 97–108. (in Chinese)

Qishan County Chronicles Compilation Committee (Qishan CCCC), 1992. Qishan County Annals. Xi'an: Shaanxi People's Publishing House. (in Chinese)

Qing Fengxiang Magistrate Da Line, 2002. Revision on the Fengxiang Government Record. Xi'an: Xi'an Map Publishing House, The Chinese Local Chronicles the Baoji Office Jiaozhu Reprint. (in Chinese)

Ren Zhenqiu, 1986. Climate anomalies and astronomy nearly five thousand years of China. *Agricultural Archaeology*, (1): 298–303. (in Chinese)

Shi F, Yang B, Von Gunten L, 2012. Preliminary multiproxy surface air temperature field reconstruction for China over the past millennium. *Science China Earth Sciences*, 55(12): 2058–2067.

Taibai County Chronicles Compilation Committee (Taibai CCCC), 1998. Taibai County Annals. Xi'an: Sanqin Press. (in Chinese)

Wan Honglian, 2014. Flood disaster and its social impacts in Baoji area during the past 1400 years. *Journal of Arid Land Resources and Environment*, 28(4):79–82. (in Chinese)

Wan Honglian, Liu Dongyue, Song Hailong, 2016. Earthquake disasters and its spatial and temporal distribution characteristics of Baoji in history period. *Journal of Baoji University of Arts and Sciences* (*Natural Science Edition*), 36(3): 1–5. (in Chinese)

Wan Honglian, Song Hailong, Zhu Chanchan *et al*., 2017. Analysis of hail disasters and its spatial and temporal distribution characteristics in Shaanxi region from 1368 to 2013. *Journal of Arid Land Resources and Environment*, 31(2): 123–127. (in Chinese)

Wan Honglian, Song Hailong, Zhu Chanchan *et al*., 2017. Drought and flood disaster chain and its response to climate change in Baoji region during the Ming and Qing dynasties. *Acta Geographica Sinica*, 72(1): 27–38. (in Chinese)

Wan Honglian, Zhou Qi, Fan Weihan *et al*., 2013. Flood disasters in the Baoji region during the period of AD. 600–2000. *Arid Zone Research*, 30(4): 697–704. (in Chinese)

Wang Jinsong, Chen Fahu, Yang Bao *et al*., 2006. New advances in research on the Little Ice Age climate change. *Advances in Climate Change Research*, 2(1): 21–27. (in Chinese)

Wang S W, Wen X Y, Luo Y *et al*., 2007. Reconstruction of temperature series of China for the last 1000 years. *Chinese Science Bulletin*, 52(23): 3272–3280.

Wang Shaowu, Ye Jinlin, Gong Daoyi, 1998. Climate in China during the Little Ice Age. *Quaternary Sciences*, 18(1): 54–64. (in Chinese)

Wang Shaowu, Zhao Zongci, 1979. An analyses of historical data of droughts and floods in last 500 years in Chi-

China. *Acta Geographica Sinica*, 34(4): 330–334. (in Chinese)

Wang Shousen, 2002. Brief Records on Historical Natural Disasters in Shaanxi. Beijing: China Meteorological Press. (in Chinese)

Water Conservancy Newsroom (WCN), 1985. Baoji: The historical inundation and drought of Baoji. (in Chinese)

Wen Kegang, Zhai Youan, 2005. Encyclopaedia of China's Meteorological Disasters: Shaanxi Volume. Beijing: China Meteorological Press. (in Chinese)

Xiao L B, Fang X Q, Zhang Y J *et al*., 2014. Multi-stage evolution of social response to flood/drought in the North China Plain during 1644–1911. *Regional Environmental Change*, 14(2): 583–595.

Xiao L B, Fang X Q, Zheng J Y *et al*., 2015. Famine, migration and war: Comparison of climate change impacts and social responses in North China between the late Ming and late Qing dynasties. *Holocene*, 25(6): 191–196.

Xu Xiaoyu, Zhu JiWei, Xie Jiancang *et al*., 2015. Analysis of spatial and temporal distribution characteristics and evolution trend of drought and flood disasters from 1470 to 2012 in Shaanxi Province. *Journal of Xi'an University of Technology*, 31(2): 231–237. (in Chinese)

Xu Zhentao, Jiang Yaotiao, 1990. Research and Modern Applications of the Sunspot in Ancient China. Nanjing: Nanjing University Press. (in Chinese)

Yang B, Qin C, Wang J L *et al*., 2014. A 3,500-year tree-ring record of annual precipitation on the northeastern Tibetan Plateau. *Proceedings of the National Academy of Sciences of the United States of America*, 111(8): 2903–2908.

Yang Xuexiang, 2008. Disaster chain rules can't be ignored. *Geography Teaching*, (5): 1–4. (in Chinese)

Ye Y, Fang X, Khan M A U, 2012. Migration and reclamation in Northeast China in response to climatic disasters in North China over the past 300 years. *Regional Environmental Change*, 12(1): 193–206.

Yuan Lin, 1994. Disaster History in Northwest China. Lanzhou: Gansu People's Publishing House. (in Chinese)

Yuan Yuan, Huang Shaoni, Guo Chunyan *et al*., 2015. The reconstruction and trend study of Shaanxi province's drought and floods grade in recent 500 years. *Agricultural Research in the Arid Areas*, 33(5): 232–236, 244. (in Chinese)

Zhang De'er, 2000. A Compendium of Chinese Meteorological Records of the Last 3000 Years. Nanjing: Jiangsu Education Press. (in Chinese)

Zhang D D, Zhang J, Lee H *et al*., 2007. Climate change and war frequency in eastern China over the last millennium. *Human Ecology*, 35(4): 403–414.

Zhang P Z, Cheng H, Edwards R *et al*., 2008. A test of climate, sun, and culture relationships from an 1810-year Chinese cave record. *Science*, 322(5903): 940–942.

Zheng Jingyun, Hao Zhixin, Zhang Xuezhen *et al*., 2014. Drought/flood spatial patterns in centennial cold and warm periods of the past 2000 years over eastern China. *Science Bulletin*, 30: 2964–2971. (in Chinese)

Zheng Jingyun, Shao Xuemei, Hao Zhixin *et al*., 2010. An overview of research on climate change in China during the past 2000 years. *Geographical Research*, 29(9): 1561–1570. (in Chinese)

Zheng Jingyun, Wang Shaowu, 2005. Assessment on climate change in China for the last 2000 years. *Acta Geographica Sinica*, 60(1): 21–31. (in Chinese)

Zheng Jingyun, Zhang Peiyuan, Zhou Yufu, 1993. During historical times by using the number of drought/flood counties. *Geographical Research*, 12(3): 1–9. (in Chinese)

Zhou Qi, 2003a. Analysis on the correspondence between the agricultural disasters caused by droughts and waterloggings in Baoji and the climate change in east China during the past 1500 years. *Arid Zone Research*, 20(2): 123–126. (in Chinese)

Zhou Qi, 2003b. Agriculture response to environmental change in west Guanzhong Plain during the past 1500 years. *Journal of Arid Land Resources and Environment*, 17(5): 26–29. (in Chinese)

Zhu Kezhen, 1973. The primary study of climate changes in China since the past 5 ka. *Science in China* (*Series B*), (2): 169–189. (in Chinese)

Zhu Shengzhong, 2012. Spatial and temporal distributions of floods and droughts in Liangshan in Ming and Qing dynasties. *Geographical Research*, 31(1): 23–33. (in Chinese)

Zhu Shiguang, Wang Yuanlin, Hu Lingui, 1998. Study on climate variations in the region of Guanzhong in the historical period. *Quaternary Sciences*, (1): 1–11. (in Chinese)