Extreme historical droughts and floods in the Hanjiang River basin since 1426

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Abstract: The major droughts and floods in the Hanjiang River basin have a significant impact on the flood prevention and control in the middle reaches of the Yangtze River and water resources management in the areas of the South-North Water Diversion Middle Line Project of China. However, there is a lack of understanding of the multi-decadal to centennial scale patterns of extreme droughts and floods in the river basin. Applying the yearly drought/flood records from historical documents and precipitation data in the period of instrumental measurements, this study constructs a time series of extreme droughts and floods in the Hanjiang River basin from 1426-2017, and analyzes the temporal and spatial characteristics of the extreme drought/flood events variations. The results show that there were 45 extreme droughts and 52 extreme floods in the river basin over the past 592 years. Extreme droughts and floods were highly variable on multi-decadal to centennial scale, with both the first and last more than 100 years of the whole period witnessing higher frequencies. Spatially, the frequency of extreme droughts and floods is generally higher in the middle and lower reaches than in the upper reaches. It was also found that there is a good correlation of droughts and floods frequencies between the upper Hanjiang River basin and North China. These results are informative for the study of mechanisms and predictability of multi-decadal to centennial scale variability of extreme hydro-climatic events in the river basin.

Key words: Drought; Flood; Climate variation; Historical documents; Hanjiang River; Yangtze River; China

1 Introduction

Extreme droughts and floods often severely impact agricultural production, people's livelihoods, and socio-economic development. Throughout the history of human development, there have been "almost no years without disaster" (Deng, 1958). In the historical records of natural disasters in China, droughts and floods dominate in particular, showing their tremendous impact on the society and economy.

According to the IPCC Fifth Assessment Report (AR5), the global mean surface temperature showed a significant upward trend from 1880 to 2012, increasing by 0.85℃, and the global temperature increase in the 21st century will probably exceed 1.5-2.5℃ (IPCC, 2013). The climate warming not only directly affects changes in temperature extremes but also lead to changes in the frequency of regional droughts and floods (Goswami et al., 2006; Krysanova et al., 2008; Dai, 2013; Aiken and Rauscher, 2019). Observational studies have shown an increasing trend in precipitation over much of the mid to high latitudes during 1901-2010. However, decreasing trends of precipitation have been observed in other regions including northern Africa, the Mediterranean, southern Africa, and much of eastern and southern Asia (IPCC, 2013). In China, since the late 1970s, the eastern region showed a pattern of "south floods and north droughts" (Sun and Chen, 2003; Hsu et al., 2014), with precipitation in Northern China, Southwest China and southern Northeast China going to decrease. In contrast, precipitation and heavy rainfall in the Yangtze River basin and southeast coastal areas increased (Ding et al., 2008; Zhang et

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删除[X.dan]: The frequency of extreme droughts was high during the 15th century, early 16th century, the 17th, and the 20th centuries, with the 20th century being the highest. For extreme floods, the frequency was high in the 16th century, the 17th century, the 19th century, and the 20th century, with the 19th to 20th centuries being the highest. The 18th century was a common low period of extreme droughts and floods, while the 20th century saw a high frequency of both.

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al., 2008; Chen et al., 2012; Wang and Fan, 2013). However, since the beginning of the 21st century, the precipitation pattern in the eastern part has shown a reversal trend, with the precipitation in the Yangtze River Basin decreasing significantly, the precipitation in North China and southwestern Northeast China beginning to increase, and the drought in Southwest China intensified (Ren et al., 2015a; Ding et al., 2020).

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An essential scientific question currently facing the academic community is how extreme precipitation, droughts and floods will change in East Asia in the future under global climate warming, and what are the differences in future extreme precipitation events in different large river basins in eastern China's monsoon region. Climate model simulations and observational studies based on historical series of precipitation, drought and flood data are the primary means for understanding the patterns and mechanisms of decadal to century scale variability in precipitation and droughts/floods. Meanwhile, understanding the patterns and mechanisms of past precipitation variability is a prerequisite for predicting future precipitation and extreme precipitation. In particular, the long series of climate data can be used to study patterns of historical precipitation and drought/flood variation, and they are also essential for testing the climate models used for projecting future climate. Therefore, the long-term observations or proxy data of the past hundred to several hundred years at different spatial scales are first required to meet the demand of the studies.

In most parts of the world, including eastern China's monsoon region, however, the duration of instrumental meteorological data is less than 100 years. Furthermore, instrumental observations are extremely scarce in the early 20th and late 19th centuries, and only sporadic climatic records before the mid-19th century were available, making it impossible to satisfy studies of historical precipitation and droughts/floods variability. Therefore, using long-term high-resolution historical drought and flood records to reconstruct the sequence of extreme precipitation, drought and flood events at basin and regional scales are scientifically essential for studying the patterns and mechanisms of climate variation in historical periods (Mikami, 2008; Cook et al., 2010; Machado et al., 2011; IPCC, 2012, 2013; Fenby and Gergis, 2013; Shi et al., 2018, 2019).

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China has a wealth of continuous historical documents that provided precious material for studying climate change in historical periods, with the wealthiest records of historical droughts and floods (Zheng et al., 1993). Since the 1970s, Chinese scholars have used historical data on droughts and floods to reconstruct the time series of the past climate and extreme climate, achieving fruitful research results (Zhao and Wang, 1979; Zhang and Gong, 1979; Central Meteorological Bureau, 1981; Zhang, 1989; Hao et al., 2010; Han and Yang, 2017; Zheng et al., 2020). These studies laid a good foundation for further investigating into the multi-decadal to centennial scale variability of historical droughts and floods in the country. However, most of the above studies only examined characteristics of precipitation or drought/flood variations from a large spatial perspective. There are few studies using historical drought and flood records to explore the extreme precipitation patterns and mechanisms at a regional level, particularly in a medium to small scale river basin (e.g., Chen, 1987; Zhang et al., 2004; Ren et al., 2015b). Due to the comprehensive influence of multiple factors such as topography and geomorphology, long-term precipitation variation characteristics in different regions and basins are usually not similar. Even within a medium to small scale basin, there are big spatial differences in precipitation and drought/flood events in historical periods. In the climatic transition zones, the spatial characteristics of climate change and variability are more complex (Zheng et al., 1993; Liu et al., 2010; Wan et al., 2018; Mei et al., 2019).

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The Hanjiang River is one of the major tributaries of the Yangtze River. Located in the northern subtropical climate zone to the south of the Qinling Mountains, and in the transition zone between China's northern and southern climates, the Hanjiang River Basin (HRB) is sensitive to climate and environmental change (Zhu, 1958; Miao et al., 2009). On the other hand, the drought/flood control and water supply in the basin are of great importance in the national socio-economic development and ecological restoration. As the water source area of the South-North Water Diversion Middle Line Project and a key river basin for flood control in the middle reaches of the Yangtze River, the Hanjiang River has a wide range of socio-economic impacts in terms of precipitation and drought/flood variability (Liu et al., 2018; Wang et al., 2021). Therefore, there is an urgent need for research on precipitation and drought/flood variability at the multi-decadal to centennial scales in the HRB.

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There were a few of previous studies on the HRB's historical precipitation, but most of them were focused on the upper Hanjiang River region (Yin et al., 2010; Yin et al., 2013; Huang et al., 2013; Peng et al., 2013; Zhou et al., 2014; Zhou et al., 2014; Yin et al., 2015; Mao et al., 2016; Zhou et al., 2016; Tan et al., 2018); there were relatively few relevant studies on the entire basin (Zhou et al., 2006; Ding and Zheng, 2020). An in-depth understanding of the multi-decadal to centennial scale variability of historical drought/flood is lacking. Therefore, research on the reconstruction of the high-resolution drought/flood series and their variation patterns in the HRB's historical period still needs deepening and refinement.

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This paper reports a reconstruction and analysis of high-resolution historical extreme drought and flood time series over the HRB from 1426 to 2017. The results presented in the paper would be helpful for understanding the multi-decadal to centennial variability of extreme precipitation and drought/flood events in the important branch of the Yangtze River.

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2 Research area, data and methods

2.1 Research area

The study area is the HRB (Figure 1). The Hanjiang River originated at the southern foot of the Qinling Mountains. It flows through Shaanxi, Henan and Hubei provinces before merging into the Yangtze River at Wuhan, with a total length of 1,577km, a basin area of 159,000km^2, average annual precipitation of 700-1300mm and an average annual runoff of 51.7 billion m^3 (1960-2010; Yin et al., 2015). HRB has a humid subtropical monsoon climate with a pronounced spatial difference of precipitation. The annual precipitation increases from northwest to southeast and mainly concentrates in summer and autumn, with July to September accounting for about 70% of the annual total precipitation. Droughts and floods are both severe in the HRB, mainly because the river's upper reaches (above the Danjiangkou) are mountainous, with narrow, deep, meandering channels and fast currents. Flash floods and prolonged droughts can cause severe impacts. And in the middle and lower reaches (Danjiangkou to Zhongxiang is the midstream and below Zhongxiang is the downstream) of the Hanjiang River, the slow currents flow due to the low slope of the Jianghan Plain leads to unstable channels and inadequate discharge capacity, resulting in frequent floods (Institute of Geography of Chinese Academy of Sciences, 1957). Since the 1990s, the HRB has been experiencing continuous drought, severely impact the ecological environment, the rational allocation of water resources, and water supply in the basin (Chen et al., 2006; Wang and Guo, 2010; Yin et al., 2015).

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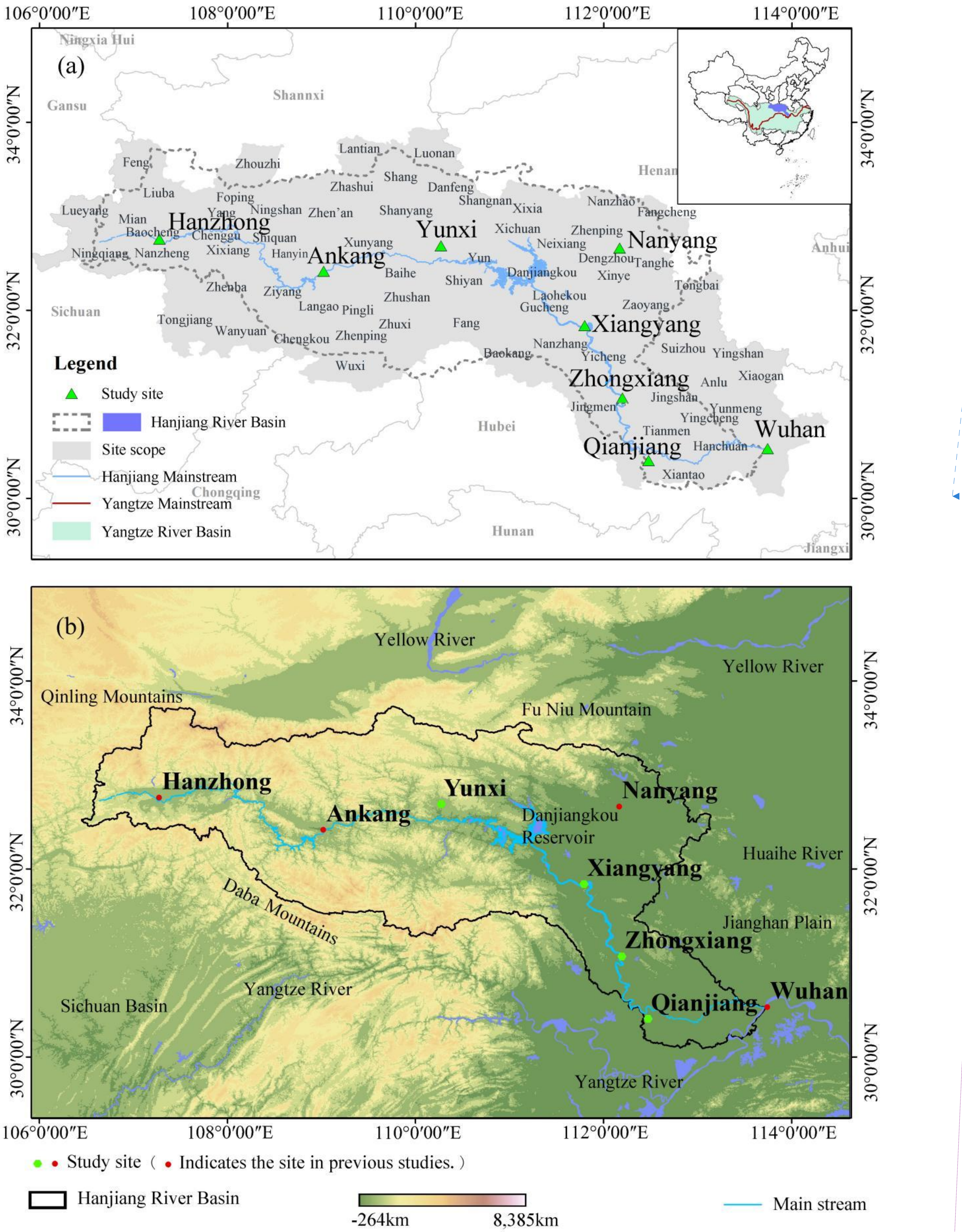

Figure 1: Study area and locations of the eight prefecture capitals used for reconstruction of drought and flood (a, b). Study sites in previous work (Central Meteorological Bureau, 1981) are marked as red points in (b). The inset in (a) indicates the relative location of the study area in China.

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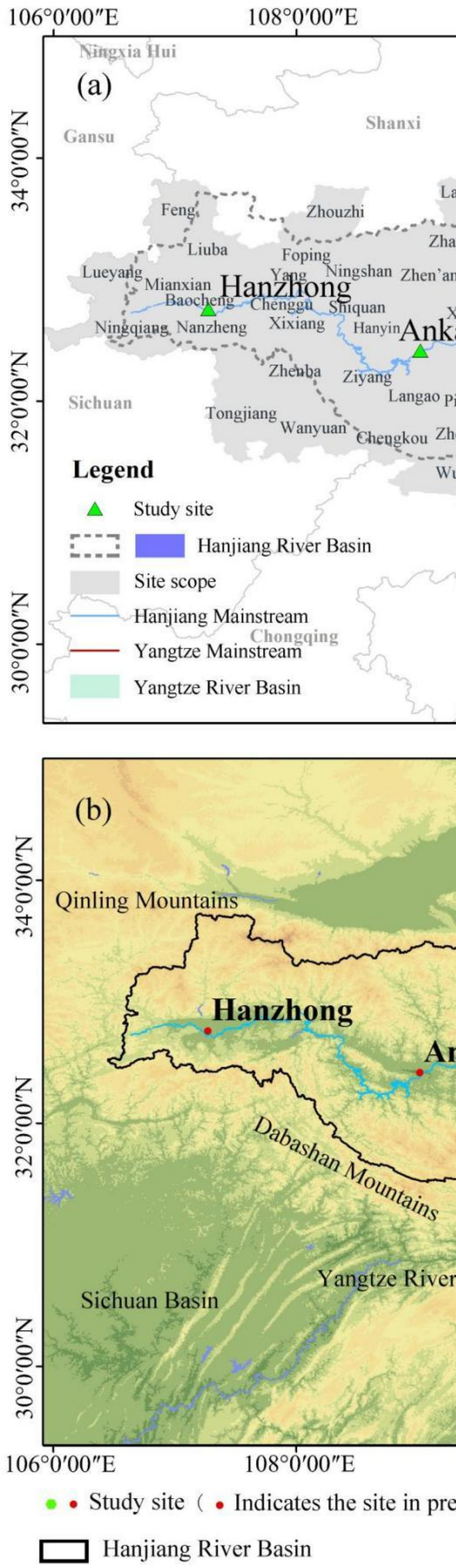

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2.2 Data

Four datasets were used in this work. These include the historical drought and flood records of the HRB (this study), the drought and flood index series in North China (the Yellow River and the North China Plain, 1470-2000), the Asian Monsoon Index series, and the chronologies of strong ENSO events.

(1) Historical drought and flood data series and documentation

The information used in this study to reconstruct the drought and flood sequences was divided into two parts: historical data and instrumental data. Sources of historical data included local chronicles, Qing Dynasty archives (memorials, Shangyu) etc. Primary historical data source was "A Compendium of Chinese Meteorological Records of the Last 3000 Years" (Zhang, 2004). This collection of materials systematically compiled various kinds of written records on weather and climate in China for more than 3000 years from the 13th century BC to 1911 AD. In addition, other datasets were also collected and used, including "The historical Documents on Flood and Waterlogging of Southwest International Rivers in the Yangtze River Basin in Qing Dynasty (1636-1912 AD)" (Yang and Guo, 1991), "The Disaster Annals in Modern China" and "The Continuation of Disaster Annals in Modern China (1919-1949)" (Li et al., 1990; 1993), "Zaixu Xingshuijinjain-Yangtze River Volume" (Wu and Zhao, 2004), and "Compilation of the Memorials to the Throne in Qing Dynasty: Agriculture·Environment " (Ge, 2005). The data were mainly derived from official documents, notes, letters, local chronicles, inscriptions, newspapers, magazines and river worker file transcripts of the Qing Dynasty. Moreover, drought and flood records from 1911 to 1949 AD in "The China Meteorological Disaster Dictionary" (Shaanxi Volume, Henan Volume, Hubei Volume; Wen, 2005, 2005, 2007) were also collected and used as supplementary data.

In terms of the overall distribution of information, the records of drought/flood in the local chronicles are more continuous and complete. They can also reflect information on the extent of disasters and disaster relief in each prefecture and county, effectively showing disaster's spatial distribution and temporal change. The archival information is of the highest credibility (Ge and Zhang, 1990). It provides a primary basin-wide picture of droughts/floods with a clearer spatial and temporal resolution accurate to the county level.

The instrumental data (started in 1951) comes from the monthly precipitation dataset "China National Ground Meteorological Station Homogenized Precipitation Data Set (V1.0)". This set of precipitation observations were quality controlled, and tested and adjusted for inhomogeneity caused by non-climatic factors such as the relocation of stations and instrumentation. This study uses precipitation data from 8 meteorological stations (Hanzhong, Ankang, Yunxi, Nanyang, Xiangyang, Zhongxiang, Qianjiang and Wuhan) in the HRB (Figure 1).

(2) Other historical data series

Drought and flood index series in North China (the Yellow River and the North China Plain, 1470-2000) were used to compare the result of this analysis with those of other regions. The data were from “The Atlas of Drought and Flood Distribution in China in the Last 500 Years” (hereafter referred to as Atlas; Central Meteorological Bureau, 1981), and the drought and flood grades of North China were read out from the Atlas.

Asian monsoon index. The East Asian summer monsoon index dataset (1426-1949) reconstructed by the δ^{18}O content of Vientiane Cave by Zhang et al. (2008) and the South Asian summer monsoon index dataset (1426-2000) reconstructed using Indian tree ring data by Shi et al. (2017) were used in this study.

ENSO Sequence Chronology (1525-2002). The El Niño and La Niña events in the historical ENSO chronology reconstructed by Gergis and Fowler (2009) from tree-ring, ice-core, coral records and historical documents were used. These El Niño and La Niña events were divided into five grades as extreme (E), very strong (VS), strong (S), medium (M), and weak (W). This study selected VS and E grades as strong ENSO events. There were 45 strong El Niño and 56 strong La Niña events identified during 1525-2002.

2.3 Methods

(1) Reconstruction method of historical drought and flood grade

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Based on the criteria provided in the Atlas, single-station and regional drought/flood series were established using the grading method. The degree of drought/flood or precipitation was divided into five grades: Grade 1-Flood, Grade 2-Mild Flood, Grade 3-Normal, Grade 4-Mild Drought, Grade 5-Drought. The drought and flood grades at each site indicated the degree of regional precipitation anomalies within a specific administrative range (i.e. including several counties and cities) represented by that site. Historical drought/flood grades were mainly based on historical records. In assessing the drought/flood grades for a region based on several drought/flood records for a given year, the primary considerations were the precipitation conditions in spring, summer and autumn, as well as the timing, extent and severity of their occurrence. If droughts and floods occurred successively at the same site in the same year, for instance, spring droughts and summer floods, or summer droughts and autumn floods, etc., the summer condition was considered prevailing. If there were droughts and floods within the representative area (i.e. the site), the judgment would be based on most counties or cities' situation. If a site has a gap in records of less than 3 years, it is considered to have no drought or flood and was graded 3; a site with a gap in records of more than 3 years was not graded.

In order to take into account the frequency of occurrence of each grade, the ideal frequency criteria of 10% (Grade 1-Flood; Grade 5-Drought), 20%-30% (Grade 2 Mild-Flood; Grade 4-Mild-Drought), 30%-40% (Grade 3-Normal) (Central Meteorological Bureau, 1981) were used to adjust the classification of drought and flood grades in the HRB throughout the study period. Moreover, when precipitation records were available, the May-September precipitation for the area where the site is located was used to be consistent with the frequency of drought and flood grades obtained from historical data (Central Meteorological Bureau, 1981). Table 1 shows the division criteria in the HRB into various grades and their typical descriptions in historical sources (the criteria for judging the historical sources according to the Atlas) and the criteria for grading precipitation (Central Meteorological Bureau, 1981).

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Table 1: Criteria for classifying droughts and floods in the HRB and their typical descriptions in historical sources and criteria for grading precipitation in modern time

Event grade	Event Type	Criteria for historical records	Criteria for modern precipitation
1	Flood	Intense and prolonged precipitation, widespread floods and very heavy storms, such as: "Houses were swept away and overflowed, and countless people died in the floods"; "The torrential rain continued for more than half a month and still did not stop. Houses and fields were flooded, people had to rely on boats to get in and out of the city" etc.	$R_i > (R+1.17\sigma)$
2	Mild Flood	Sustained precipitation, local floods and hurricane rains that are not very severe and occurred in a single-season or single-month, such as: "It has been raining in the autumn, resulting in the crop failure or growing affected negatively"; "There was a flood in May" etc.	$(\bar{R}+0.33\sigma) > R_i \le (\bar{R}+1.17\sigma)$
3	Normal	It is recorded as a harvest year, or droughts and floods are not recorded, such as: "The autumn harvest"; "A year of great harvest" etc.	$(\bar{R}-0.33\sigma) < R_i \le (\bar{R}+0.33\sigma)$

4	Mild Drought	Single-season or single-month droughts that are less severe or localised, such as: “There was a drought this spring”; “The lack of rain in spring, in March, made seeding difficult” etc.	$(\bar{R}-1.17\sigma) < Ri \leq (\bar{R}-0.33\sigma)$
5	Drought	Drought lasting several months or inter-seasonal drought, widespread severe drought, such as: “Wells run dry, rivers cut off”; “There was a great drought, and people began to eat human flesh” etc.	$Ri \leq (\bar{R}-1.17\sigma)$

Ri means May-September precipitation in a year, $\bar{R}$ means May-September average precipitation in a reference period, σ means standard deviation.

Based on the above methods and the characteristics of the spatial and temporal distribution of drought/flood historical data in HRB, and following the principle of uniform spatial distribution and the abundance of historical data, a total of eight sites were determined for constructing drought/flood grade series. These sites are Hanzhong, Ankang, Yunxi, Nanyang, Xiangyang, Zhongxiang, Qianjiang, and Wuhan, which also possess the stations of modern meteorological observation within the HRB (Figure 1). Among them, four were ever used in the Atlas, but the data have been renewed with additional records from the documents. The grade data of the four new sites were completely developed in this study. The name of each site is the name of the county and municipality within the basin. However, the drought and flood it represents were not limited to the administrative area to which the site name refers and encompass a particular geographical area around it (Table 2).

Table 2: Eight sites of drought and flood grade sequence and the spatial ranges (regions) they represented in the HRB during 1426-1950.

Site	Regions
Hanzhong	Hanzhong, Mian, Chenggu, Nanzheng, Baocheng, Liuba, Yang, Ningqiang, Lueyang, Foping, Zhouzhi, Zhen’an, Zhashui, Feng, Ningshan
Ankang	Ankang, Xunyang, Langao, Zhenping, Pingli, Zhuxi, Chengkou, Wuxi, Zhenba, Ziyang, Tongjiang, Shiquan, Xixiang, Hanyin, Wanyuan
Yunxi	Yunxi, Baihe, Shanyang, Shang, Luonan, Lantian, Shangnan, Danfeng, Fang, Zhushan, Baokang
Nanyang	Nanyang, Nanzhao, Dengzhou, Yun, Zhenping, Tanghe, Xixia, Fangcheng, Neixiang, Xichuan, Shiyan
Xiangyang	Xiangyang, Xinye, Nanzhang, Zaoyang, Tongbai, Laohekou, Danjiangkou, Gucheng
Zhongxiang	Zhongxiang, Yicheng, Jingmen, Xiaogan, Anlu, Yunmeng, Suizhou, Yingshan
Qianjiang	Qianjiang, Xiantao, Tianmen, Jingshan
Wuhan	Wuhan, Hanchuan, Yingcheng

A total of 4328 records of droughts and floods in the HRB from 1426-1950 were collected from the above-mentioned historical documents. Historical documents have the common feature of "the closer to the present day, the more detailed and richer the record; the further from the present day, the less documented" (Zheng et al., 2014). Simultaneously, there are also

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sudden jumps in the number of records, which were mainly due to dynastic changes and technological progresses. In order to evaluate and correct the non-uniformity of the number of records over time, we counted the number of local chronicles and archives before 1951 in the study area with reference to the method reported in Yang and Han (2014). On this basis, the homogeneity test of the number of available data at 95% confidence level was performed to determine whether there was systematic bias in the available records. It was revealed that there was a significant abrupt change in the number of records in 1812, indicating a significant increase in the number of local records and archival materials in the 1810s. Furthermore, after 1951, with the construction and development of the modern meteorological observation network, the number of meteorological observation stations in the HRB increased significantly, and precipitation observation began to enter the period of instrumental measurement, which represents a radical change in data category. Therefore, 1812 and 1951 were regarded as the time nodes of discontinuity in the temporal distribution of the data, respectively. The whole period of 1426-2017 were thus divided into three time stages: 1426-1812, 1813-1950, and 1951-2017. The eight sites' average recording rates during these three time periods were 61.11%, 91.28% and 100%, respectively (Figure 2). The key to this method is a phased evaluation approach, which constructs a platform for comparison between historical periods, and historical and instrumental data. That is, because of the nature of "concerning only disasters but not normal conditions" in the historical documents (Zheng et al., 2014), the average recording rates suggest that a significant proportion of drought and flood events were recorded in the HRB from 1426-1950. Even in the period when the average rate of data recording at a single site was lowest (42.6% of the Ankang during 1426-1812), it was greater than 20% (i. e., the ideal frequency of extreme droughts and floods) and therefore still met the needs of the study.

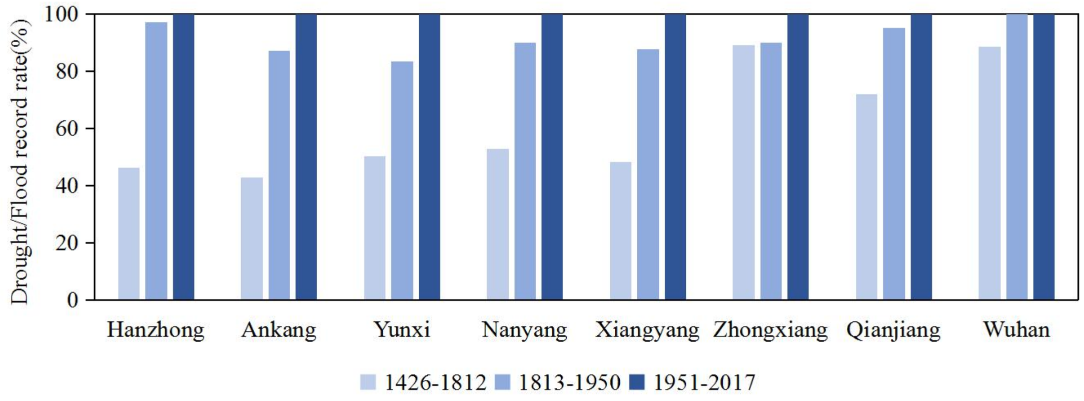

Figure 2: Proportion of drought and flood records in different periods of various sites

Precipitation anomaly percentages were calculated for May-September of 1951-2017. The method is [annual precipitation - average precipitation] / average precipitation (the reference period for calculating average precipitation and anomalies is 1951-2017). Then, compared to the drought and flood grades established in this study (Figure 3). The comparison showed that the drought and flood grades and the precipitation anomaly percentages were highly consistent on inter-annual to decadal variability, and their correlation passed the 0.01 significance test. Therefore, the drought and flood grades of the instrumental measurement period calculated using the method in the Atlas can be connected with the drought and flood grades of the historical period for analysis. The applicability of the procedure was also confirmed in previous studies (Wang and Zhao, 1979; Fang et al., 2014).

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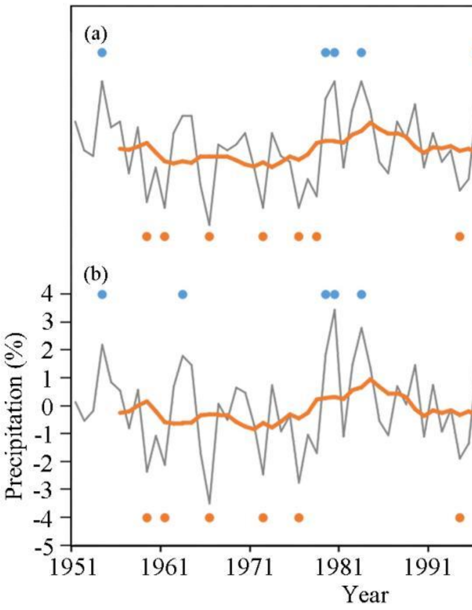

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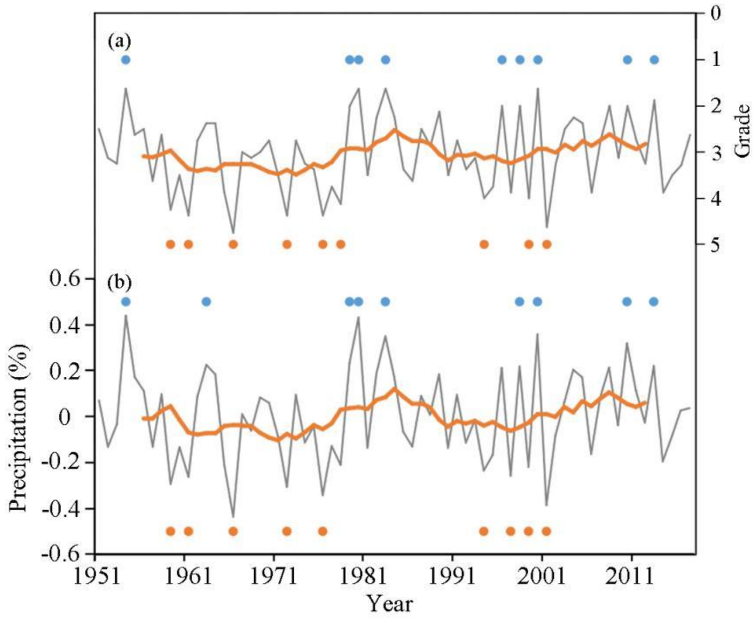
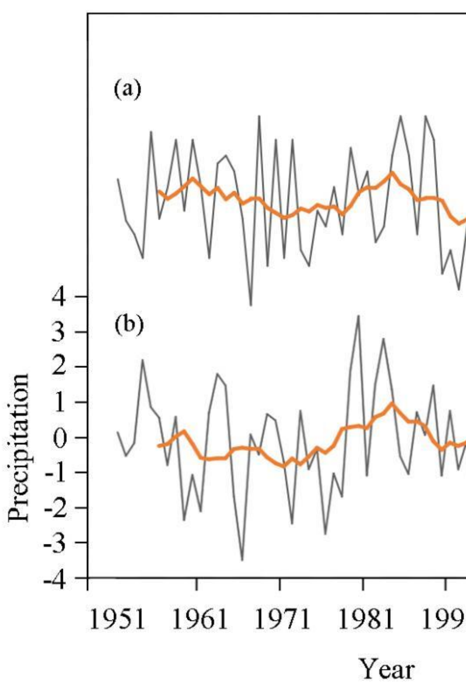


Figure 3: A comparison of drought and flood grades (a) and precipitation anomaly percentage (b) in the HRB during 1951-2017. Blue dots indicate extreme flood years and orange dots indicate extreme drought years.



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Furthermore, since there were missing data records at each site in historical periods, the more documented periods have richer records of droughts/floods, and vice versa. However, the lack of data should not significantly impact the proportion of droughts/floods in the available drought/flood records. Therefore, the following standards were used to identify extreme drought/flood events in the basin (Hao et al., 2010): Firstly, the number of sites with a drought or flood grade of 3 (i.e. a normal year) out of the total number of sites recorded in the same year does not exceed 25% of the total number of sites recorded. Secondly, among the sites with records of droughts and floods (i.e. except for sites with a drought/flood grade of 3), at least 75% of the sites have droughts or floods at the same time, meanwhile, at least 2 of these adjacent sites were experiencing either severe drought (i.e. grade 5 drought) or severe flood (i.e. grade 1 flood) at the same time. If the above two conditions were met, the year could be identified as a year of extreme drought or flood in the basin.

(2) Inverse Distance Weighted (IDW)

The Inverse Distance Weighted (IDW) is a weighted average using the distance between the interpolation point and the sample point as parameter. The closer the sample point to the interpolation point, the greater the weight given. Xie et al. used four spatial interpolation methods with the Upper Sangamon basin and analyzed the accuracy of the interpolation results separately. They found that IDW had the highest interpolation accuracy when the study area was small and the number of meteorological observation stations was relatively small (nine sites of observational stations in the basin; Xie et al., 2018). In this study, we used ArcGIS10.6 with the IDW built-in to map the data of the study sites and to visualize the spatial variability of the droughts and floods grades (Vicente-Serrano et al., 2003; Xie et al., 2018).

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3 Results and discussion

3.1 Variation characteristics of extreme drought and flood events

There were 45 extreme drought events and 52 extreme flood events identified in the period 1426-2017 (Table 3) . They account for 7.6% and 8.8% of the total number of years, respectively, equivalent to an extreme drought event per 13 years and an extreme flood event per 11 years. The occurrence probability of extreme flood years is marginally higher than that of extreme drought years. During this period, extreme drought/flood events had prominent phased and clustering characteristics

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of occurrences. Figure 4 shows the statistical results (frequency) of the extreme drought and flood events per decade (1430-2009), and following features can be generalized:

Table 3: Statistics on historical extreme drought/flood per century, 1426-2017

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Century	Extreme drought	Total (year)	Extreme flood	Total (year)
15th (1426-)	1433, 1441, 1442, 1444, 1450, 1458, 1479, 1480, 1485, 1489, 1498	11	1460, 1474	2
16th	1509, 1522, 1528, 1544	4	1500, 1516, 1517, 1519, 1551, 1560, 1566, 1569, 1591, 1593	10
17th	1617, 1640, 1644, 1652, 1674, 1684, 1689, 1690, 1692	9	1607, 1608, 1613, 1631, 1647, 1650, 1653, 1658, 1676, 1677	10
18th	1768, 1778, 1785	3	1724, 1742	2
19th	1813, 1856, 1877	3	1822, 1831, 1832, 1848, 1852, 1870, 1883, 1887, 1889, 1897	10
20th	1900, 1914, 1928, 1941, 1942, 1944, 1959, 1961, 1966, 1972, 1976, 1978, 1994, 1999	14	1906, 1909, 1910, 1919, 1921, 1924, 1931, 1933, 1935, 1954, 1979, 1980, 1983, 1996, 1998	15
21th (-2017)	2001	1	2000, 2010, 2013	3

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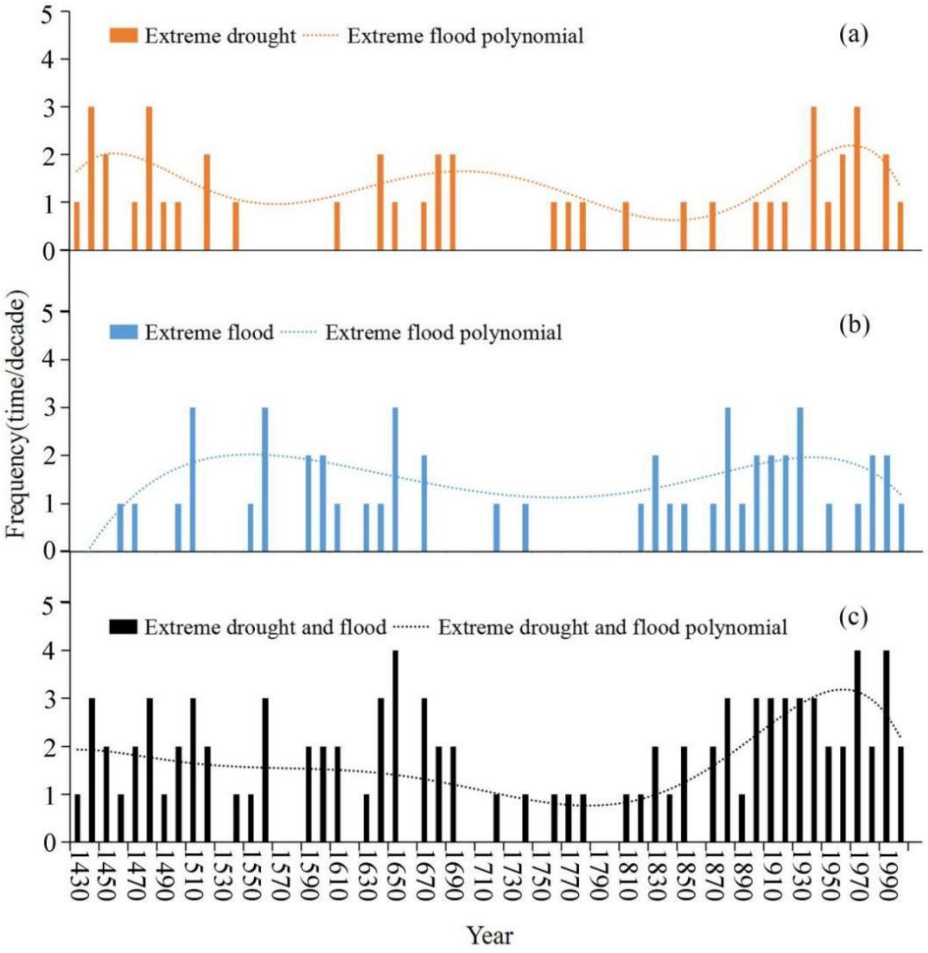
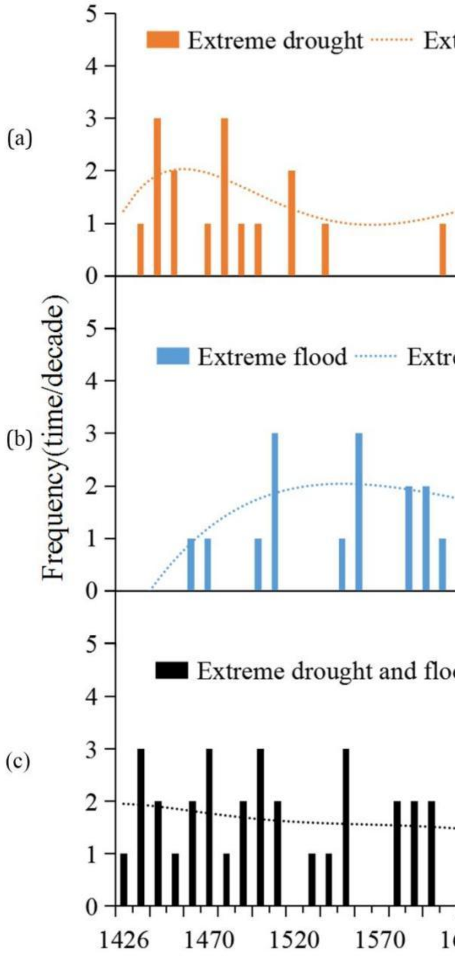


Figure 4: Change in frequency of extreme droughts/floods during 1430-2009 (times/decade). (a) Years of extreme droughts; (b) Years of extreme floods; (c) Years of extreme droughts/floods. The dashed line is the 6th order polynomial fit curve.

(1) The high-incidence period of extreme drought events occurred in the 15th to early 16th, 17th, and 20th centuries; both lasted around 100 years. Previous studies showed that the frequency of drought disasters in the HRB was highest in the 1480s and 1630s (Wang and Guo, 2010); 1628-1641 and 1900-1970 were the two periods of the high occurrence of mega-drought disasters in the upper HRB, occurring once every 1.67 years and 3.33 years respectively on average (Yin et al., 2015). Furthermore, 1441-1442, 1479-1480, 1689-1690, and 1941-1942 were consecutive years of extreme droughts. These continuous extreme drought events have had a more severe impact on agricultural and social life. For example, during 1941-1942, the HRB suffered a summer and autumn drought without rain, and the seedlings withered without harvest. This tremendous northern drought, centred on Henan Province (Dong et al., 2014), not only led to food failures and shortages but also caused millions of refugees to die as a result of the famine (Li, 2019). The 20th century saw the highest incidence of extreme drought events, occurring about once per seven years. There was a severe drought in Northwestern China in 1928, with annual precipitation comparable to that during the Ming Chongzhen drought (the extreme drought that occurred from 1637-1643 affected more than 20 provinces in northern China; Tan, 2003). There were many records in the HRB regarding the drought in 1928, such as: "The sun is harsh in the summer, and the rivers are parched", " The victims had eaten all the bark and grass within hundreds of miles and recently had to dig the soil in the mountains to eat, causing many of them to die from dry stools ", "Last year (1928), a severe drought affected thousands of miles within a radius from spring to summer", etc. The upper reaches of the Danjiangkou Reservoir (completed in 1973, and it is now the water source of China's South-North Water Diversion Middle Line Project) had been in drought for years during the late 20th century, especially since the mid-1990s, and the average precipitation in the 1990s were 11.6% less than the multi-year average (Chen et al., 2006); in 1997, the HRB was in continuous drought in summer and autumn, and the annual rainfall was only 605mm (Wang



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and Guo, 2010). However, there were no extreme drought events in some of the historical periods, including the 1460s, 1510s, 1530s, 1550-1600s, 1620-1630s, 1660s, 1700-1750s, 1790-1800s, 1820-1840s, 1860s, 1880-1890s, 1930s and 1980s.

(2) The high-incidence period of extreme flood events occurred in the 16th to 17th centuries and the 19th to 20th centuries, both lasted around 200 years. The 19th to 20th centuries saw the highest incidence of extreme flood events, occurring once per eight years. The recently more frequent extreme floods have been reported in previous studies. Yin and Huang (2012) showed that severe floods with flow rates greater than 15,000 m^3/s occurred 20 times in the Ankang area only from 1960 to 2010. They also found the highest frequency of floods occurred in the 1980s, when there were eight severe floods occurred in Ankang, with the maximum flood flow reaching 31,000 m^3/s. In particular, the worst flood in the last 100 years (once in 130 years) occurred in Ankang in July 1983, which caused the inundation of the entire city and nearly 1,000 people died (Shaanxi Province local history codification committee, 2000). From 1822 to 1955, there were 130 breaches of the mainstream embankments during 73 years in the middle and lower reaches of the HRB, with an average of about one breach in two years (Guo et al., 2020). In 1870, an most enormous flood in the Yangtze River Basin in more than 800 years occurred (Yao, 1991), flooding 30,000km^2 of the Jianghan Plain (Shi et al., 2004), including the downstream areas of the HRB. In the extreme flood of 1931, Hankou (Wuhan) reached record (1840-2000) high water level (28.28m), with a peak flow of 50,000m^3/s at Danjiangkou and 145,000 deaths across the Yangtze River Basin (Shi et al., 2004). Lake Taibai (Current location is 29°58′N, 115°23′E), the largest lake in the Jianghan Plain in the 17th century, was silted up to a low-lying swamp by the end of the 19th century due to the Yangtze and Hanjiang rivers' frequent floods, which led to a sharp increase in sediment (Yao, 1991). Furthermore, consecutive years of extreme floods occurred in the history, and they includes the years of 1516-1517, 1607-1608, 1676-1677, 1831-1832, 1909-1910 and 1979-1980. However, there were no extreme flood events in the years of 1430s-1450s, 1480-1490s, 1520-1540s, 1570-1580s, 1620s, 1660s, 1680-1710s, 1730s, 1750-1810s, 1860s, 1940s and 1960s.

(3) The 18th century was a period of relatively few extreme drought/flood events, with 3 extreme drought events, 2 extreme flood events and approximately 1 extreme drought or flood event per two decades. The sparsity of extreme droughts and floods in this century was reported in a previous study applying historical documents (Wang and Guo, 2010). The stalagmite records from Central China and the hydrographic stonework from the Three Gorges area of the Yangtze River also suggested fewer droughts and floods in the 18th century. For example, Liu et al. (2011) used high-resolution stalagmite $\delta^{18}O$ and high-precision ^{230}Th dating data from Wanxiang Cave, Wudu County (33°30′N, 104°56′E), and combined with historical drought and flood index series from the surrounding area. They found that 1701-1780 was a stable period for precipitation, with above-average precipitation and no extreme drought or flood events. Qin et al. (2020) analyzed the frequency of severe drought events in the Yangtze River's upper reaches through the hydrographic stone carvings of Baiheliang stonefish in the Three Gorges Reservoir area (31°03′N, 109°57′E) of the Yangtze River. They found that there were significantly fewer records of extreme drought events in the 18th century. Studies combining ice cores, tree ring index, lake sediments, and historical climate records indicated that the 18th century was a relatively warm period during the Little Ice Age, when temperatures in China began to rise and climatic conditions improved significantly relative to the previous period (Yang et al., 2002).

(4) The 20th century was a common high period of extreme drought/flood events, with 14 extreme droughts and 15 extreme floods occurred, and approximately 1 extreme drought or flood event average 3-4 years. Previous studies showed that annual precipitation in the Hanjiang River valley had decreased since 1960, and drought disasters had increased. At the same time, flood disasters had become more frequent because precipitation was more concentrated in the summer, and inter-annual fluctuations in precipitation had also increased significantly (Yin et al., 2010). For example, floods occurred in the Tangbai River basin, a tributary of the HRB, in 1919 and 1953, but the floods were followed by two months of no rain and then a severe drought (Institute of Geography of Chinese Academy of Sciences, 1957). Tree-ring reconstruction studies (Liang et al., 2003; Zhang et al., 2005) indicated that the monsoon precipitation variability in Northern China over the last 100 years has been high, with significant wet and dry changes and widespread extreme drought events. Ding et al. (2007) and Ren et al. (2010) pointed out that in the context of global warming, the frequency and intensity of extreme precipitation events and the extent of drought in China increased during the 20th century, especially in the past half-century, the extreme precipitation in Northwest China has increased significantly. However, the drought events in Northern China, northeast and

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southwest China have increased significantly. The analysis results of this study are in good agreement with previous research conclusions.

(5) The frequency of extreme droughts was relatively high in the 20th century, especially after the 1930s. Historically, however, the frequency of extreme drought in the 20th century does not appear to be the highest, with a similar frequency of extreme drought events occurring in the mid-15th century. The decline in the frequency of extreme droughts during the 18th-19th centuries amid the Little Ice Age is equally evident in Figure 4. However, extreme flood frequency appears to have been higher in the 20th century and significantly more frequent than in the 18th and early 19th centuries.

3.2 Spatial characteristics of historical extreme droughts and floods

Frequency of Grade 1 floods and Grade 5 droughts at each site was shown in Table 4, and the distributions of frequency were plotted as scatterplot using ArcGIS 10.6 (Figure 5). The results showed that the spatial distribution of the frequency of the extreme droughts and floods in the HRB varied significantly. The high-frequency centers of Grade 1 floods and Grade 5 droughts are both distributed in the middle and lower reaches of the HRB. Zhongxiang site in the middle reaches of HRB had a total of 60 Grade 5 droughts, while those at the Nanyang site are relatively less frequent, with 30. Qianjiang site in the lower reaches of HRB had a total of 67 Grade 1 floods, and the Ankang site, which is in the upper reaches, experienced relatively fewer Grade 1 floods with 40. The frequency of both Grade 1 floods and Grade 5 droughts is generally higher in the middle and lower reaches than that in the upper reaches.

Table 4: Frequency of Grade 1 floods and Grade 5 droughts at each site in the HRB

Site	Frequency (extreme drought/extreme flood)	Site	Frequency (extreme drought/extreme flood)
Hanzhong	32/44	Xiangyang	36/44
Ankang	36/40	Zhongxiang	60/58
Yunxi	30/44	Qianjiang	39/67
Nanyang	32/47	Wuhan	44/62

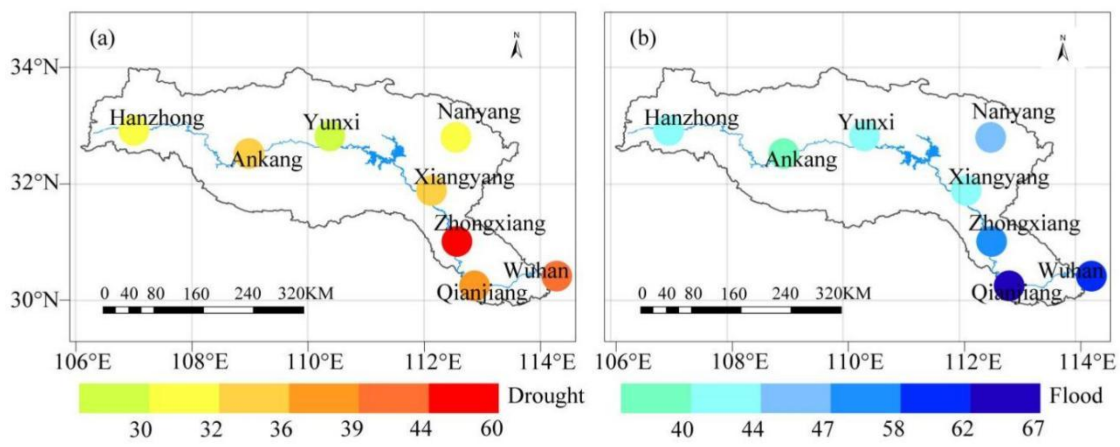

Figure 5: Spatial distribution of the frequency of Grade 5 droughts (a) and Grade 1 floods (b) in the HRB.

According to the previous study (Institute of Geography of Chinese Academy of Sciences, 1957; Commission Water Resources Commission of the Ministry of Water Resources, 2002), the upper reaches of the HRB are more water-scarce and relatively less resistant to drought than the middle and lower reaches. However, the frequency of drought is highest in the hilly and mountainous areas in the middle reaches of the HRB. That is because the the hilly and mountainous areas in the middle reaches have high arable land, but low water table and river surface, and also fewer springs, so in the event of drought, the damage is more serious (Institute of Geography of Chinese Academy of Sciences, 1957). That is the reason why the drought near the Zhongxiang site in the historical period is relatively more abundantly documented. From Figure 5, it can

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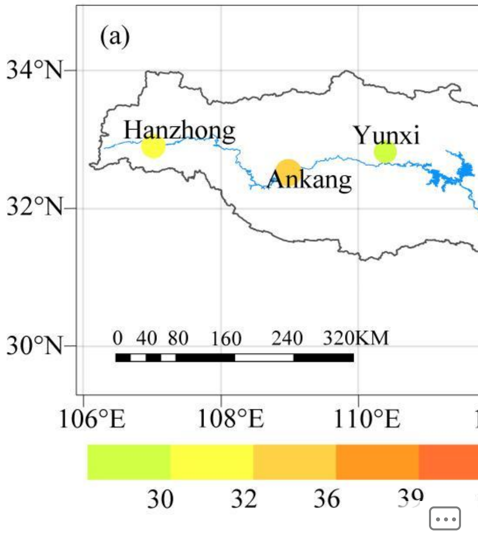

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also be seen that the frequency of droughts and floods is both higher in the middle and lower HRB and plain areas, and lower in the mountainous areas in the upper. This is probably because the middle and lower reaches of the HRB were economically developed earlier, with a more concentrated population and arable land than in the upper reaches. During the Ming and Qing dynasties (1368-1912), the middle reaches of the Yangtze River Plain (including the Jianghan Plain), centered on Hubei Province and Hunan Province, had been developed into a national commodity grain supply base. The central government paid as much attention to these areas (Zhu, 2018; Lu, 2019), so the lower reaches of the HRB had documental records in more quantity and detail during the historical period relative to the upper reaches (Figure 2), which may have an influence on the statistical results (Zheng et al., 2014).

Furthermore, the sensitivity of different regions to droughts and floods cannot be ignored. The severest droughts and floods years in the HRB were identified for each of the 15th-20th centuries (1426-1999), respectively. The years of the severest floods in each century are 1474, 1516, 1647, 1742, 1889, and 1931; the years of the severest droughts are 1433, 1528, 1690, 1768, 1877, and 1928. Then the average drought and flood grades for each site in the above years were calculated separately and spatially interpolated using the IDW. Each site's drought and flood grades were then plotted using ArcGIS10.6 (Figure 6). It was found that the sites of Ankang, Nanyang, and Qianjiang were relatively more likely to be affected by severe drought, while those of Ankang, Xiangyang, and Zhongxiang were relatively more likely to suffer from severe flood. In particular, the sensitivity of the Ankang to both droughts and floods is high. Previous studies have shown that the Ankang region is one of the most frequently flooded regions in the northwest (Department of geography, Shaanxi Normal University, 1986; Ankang City local history compilation committee, 2004), with a highly uneven distribution of precipitation over four seasons. After 1950, although the overall upper HRB was drought-prone and the frequency of floods tended to decrease, the frequency of large floods increased significantly, among which the flood events with peak flows exceeding 19,000 m3/s occurred in 1965, 1968, 1974, 1983, 1984, 1987 and 2005 in Ankang (Yin et al., 2010). In comparison, although droughts in the Ankang area are less frequent than floods, they often last longer and have a huge impact on agriculture, making it the most vulnerable area for agricultural droughts in Shaanxi Province (Zhang and Yin, 2012; Xu, 2016).

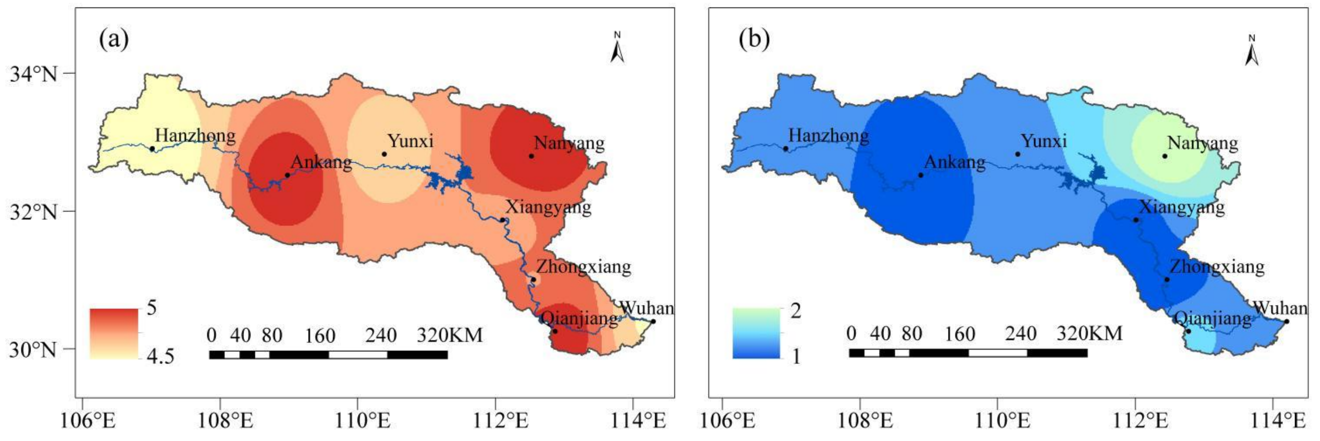

Figure 6: Distribution of average drought and flood grades for each site corresponding to the severest drought and flood years in each century.

In order to examine the association of the droughts and floods of the HRB with the severe droughts and floods in other regions, we made a compound analysis of drought and flood grades in the HRB when severe droughts occurred in North China (inc. the Yellow River and the North China Plain) and severe floods occurred in the Yangtze River. Table 5 and Figure 7 show the results for 5 representative severe droughts of North China (1637-1643, 1689-1692, 1877-1878, 1928-1930 and 1942-1943 were selected, respectively, based on Wang, 1999; Tan, 2003; and Qu et al., 2018), and 5 representative severe floods in the Yangtze River (1788, 1849, 1953, 1954 and 1998 were selected, respectively, based on Tao et al., 1998; Luo, 2006; Yang and Zheng, 2008; and Li and Zhou, 2020). It was found that the middle and lower HRB was more sensitive to floods in the Yangtze River basin, while the upper HRB was more correlated with droughts in North China. In order to verify

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the correlation between the HRB and North China, the drought and flood grades of the eight sites in the HRB were correlated with the average grade series of North China (Figure 8; Central Meteorological Bureau, 1981). Among them, seven sites are significant at the 0.01 level, and one site (Wuhan) passed the correlation test at $p<0.05$ level.

Table 5: Average of drought and flood grades of the HRB when severe droughts occurred in North China, and severe floods occurred in the Yangtze River.

Time Site	Hanzhong	Ankang	Yunxi	Nanyang	Xiangyang	Zhongxiang	Qianjiang	Wuhan
1637-1643	3.3	3.7	3.6	3.3	2.7	3.3	2.7	3.4
1689-1692	4.3	4.7	4.5	3.8	4	3.5	2	3.8
1877-1878	4.5	3.5	4.5	4.5	5	5	4.5	3
1928-1930	4	5	3	4.3	3.7	3.3	3.3	3.7
1942-1943	2.5	4	4	4.5	3.5	3.5	3.5	4
1788	3	4	3		2	1	1	1
1849	2		3	4	3	1	1	1
1935	4	5	1	1	1	1	1	1
1954	4	2	1	1	2	1	1	1
1998	2	4	4	1	2	1	1	1

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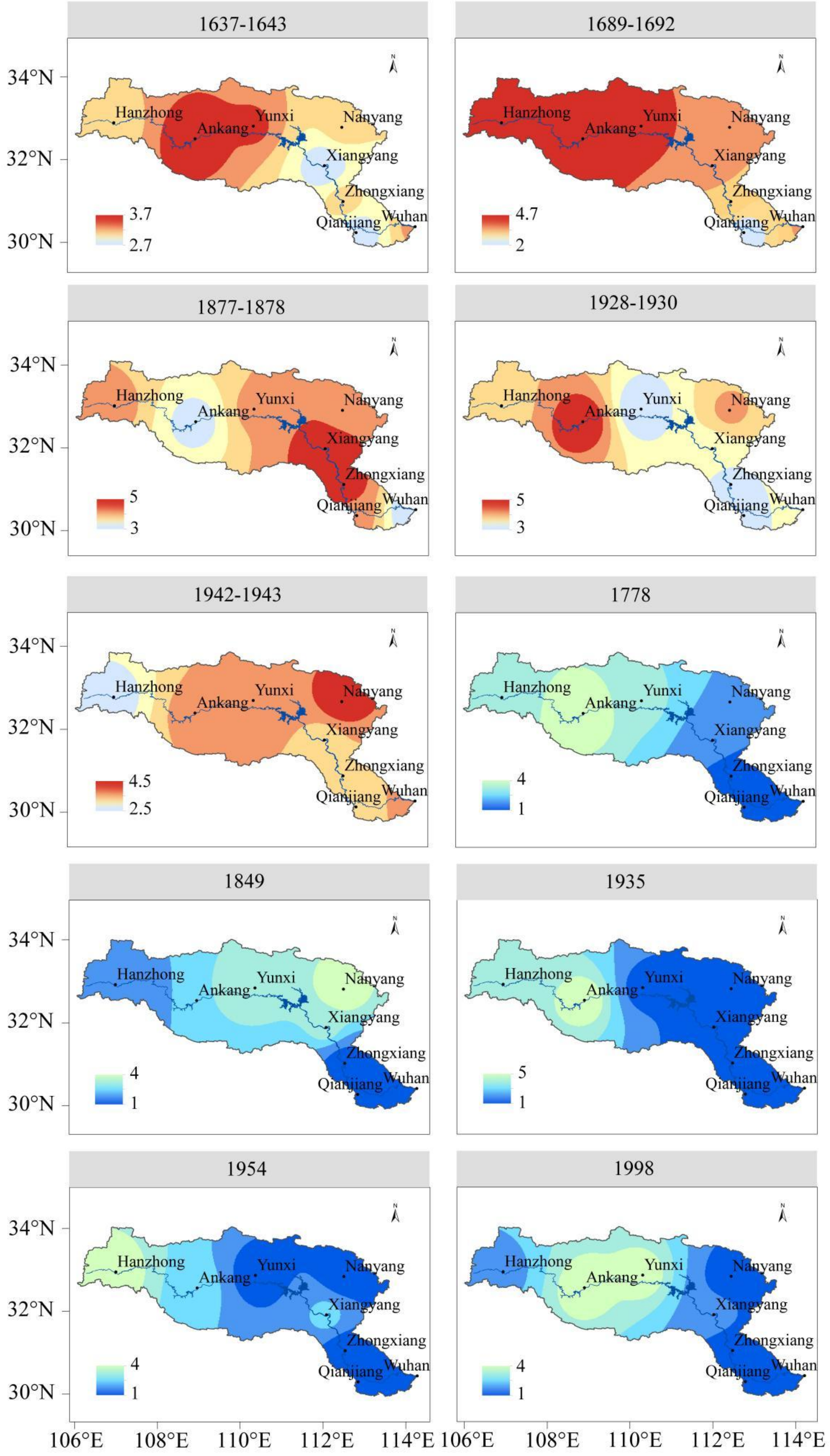

Figure 7: The spatial distribution of average drought and flood grades in the HRB during severe droughts in North China (1637-1643, 1689-1692, 1877-1878, 1928-1930 and 1942-1943) and severe floods in the Yangtze River basin (1788, 1849, 1953, 1954 and 1998).

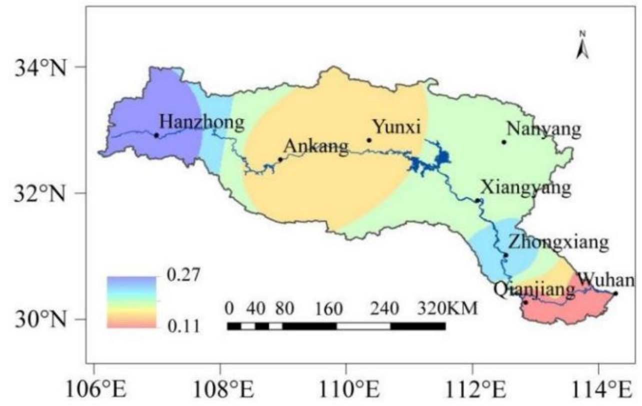

Figure 8: Spatial distribution of correlation coefficients of drought grades between eight sites of the HRB and North China (1470-2000). The correlation coefficients of Hanzhong, Ankang, Yuxi, Nanyang, Xiangyang, Zhongxiang, and Qianjiang are significant at the 0.01 level., and Wuhan is significant at the 0.05 level.

The South-North Water Diversion Middle-Route Project, which transfers water from the Danjiangkou Reservoir in the upper HRB to the North China Plain, is a huge hydro-project for supporting North China's sustainable development. Therefore, the synchronous encounter probability of rich-poor precipitation between the water source area in the upper HRB and the receiving area in North China Plain is an important issue for inter-basin water resources deployment, directly related to the reliability of the South-North Water Diversion Project (Chen et al., 2007; Gu et al., 2012). However, since the 20th century, the probability of the co-drought in each basin of the South-to-North Water Diversion Middle-Route Project's water source and recipient areas is at a historical high, and water transfer has been under great pressure (Ren et al., 2011; Qin et al., 2021). Previous studies have shown that the frequency of synchronization between the water source and the water receiving area is highest in the non-flood season. However, the precipitation in the water source area in the non-flood season is much smaller than the precipitation in the flood season, so the amount of water that can be transferred north is minimal (Yan et al., 2007). On an annual scale, when the most desirable water transfer scenarios were taken as a premise, the synchronous encounter probability of rich-poor precipitation in North China and the upper HRB was only 24% (Zheng and Liu, 2000). In addition, the probability of co-drought events in the upper HRB and the Haihe River Basin (the largest water system in North China) shows an increasing trend throughout the year under two future climate change scenarios of RCP4.5 and RCP8.5. In particular, the probability of experiencing co-drought in the flood season and co-severe drought in the non-flood season may increase significantly (Yu et al., 2018). However, most of the previous studies were focused on analyses of instrumental precipitation data, and a comparative study of more than 100 years was much needed. This study shows that drought conditions in the upper HRB, and North China also had a positive correlation on a long time period of nearly 600 years. Therefore, it is urgent and necessary to take measures for scientific regulation and reasonable configuration of the South-North Water Diversion Middle Line Project, so that the impact of unfavorable synchronous encounter probability of rich-poor precipitation could be reduced as much as possible.

4 Discussion

4.1 Factors influencing the variability of extreme droughts and floods

It is generally accepted that the amount of precipitation over most of China is clearly influenced by the variability of the Asian monsoon (i.e., East Asian monsoon and South Asian monsoon) and by ENSO (i.e., El Niño and La Niña) events (Zhu, 1934; Niu et al., 2004; Hao et al., 2008; Wang et al., 2020; Gao et al., 2017). Because the HRB is located at the junction of Central, North and Northwest China, it may be influenced by both factors (Su, 1981; Yin et al., 2015).

Figure 9 shows a comparison of extreme drought and flood events of the HRB with the East Asia-South Asia Summer

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monsoon Index. Following correspondence can be found that:

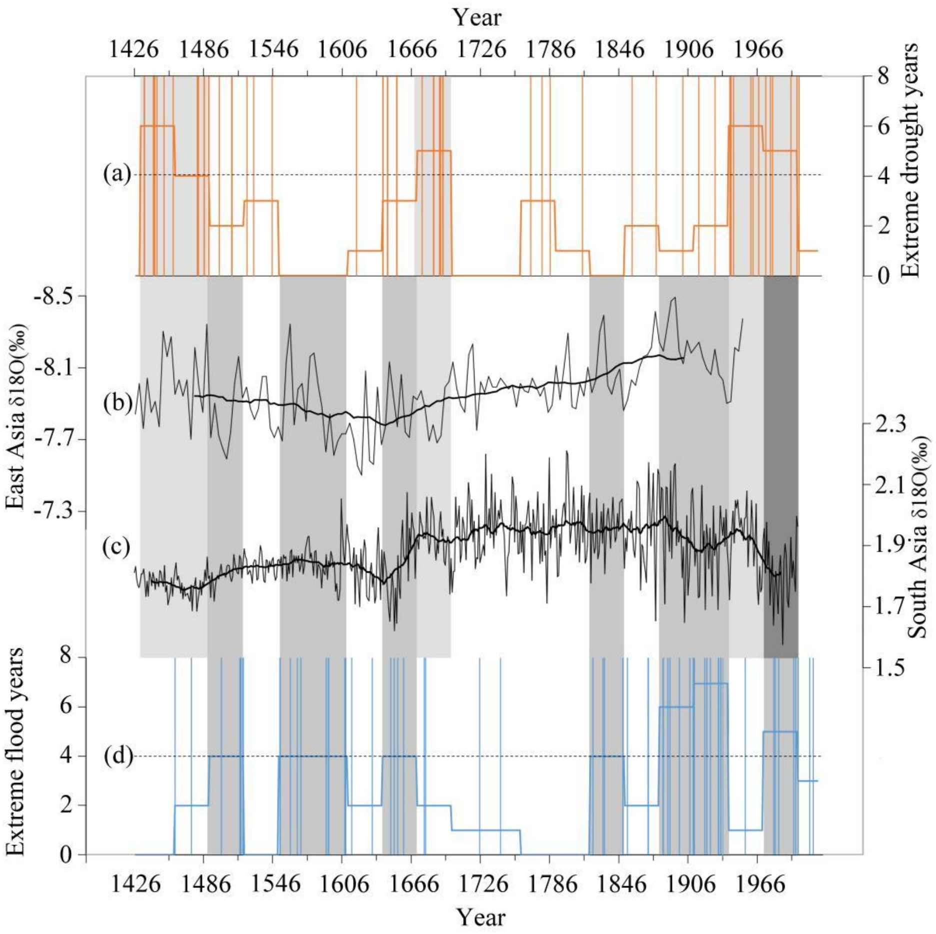


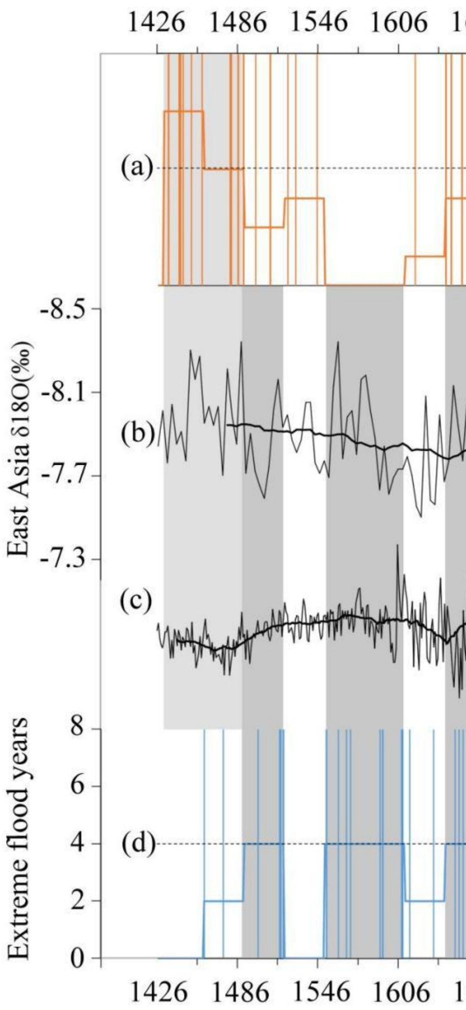
Figure 9: Comparison of the HRB extreme drought/flood years with the Asian monsoon index. (a) Vertical line shows the extreme drought years, and the ladder is the number of extreme drought years per 30 years. (b) East Asian summer monsoon index, 1426-1949 (Zhang et al., 2008). (c) South Asian summer monsoon index, 1426-2000 (Shi et al., 2017). (d) The vertical line shows the extreme flood years, and the ladder is the number of extreme flood years per 30 years.

(1) In the 15th-17th century, the summer monsoon was generally weak, with 24 extreme drought events and 22 extreme flood events occurring in the HRB, and extreme drought events were relatively more likely to occur.

(2) In the 18th-19th century, the summer monsoon gradually strengthened, and there were six extreme drought events and 12 extreme flood events in the HRB. Specifically, there were relatively few extreme events in the 18th century and an increase in extreme events in the 19th century, with 10 extreme floods and three extreme droughts in the 19th century, more than three times as many extreme floods as extreme droughts. This phenomenon further illustrates the complexity of the mechanisms by which extreme drought and flood events occur.

(3) The second half of the 19th century and the 20th century saw a significant strength of summer monsoon and a marked increase in extreme drought and flood events, with 16 extreme drought events and 21 extreme flood events occurring in the study region. As revealed by other studies (Huang et al., 1999; Lu, 2002; Niu et al., 2004), in the second half of the 20th century, abrupt changes in global atmospheric circulation and an unusual weakening of the summer monsoon led to an increase in drought events, with a total of 8 extreme drought events. Extreme droughts and floods in the 20th century have broadly evolved through a process of major floods followed by a shift from floods to droughts, which is consistent with the results of previous analyses (Ye and Zhao, 1995).

The correlation analysis of extreme drought and flood grades with the East Asian-South Asian summer monsoon strength index at a 30-year time window all passed the significance test ($p<0.01$). As a whole, this suggests that the multi-decadal



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variations in the frequency of extreme drought/flood events of the HRB are influenced to some extent by changes in the strength of the Asian monsoon, with relatively more extreme drought events when the monsoon is weak and more extreme flood events when the monsoon is strong.

The correlation coefficients between the frequencies of strong ENSO events (per 30 years) and extreme droughts/floods (per 30 years) in the HRB was calculated for the period of 1525-2002. We found that extreme floods are significantly positively correlated with strong El Niño events at a multi-decadal scale, and the correlation passed the significance test (p<0.05) (Figure 10). Extreme droughts and strong El Niño/La Niña events and extreme floods and strong La Niña events also showed positive correlations, but they did not pass the significance test (p<0.05).

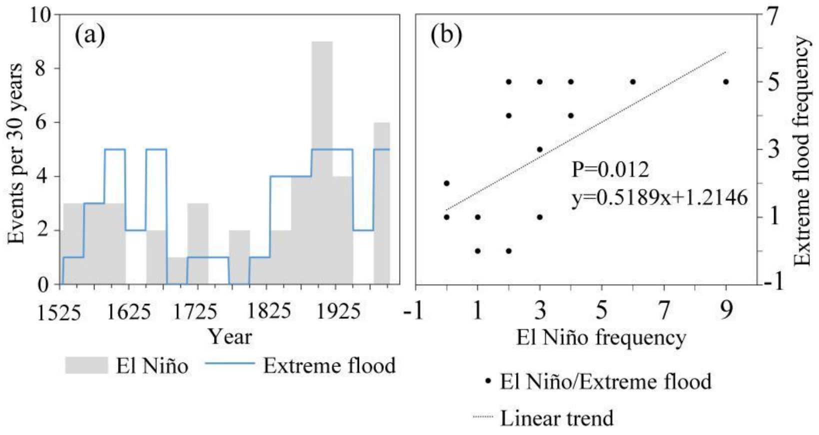

Figure 10: Correlation of extreme floods in the HRB and strong El Niño frequency (per 30 years) during 1525-2002. a. Frequency distribution of extreme floods in the HRB and strong El Niño events; b. Correlation between frequencies of extreme floods and strong El Niño events.

Previous studies reported similar findings (e.g. Su, 1981; Yin et al., 2015). Yin et al. (2015) found that the upper Hanjiang River was more prone to flood disasters in years with stronger El Niño at the end of the previous year or at the beginning of the same year, and in years when El Niño was switched to La Niña. They also found that, during the weak East Asia-South Asia Summer monsoon, the rain belt hovers over the Yangtze River and its south, and drought is more likely to occur in the HRB, especially in the upper reaches. Conversely, during the strong East Asia-South Asia Summer monsoon, the upper HRB is prone to heavy rainfall, even floods, in summer, and continuous rain or floods in autumn. Moreover, the South Asian summer monsoon alone has also an impact on precipitation in the HRB. When the South Asian summer monsoon is stronger, the upper and middle reaches of the HRB is more prone to floods (Su, 1981; Yin et al., 2015).

Therefore, as a transitional zone between northern and southern China and between the subtropical and warm temperate zones, to a certain extent, the HRB is influenced by the variability of Asian monsoon strength. In addition, as one of the strong signals of inter-annual variability in sea-air interactions, the ENSO events strongly influence the strength of the Asian summer monsoon (Wang et al., 2020), leading to large variability of the HRB summer rainfall. However, precipitation and extreme droughts/floods are also affected by other environmental factors and the complex interactions among the different factors, such as volcanic eruptions, AMO and PDO. And the correspondence between precipitation trends and monsoon is still controversial in proxy and modeling studies (e.g., Lu et al., 2019; Shi et al., 2021). Meanwhile, there may also be a difference in the monsoon's impact on precipitation between the upper and lower reaches of the Hanjiang River. Therefore, the relationship of historical basin-based extreme droughts/floods in the HRB with the Asian Monsoon Index and ENSO events on decadal to multi-decadal scales may not be a one-to-one correspondence. Obviously, further study is needed.

4.2 Limitations of the method

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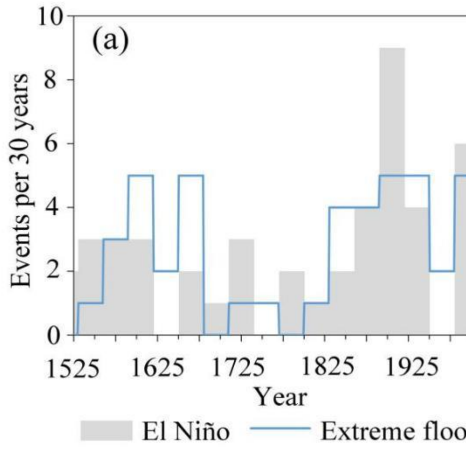

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Although a great effort has been made to collect historical documents and reconstruct the extreme droughts and floods of almost last six centuries in the HRB, the methods used in this study to reconstruct the drought and flood grade series of historical periods has the following two limitations:

First of all, the reconstruction method of the Atlas is to take the year as unit, combine the drought and flood disasters in spring, summer, and autumn within that year, and base the grading on the most severe disaster. When both droughts and floods occur in a given year, the disaster situation in summer is dominant. This definition is consistent with the climate in most of China, especially suitable for areas where rice is mainly grown (the HRB is dominated by rice cultivation)(Chen, 2020). However, droughts and floods are also frequent in the HRB in other seasons (Ding and Zheng, 2020), which result in the neglect of climate abnormality in other seasons. Meanwhile, not all drought and flood disasters in historical documents clearly indicate the time of occurrence (season, month, etc.), so it is easy to be misremembered that this disaster occurred in summer (Chen, 2020).

Secondly, the method of dividing time points according to the number of historical period materials also suffers from the unavoidable uncertainty of using proxy data for reconstruction work. In this study, the uncertainties are mainly in the subjective description of historical information, which is unavoidable in grading. Because historical materials include a variety of information, there are complex relationships between different carriers and different records, which may lead to subjectivity and ambiguity. This cannot be avoided entirely even if we do not base the grading on the linguistic descriptions of historical materials alone when selecting the available historical materials (Yang and Han, 2014).

5 Conclusions

This study investigated the multi-decade to centennial scale variation of extreme drought and flood over the HRB based on the 8-site precipitation grade reconstruction for 1426-2017. The main conclusions are as follows:

1) A total of 45 extreme drought events and 52 extreme flood events occurred from 1426-2017, equivalent to an extreme drought event per 13 years and an extreme flood event per 11 years. Extreme flood events occurred slightly more frequently than extreme drought events.

2) The relatively frequent periods of extreme drought events occurred in the 15th century to the early 16th century, the 17th century, and the 20th century. The highest frequency of extreme drought events occurred in the 20th century, while the 18th century saw the lowest frequency of extreme drought events.

3) The relatively frequent periods of extreme flood events occurred in the 16th to 17th centuries and the 19th to 20th centuries. The highest frequency of extreme flood events occurred in the 19th and 20th centuries, while the 18th century saw the lowest frequency of extreme flood events.

4) The frequency of both extreme drought and flood events was low in the 18th century, and there was probably a favorable climate in the 100 years. However, the 20th century saw a high frequency and increased risk of both extreme drought and flood events in the HRB.

5) The spatial distribution of the high-frequency extreme droughts centered in the middle reaches of the HRB, and the high-frequency extreme floods centered in the lower reaches. The frequency of droughts and floods was higher in the middle and lower reaches than those in the upper reaches. However, human factors may have some influence on the statistical results of spatial distribution.

6) Occurrence of extreme droughts and floods in the upper HRB are more strongly positively correlated with those in North China.

Data availability. All reconstructed data for the identification of extreme drought and flood events used in this study are available in the Supplement. Dataset of East Asian summer monsoon are available at https://www.ncdc.noaa.gov/paleo/study/8629 (NOAA, 2008) and South Asian summer monsoon are available at http://www.ncdc.noaa.gov/paleo/study/17369 (NOAA, 2014). Chronology of El Niño and La Niña events are available at

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Author contributions. GR and BH designed the research and guided the writing; YY and ZH guided the development of the methods; XZ conducted the analysis and; PZ guided the technical part; XZ reconstructed the drought and flood grade series, analysed the data, drew the figures and drafted the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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