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Reconstruction and characterization of droughts and floods in the Hanjiang River Basin, China, 1426–2017

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Abstract

Based on the records of drought and flood in Chinese historical documents and precipitation data during the instrumental period, and by using the five-grade classification method, this study reconstructs the drought and flood grades in the Hanjiang River Basin from 1426–2017 and analyzes their spatial and temporal variation characteristics. The results show that, on the centennial scale, drought and flood variation in the basin exhibited two dry periods (early fifteenth century to early sixteenth century, early twentieth century to the present) and one four-century long wet period (early sixteenth to early twentieth centuries), with multi-decadal drought and flood fluctuations within each period. Meanwhile, the variation shows some regional differences. For example, droughts and floods both occurred at high rates in the whole river basin during the twentieth century, with the increase in droughts relatively more remarkable in the upper reaches and the increase in floods more notable in the middle and lower reaches; throughout the study period, the drought and flood variability was larger in the upper reaches, but the drought and flood frequency was higher in the middle and lower reaches. In addition, there are a few quasi-cycles of the drought and flood variability in the middle and lower reaches, which include the quasi-cycles of 2–8 years, 10–30 years, 50 years, and 80–100 years, respectively. The upper reaches are slightly different, which have the quasi-cycles of 3–5 years, 10–30 years, and 70–80 years, respectively.

Keywords Drought · Flood · Climate change · Climate variability · Hanjiang River · Yangtze River

1 Introduction

With population growth and socio-economic development, human demand for water resources has increased dramatically, and the problems with water scarcity and frequent droughts and floods have become major constraints to regional economic and social development.

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In the context of global warming in recent decades, the precipitation and the other components of water cycle were changed in some extents, with the frequency and intensity of extreme drought and flood (DF) events increasing significantly in some regions and a serious regional water crisis (Gosling and Arnell 2016). According to the IPCC Sixth Assessment Report (AR6), approximately four billion people worldwide experience severe water scarcity for at least one month every year (Pörtner et al. 2022). Since the 1970s, 7% of global disaster events have been drought-related, and floods account for 44% of all disaster events (Pörtner et al. 2022). In addition, projections of changes in the global water cycle and their impacts on humans and ecosystems found that, when the globe warms by 1.5 °C–3.0 °C, the risk of floods doubles, with a concomitant increase in economic, agricultural, and potential hydropower losses (Pörtner et al. 2022).

China is one of the most significant warming areas globally in recent decades; the increased water-holding capacity of the atmosphere in the context of a warming climate may have led to a significant increase in the frequency of extreme precipitation in China; however, the overall climate is fluctuating towards aridity, with most areas showing an increasing drying trend (Wen et al. 2019). Previous studies showed that the variation of precipitation in China after 1961 had obvious regional differences: precipitation decreased significantly in North China, southern Northeast China, and a small area in Southwest China; while precipitation in most of Northwest China, the Qinghai-Tibet Plateau, the Jianghuai (Yangtze-Huaihe rivers) area and the coastal areas of South China increase relatively (Ren et al. 2015). However, since the twenty-first century, a reversal of precipitation patterns occurred, with precipitation in southern China and the Jianghuai area beginning to decrease and the frequency, intensity, and duration of extreme drought increasing significantly, and precipitation in northern China increased relatively (Qin et al. 2021).

China's water resource systems are very vulnerable to climate change and variability, and most basins are very sensitive to changes in precipitation (Ren et al. 2008). Climate change and variability have already caused shifts in the distribution patterns of precipitation in China, which is likely to increase further the contradiction between the supply and demand of regional water resources and exacerbate the risk of floods and droughts in some basins (Qin et al. 2021). However, the further back in time one goes, the less instrumental observations were recorded. In the eighteenth century, for example, there were only about 50 meteorological stations worldwide, and more than 90% of the world's areas with continuous instrumental records were in western Europe (Zhang 1996). Chinese instrumental data are only complete for the recent 70 years, with few series reaching 100 years or more in length; therefore, the use of instrumental data to study changes in precipitation or DF over historical periods is currently difficult to achieve.

In recent decades, the study of climate change and variability on long-time scales based on historical documents has become a globally accepted research method, with sources including diaries, newspapers, inscriptions, missionary accounts, etc. (Brázdil et al. 2010, 2018; Zheng et al. 2014b; Ge et al. 2016a). Adequate use of various proxy records, including historical documents, to objectively reconstruct and analyze the changing characteristics of DF in historical periods can reveal the changing patterns of regional climate at multiple scales, especially at multi-decadal scales and beyond (Qian et al. 2012; Brázdil et al. 2018). Meanwhile, it can also provide an insight into where the current trends in extreme DF variability stand in terms of historical perspective and provides historical analogies or statistical models for future climate predictions.

China has a rich historical record of DF, which are accurately dated and have clear climatic significance, and are valuable information for understanding the characteristics of DF variability. Since the 1970s, Chinese scholars have used the DF records from historical documents to reconstruct paleoclimatic time series, explore regional changes in wet and dry and precipitation, and the evolutionary patterns of historical DF (e.g., Central Meteorological Bureau or CMB 1981; Zhang 1996; Hao et al. 2010; Ge 2011; Qian et al. 2012; Zheng et al. 2014a, b). In particular, there have been lots of studies on large areas such as eastern China, the Yangtze River Basin, and the Yellow River Basin, while relatively few works focused on the characteristics of historical climatic variability in local areas or smaller basins. However, due to a combination of factors such as geographical location and sea-land distribution, there are many types of climate variability features even within small and medium-scale basins, which have a non-negligible impact on the basin's DF and their spatial and temporal distribution, especially in climatic transition zones, where the spatial characteristics of climate variability are more complex (Water Resources Commission of the Ministry of Water Resources 2002).

The Hanjiang River Basin (HRB; Fig. 1) is located in Central China. As the water source area for the Middle-route of South–to–North Water Diversion (MSNWD) project and a key basin for flood control in the middle and lower reaches of the Yangtze River, DF changes in the HRB have an extensive ecological, environmental, and socio-economic impacts (Gu et al. 2012). In the context of climate change, the probability of simultaneous DF occurring in the upper HRB and North China (the Water-receiving area of the MSNWD project) is at a historically high level since the mid-twentieth century; in addition, the annual runoff depth of the entire HRB has declined since 1990, putting great pressure on the ecological environment and water resources management (Ren et al. 2011; Ban et al. 2018). However, there is less research on the patterns of precipitation variability as well as DF in the HRB during historical periods, and most works already published focus on the upper HRB (e.g., Yin 2015). In our previous work, we analyzed the spatial and temporal characteristics of extreme DF events in the HRB since 1426 (Zhang et al. 2022), but scientific issues such as the spatial and temporal pattern of historical DF variability, the impact of recent climate change on the frequency and intensity of DF, and the rich-poor precipitation encounters in the HRB and North China on multi-decade to century scales, are still poorly understood and subject to large uncertainties.

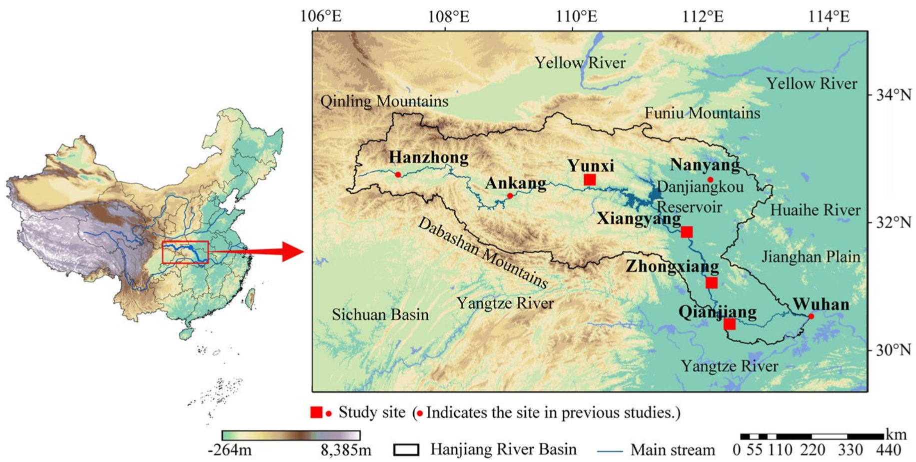

Fig. 1 Study area and locations of the eight prefecture capitals used for reconstruction of DF. The red squares represent the sites reconstructed in this study, and study sites in previous work (CMB 1981) are marked as small red dots

This study reconstructed the yearly time series of DF grades (DFGs) in the HRB from 1426–2017 using historical documentation and instrumental measurement data. The spatial and temporal variation characteristics of DFGs across the basin and in different zones (the upper HRB and the middle and lower HRB) were then examined. It was our hope through this work to provide reference and basic data for further understanding of the characteristics and historical status of the current DF changes in the HRB, which would help in optimizing the water resources management of the MSNWD project and coping with future climate change and variability in the river basin.

2 Study area, data, and methods

2.1 Study area

The study area is the HRB, located in central China, and it has been generally accepted that the Hanjiang River is the longest tributary of the Yangtze River (Fig. 1). Originating in the southern slope of the Qinling Mountains, the Hanjiang River flows mainly through Shaanxi, Henan, and Hubei provinces, with a total length of 1,577 km and a basin area of 159,000 km^2. The HRB belongs to the northern sub-tropical monsoon climate with an average annual precipitation of 700–1300 mm (1960–2010); the precipitation is mainly concentrated in summer and autumn, with July–September rainfall accounting for about 70% of the annual precipitation (Yin 2015). As a sensitive and transitional zone for climate and environmental change, the HRB frequently suffered from DF in history and modern times (Yin 2015).

On 12 December 2014, the MSNWD project was completed after 11 years of construction and began to supply water to North China from the Danjiangkou Reservoir, and by 22 July 2022, the project had transferred more than 50 billion cubic meters of water and benefited more than 85 million people (China Government Web 2022). The importance of the HRB, especially the upper reaches of the river as the source area of the huge hydro project, in the national water resources management has been growing. Change and variability in precipitation, and DF in particular, in the river basin at multi-decadal to century scales, have become a key issue in studies of the climate and environmental sciences.

2.2 Data

The data used in this study was divided into two parts: historical data and instrumental data. The historical data consists mainly of local chronicles and Qing dynasty (1636–1912) archives; the instrumental data (1951–2017) are from the monthly precipitation dataset of China National Surface Meteorological Station Homogenized Precipitation Data Set (V1.0) (Yang and Li 2014). The specific data sources and characteristics, as well as the selection criteria have been described in detail in our previous work (Zhang et al. 2022). Furthermore, in this study, we re-combed a total of 158 sets of original local chronicles from the HRB during the Ming and Qing Dynasties (1368–1912), sifting through the volumes of "Xiangyi," "Jianzhi," "Chengchi," "Difang," "Tianfu," "Yiwen," "Zaji," and so on (source from China Digital Fangzhi Library: http://x.wenjinguan.com), adding a few historical records of DF, which increases the reliability of the HRB DFG series, but does not change the results of our previous work (Zhang et al. 2022).

In addition, we used the Atlantic Multidecadal Oscillation (AMO) time series (1567–1990) reconstructed using tree rings by Gray et al. (2004; https://www.ncei.noaa.gov/access/paleo-search/study/6324) for a brief discussion of the factors influencing DF variability in the HRB.

2.3 Methods

(1) Reconstruction method for historical DFG.

With lots of validation and empirical evidence (e.g., Gong 1983; Zhang 1996), the DFG method is ideal for dealing with qualitative descriptions of historical records. Therefore, we adopted the five grades to reconstruct the DFG series in the HRB by referring to the historic DF reconstruction criteria developed by the CMB (1981; now the China Meteorological Administration or CMA). This method classifies the degree of DF as well as precipitation at each representative site (equivalent to a meteorological station) into five grades, with grades 1–5 representing drought, moderate drought, normal, moderate flood, and flood. Because conditions such as the number of historical records in the HRB vary from region to region, it is difficult to collect data on a year-by-year basis if each county is used as a unit (Zhang 1996). Therefore, we selected eight representative sites in the HRB, including Hanzhong, Ankang, Yunxi, Nanyang, Xiangyang, Qianjiang, Zhongxiang, and Wuhan (Fig. 1), on the basis of administrative divisions and following the principles of spatially even distribution and temporally continuity of historical records. As shown in Figs. 1 and 2 (Online Resource), each site contains a number of counties or cities around it, and the grade of DF at each site indicates the degree of precipitation anomalies within a certain area represented by that site.

The details and limitations of the method and the criteria for the division of site areas are the same as described in our previous work (Zhang et al. 2022).

The proxy records in historical documents have the inherent characteristics of "the closer to the present day, the more detailed and rich the records; the further away, the

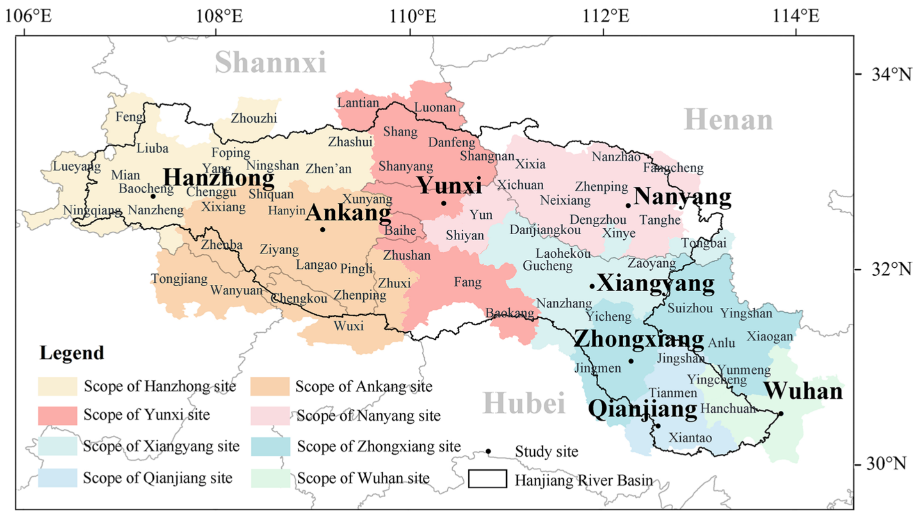

Fig. 2 Representative ranges of eight sites in the HRB during 1426–1950

fewer the records" and "the more socio-economically developed and politically important the area, the more detailed the historical records"; in addition, warfare and dynastic changes can also cause a lack of historical records (Zheng et al. 2014a, b). In order to identify the uncertainty of the results of this study in the historical period (1426–1950), we used the method of Hao et al. (2010) to classify each 50 years periods (the first of these periods is 1426–1449) of historical records for the HRB from 1426–1950 into five levels: A, B, C, D, and E, using the proportion of years with historical records to the total number of years in the period as an indicator. Each level was classified according to the proportion of years with historical records to the total number of years in the period (i.e., 50 years), based on A≥90%, 90%>B>66.7%, 66.7%≥C>50%, 50%≥D>33.3% and E≤33.3%. Since historical records are also characterized as "abnormal rather than normal conditions are far more frequently recorded" (Zheng et al. 2014a, b), the following assessment criteria could be derived in conjunction with the scientific criteria for describing the uncertainty, referring to those developed by the IPCC (Solomon et al. 2007):

1) If the number of years with historical records exceeds 66.7% of the total years (levels A and B), it is roughly equivalent to recording more than 95% of the years of DF, which is at a very high confidence level. 2) If the number of years with historical records exceeds 50% of the total years (level C), it is roughly equivalent to recording more than 80% of DF years, which is at a high confidence level. 3) If the number of years with historical records exceeds 33.3% of the total years (level D), it is roughly equivalent to recording more than 50% of DF years, which is at a medium confidence level. 4) If the proportion of historical records for a period is less than (including) 33.3% (i.e., level E), this indicates a low confidence level for that period.

As shown in Fig. 3 (e, f; Online Resource), overall, the confidence level of the historical DFG reconstruction in the whole HRB reaches A level for all periods except for 1426–1449, which was registered B level. Furthermore, based on the typical geographical distribution characteristics of the HRB (Fig. 1; i. e., the area above the Danjiangkou Reservoir is the upper HRB, dominated by high mountains; that between the Danjiangkou Reservoir and Wuhan City are the middle and lower reaches of the HRB, dominated by low hills and plain landscapes), the uncertainties of the results were assessed for the upper HRB (including Hanzhong, Ankang, and Yunxi) and the middle and lower HRB (including Nanyang, Xiangyang, Zhongxiang, Qianjiang and Wuhan) respectively. As shown in Fig. 3 (a, b, c, and d), the overall confidence level in the upper HRB was relatively low, with Level E from 1426–1449 and Level D from 1450–1499, and the rest of the period reached level C and above. In contrast, the confidence level in the middle and lower HRB is relatively high, with confidence levels reaching B and above in all periods.

(2) Arithmetic average method.

In this study, we used the arithmetic average method to sum the DFGs at eight sites in the HRB and then averaged them, allowing for visual and concise analysis of the temporal variation characteristics of DFG in the HRB as a whole. In addition, the sliding average method, which is equivalent to a low-pass filter, was used to observe the inter-decadal and multi-decadal variability characteristics of DFG in the HRB, which can also remove the influence of occasional fluctuation factors on the variation of DF to a certain extent (Wei 2007).

(3) Inverse distance weighted (IDW).

IDW is a common method for generating spatially continuous distributions from spatially discrete point observations. This method takes a weighted average of the distances

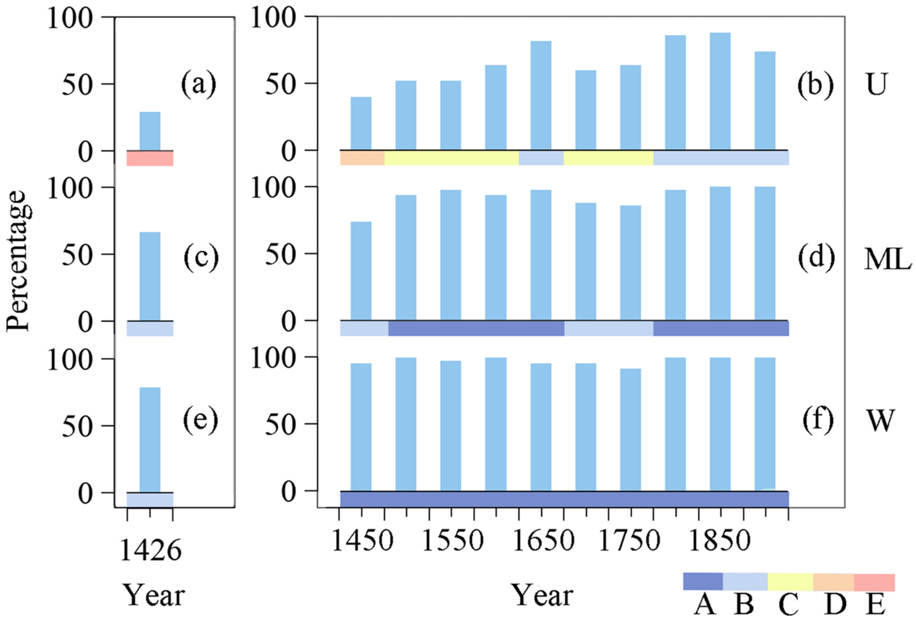

Fig. 3 Percentage of drought and flood records every 50 years (1450–1950; a, c, e is from 1426–1449) in the upper HRB (a, b; U), middle and lower HRB (c, d; ML), and the whole HRB (e, f; W). The color bars indicate confidence levels (A: full confidence; B: very high confidence; C: High confidence; D: medium confidence; E: Low confidence)

between the known and unknown data points, which gives an estimate of the unknown points. It is based on the principle that the closer the distance, the more similar it is, i.e., the closer the known point to the unknown point, the less spatial discrepancy they are. Xie et al. (2018) used four spatial interpolation methods to spatially interpolate precipitation for the upper Sangamon basin with only nine meteorological stations. They found that when the study area is relatively small and with fewer meteorological stations, IDW has the highest interpolation accuracy and is least affected by the number of meteorological stations. We used the IDW in ArcGIS 10.7 to interpolate the DFGs in the HRB to understand the spatial distribution characteristics.

(4) Wavelet analysis and spectral analysis.

Wavelet analysis and spectral analysis are both widely used in studies to reveal the characteristics of climate cycles. Wavelet analysis has excellent local discrimination in both the time and frequency domains, which can determine the scale and temporal location of climate cycles and detect the details of each cycle over time (Torrence and Compo 1998). However, the move of wavelet analysis generates redundant information that may interfere with the judgment of the results (Wei 2007). Spectral analysis is a frequency domain analysis based on the Fourier transform, which decomposes a time series into components at different frequencies, and then diagnoses the dominant periods of the time series based on the variance contribution of the fluctuations at different frequencies, which has the advantage of more definite results (Wei 2007).

The limitation of this method is that the scale transformation is single, and some edge signals are easily lost, while the multi-scale wavelet analysis can compensate for this drawback (Wei 2007). Therefore, we combined the above two methods to detect the DF cycles in the HRB at different periods in this study. Wavelet analysis were implemented using Python, in which the code for the wavelet energy spectrum is provided by the Department of Atmospheric and Oceanic Sciences at the University of Colorado Boulder (https://paos.colorado.edu/research/wavelets/); the code for the wavelet real part is non-public. We plotted the power spectral using the NCAR Command Language, code from https://www.ncl.ucar.edu/Applications/spec.shtml.

3 Results and discussion

3.1 Characteristics of temporal variations

Figure 4a shows the characteristics of temporal variations in DFG in the whole HRB from 1426–2017. Over the past 592 years, the HRB experienced two relatively dry periods and one relatively wet period. The high DFGs between the early 15th and early sixteenth centuries indicate a relatively dry climate, and the overall low DFG between the early 16th and early twentieth centuries indicates a relatively wet climate. Then after the early twentieth century, the DFGs increased again, and the climate turned relatively dry again.

Although the early fifteenth to early sixteenth centuries were relatively dry overall, there were also highly significant interdecadal fluctuations, with the most waterlogged phase being the 1460 s–1470 s. Furthermore, the driest phase occurred in the 1480 s–1490 s and was the most severe sustained drought of the entire study period. From the early sixteenth to the early twentieth centuries, the climate of the HRB was relatively wet overall, with the lowest values of DFGs occurring between the 1530 s and 1670 s, indicating a high frequency of floods during this period. Small interannual to interdecadal variability was notable in the eighteenth century, indicating a generally smooth and humid climatic condition. From the early nineteenth to the early twentieth centuries, i.e., from the 1830s until the early 1930s, there were significant interannual and interdecadal variabilities in DFGs in the HRB, with a clear trend towards an increase in the frequency of DF, reflecting the instability of precipitation variations during this period. From the early 1930s onwards, the HRB turned generally more drought on the multi-decadal time scale; however, there were also two brief periods of interannual-scale flooding in the early 1950s and early 1980s.

The sliding DFG standard deviation curves at the 50-year interval in the HRB showed (Fig. 4b) that the variability of DF was significantly higher before the mid-sixteenth century and after the mid-nineteenth century, while DF fluctuated more gently overall between the late seventeenth and early nineteenth centuries.

Previous studies based on the pollen data from Dajiu Lake and the stalagmites from Rhinoceros Cave (Ge 2011) showed that, in the early Ming Dynasty (1368–1644), the Shennongjia district was rich in precipitation and had a relatively wet climate, but after the early fifteenth century annual precipitation gradually decreased, and the climate turned dry. Since 1430, the Yangtze River Basin experienced almost 60 years of relative dryness before turning relatively wet after 1550, followed by many severe floods over the next 70 years (Ge 2011). In 1560, for example, seven provinces of the middle and lower reaches of the Yangtze River, including Hubei, were infested with severe floods (Ge 2011). The floods in the HRB were also frequent and severe, with many historical records that describe

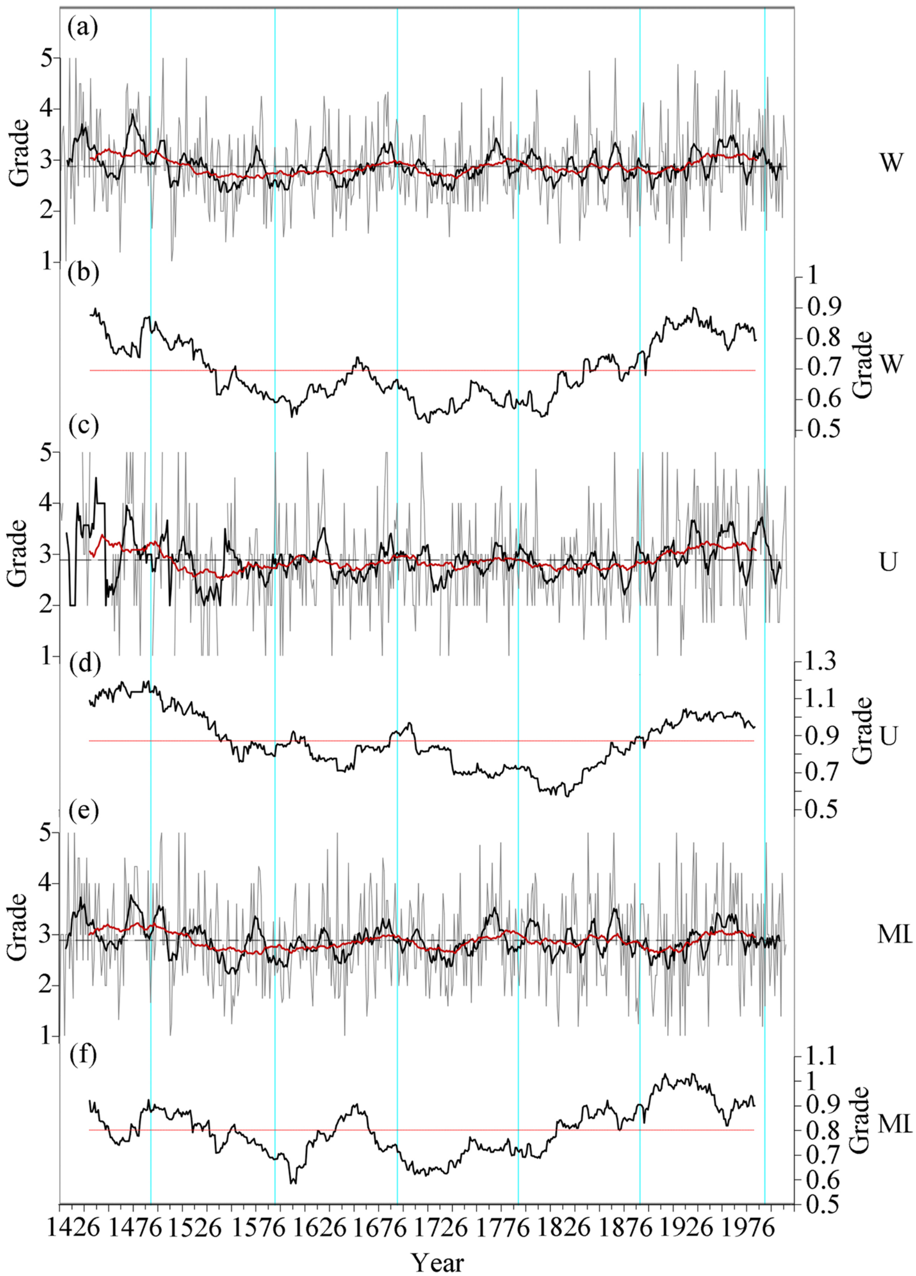

Fig. 4 Characteristics of temporal variations in DFGs in the whole HRB (a, b; W), the upper HRB (c, d; U) and the middle and lower HRB (e, f; ML) from 1426–2017. In a, c and e, the gray line indicates the annual mean DFGs; the thick black line indicates the sliding average of DFGs at 11-year sliding window; the red line indicates the sliding average of DFGs at 50-year sliding window, and the dashed straight line indicates the average value of DFGs. In b, d and f, the black line indicates the sliding average standard deviation of DFGs at 50-year interval, and the red dashed line indicates the average value of the standard deviation. The blue vertical line separates the different centuries, with the first one on left indicating 1500, and the last one on right indicating 2000

the water disasters, such as "There was a severe flood that drowned many people and livestock." “Severe floods submerged the harvest and destroyed the houses and walls” (Zhang 2004), and so on.

Previous research on the elevation records of the low water level at two inscriptions on the upper Yangtze River Basin, Baiheliang and Longjishi (Ge 2011; Qin et al. 2020), found a concentration of records of the low water level on the upper Yangtze River Basin from 1411–1530, indicating a drier climate at that time; after the sixteenth century, the number of records of low water levels at Longjishi decreased, and the appearance of the “Rock Fish” from river water became less frequent at Baiheliang, indicating that the climate turned wetter; in particular, there were significantly fewer records of low water level inscriptions at Baiheliang in the eighteenth century, indicating that there were fewer extreme drought events, and probably more extreme floods, during the period (Qin et al. 2020). Liu et al. (2011) used high-resolution stalagmites and historical records to reconstruct nearly 500 years of precipitation variability at the edge of the monsoon climate zone and found that precipitation variability from 1701–1780 was relatively small, with above-average precipitation, relatively few droughts, and no extreme drought. Previous studies also showed that, in the eighteenth century, China was warmer than in earlier and later periods, with significantly better climatic conditions (Ge 2011).

Since the mid-nineteenth century, China experienced a warming across the country and the greatest warming rate was seen in the last half a century (Qin et al. 2021). During this period, the frequency of DF in the HRB gradually increased. Based on existing inscriptions, archives, and local chronicles, Zhang (2008) found that landslides and mudflows had become a common phenomenon in southern Shaanxi (including the upper HRB) since 1840, after prolonged or heavy rainfall. (Zhang 1987, 1990) found that the DF cycles in the Jianghan Plain (the middle and lower HRB is an important part of the Jianghan Plain) during the Ming and Qing Dynasties became shorter and shorter, especially for floods, which gradually evolved from occurring once every 12 years in the early Ming Dynasty to once every 1.5 years in the late Qing Dynasty. Meanwhile, extreme droughts were also becoming increasingly severe. In 1877–1878, a severe drought occurred in North China, which was the deadliest mega-drought on record before the twentieth century, and this severe drought spread to western Hubei (Ge 2011). According to the statistics of this study, at least 38 counties or cities in the HRB experienced this severe drought, with historical documents recording the devastation in detail, for example: “No rain for two years in a row, the crops looked like they had been burnt, the wells dried up, the rice was very expensive, and terrible famine occurred.” “The trees and grass withered, a terrible famine caused people ate each other, and the roads were lined with corpses” (Zhang 2004).

In the twentieth century, especially in the recent half-century, China experienced relatively large climatic change and variability, with a changing pattern of extreme precipitation events and meteorological droughts (Ren et al. 2012; Ge et al. 2016a, b). The study of the drought occurrence in the middle and lower Yangtze River Basin from 1961 to 2019 showed that the annual number of drought days generally showed a pattern of “increasing in the northwest and decreasing in the southeast” (the HRB is located in the northwest part of the middle and lower Yangtze River Basin; Zhang et al. 2021). Since the 1990s, the HRB as a whole has continued to be relatively dry (Chen et al. 2006; Ban et al. 2018).

However, it is worth noting that, although the HRB has tended to be dry since the early to mid- twentieth century, annual rainfall and evapotranspiration within the basin are unevenly distributed across regions (Ban et al. 2018). To understand the characteristics of DF in different regions of the HRB during the historical period, we analyzed the time series of DFGs in the upper HRB and the middle and lower HRB.

As shown in Fig. 4 (c, e), the frequency of droughts in the upper HRB was highest in the early fifteenth to early sixteenth centuries (around 100 years) and from the early twentieth century to the present. Furthermore, the first half of the seventeenth century (around 15 years), the late seventeenth to early eighteenth centuries (around 18 years) and the late eighteenth century (around 20 years) were relatively dry, but the frequency of droughts was not very high. The DF in the middle and lower HRB were characterized by quasi-cyclical oscillations of around 50 years, with five more pronounced periods of drought, from the early fifteenth century to the first half of the sixteenth century (around 100 years), from the late seventeenth century to the early eighteenth century (around 30 years), from the late eighteenth century to the early nineteenth century around 40 years), from the mid-nineteenth century to the end of the nineteenth century (around 30 years) and from the mid-twentieth century to the present respectively.

The sliding standard deviation curves (50-year time window) for the upper and middle and lower HRB (Fig. 4 d, f) show that the upper HRB had the greatest DF variability before the mid-sixteenth century, followed by the late nineteenth century to the early twenty-first century, and the variability was overall flatter from the early eighteenth century to the late nineteenth century; the middle and lower HRB experienced the greatest variability in DF between the early nineteenth and early twenty-first centuries, followed by the late fifteenth and early sixteenth centuries, and also relatively significant around the mid-seventeenth century, with the second half of the seventeenth century to the early nineteenth century being the smallest.

Figure 5 shows the yearly variation of the frequency of grade 5 droughts and grade 1 floods (since the ideal frequency criteria for grade 1 and 5 is 10% (CMB 1981), as suggested by IPCC (Solomon et al. 2007), grade 1 flood and grade 5 drought means severe flood and severe drought) at all sites in the whole HRB (Hanzhong, Ankang, Yunxi, Nanyang, Xiangyang, Zhongxiang, Qianjiang, and Wuhan sites), upper HRB (Hanzhong, Ankang, and Yunxi sites) as well as middle and lower HRB (Nanyang, Xiangyang, Zhongxiang, Qianjiang and Wuhan sites) from 1426 to 2017. There is a relatively high consistency in the occurrence of severe DF in the HRB as a whole. From the early nineteenth century to the present is a common high incidence of severe DF, and the frequency of severe droughts from the early

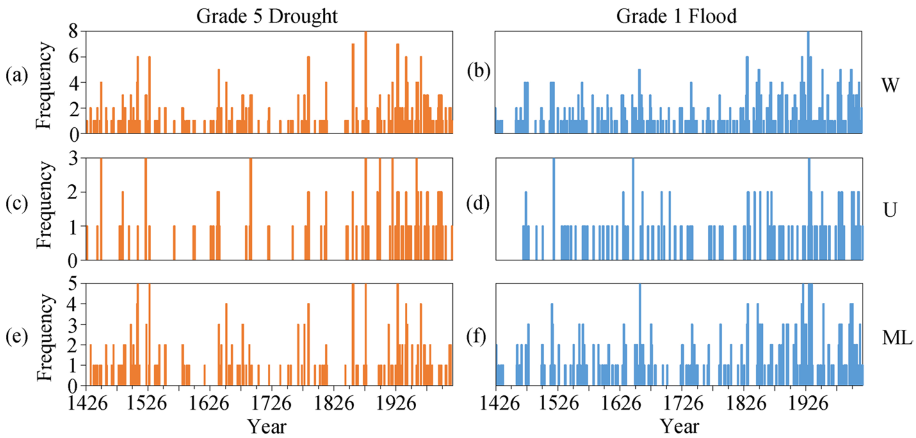

Fig. 5 Yearly occurrence of grade 5 droughts and grade 1 floods at the whole HRB sites (a, b; W), upper HRB sites (c, d; U), as well as the middle and lower HRB sites (e, f; ML), 1426–2017. (a, c, e) shows the frequency of grade 5 droughts, and (b, d, f) shows the frequency of grade 1 floods

fifteenth century to the early sixteenth century was also relatively high. From Fig. 5 (c, d, e, f), while the frequency of severe DF increased significantly in both the upper and the middle and lower basins after the nineteenth century, the frequency of severe droughts increased more in the upper HRB and was obviously the highest in the last 592 years, and the frequency of severe floods increased more in the middle and lower HRB. In the last century, therefore, a polarization appears to have occurred between severe DF of the upper and middle and lower HRB, with the relatively dry region experiencing more severe droughts and the relatively wet region experiencing more severe floods.

3.2 Characteristics of spatial distribution

Statistics on the frequency of DF at all grades (except for grade 3) at various sites in the HRB from 1426–2017 show that the high-frequency DF areas were concentrated in the middle and lower HRB (Figs. 6, 7, and 8; Figs. 7 and 8 were plotted using the IDW and given in Online Resource). The areas where floods occurred relatively more frequently were Wuhan and Qianjiang, with 231 and 227 floods, respectively, followed by the Zhongxiang site, with 196 floods; the above three sites accounted for 48% of the total number of floods in the HRB. A total of 130 floods occurred at the Ankang, which is the lowest frequency of floods in the HRB. The high-frequency centers of drought were Zhongxiang and Wuhan, with 177 and 163 droughts, respectively, and the frequency of droughts at the two sites accounted for 33% of the total in the HRB. There were 102 droughts at the Yunxi site, which is the lowest frequency of droughts in the HRB.

Figure 4b shows that the HRB had the greatest DF variability from 1890–2017 and the smallest one from 1679–1835. Figure 9 (plotted using the IDW; Online Resource) shows the standard deviation for each site in the two periods. Ankang in the upper HRB had the greatest variability in both 1890–2017 and 1679–1835. The smallest variability occurred at Zhongxiang during 1679–1835, and at Nanyang during 1890–2017, respectively.

Previous study (Ankang City Local History Compilation Committee 2004) found that, from the fourteenth century to the late twentieth century, both DF frequently occurred in Ankang, with some of the DF causing severe impacts on society and economy. Peng et al. (2011) studied the characteristics of DF in Ankang from 1961 to 2009 and found that Ankang was prone to floods in the 1980s and droughts in the 1990s; in the twenty-first century, interannual precipitation variability in the Ankang area increased with more frequent DF.

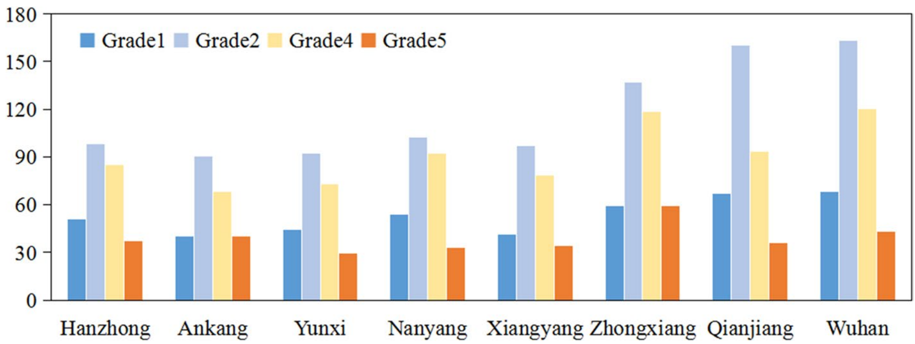

Fig. 6 Frequency of grade 1, 2, 4, and 5 occurrences at eight sites in the HRB from 1426–2017

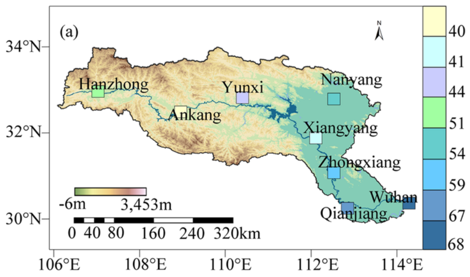

Fig. 7 Frequency of Grade 1 and Grade 5 at eight sites in the HRB from 1426–2017

Figure 4a shows that the HRB was drier overall from 1426–1515 and 1940–2017, in contrast to 1516–1939, which was generally wetter. We calculated the average values of the DFGs for each site in the HRB during the above three periods (Fig. 10, and plotted using the IDW; Online Resource). From 1426–1515, the Zhongxiang site had the highest average DFG and was mostly frequently affected by droughts, and the Ankang site had the lowest average DFG and was relatively more affected by floods; from 1516–1939, the Ankang site had the highest average DFG, and the Qianjiang site had the lowest average DFG; from 1940–2017, the highest average DFG appeared at the Hanzhong site, and the lowest average DFG was at the Qianjiang site. Qianjiang in the lower HRB was the most severely flooded place.

During the Ming and Qing Dynasties, the middle and lower HRB were swarmed with immigrants earlier than the upper reaches, and the vast lakes and riversides were rapidly developed, with the lakes gradually being reclaimed as farmland (Lu 2019). Meanwhile, the gradual construction and integration of dykes on both sides of the river constrained the main flow of the Hanjiang River within narrow dykes, which blocked the river and lake and disrupted the water system, causing frequent breaches of the dykes in the lower reaches and probably increasing the frequency of floods (Lu 2019). According to incomplete statistics, a total of 28 Hanjiang River tributaries were silted up in Hanchuan and Qianjiang during the Qing Dynasty, and 44 lakes were silted up in Hanchuan, Qianjiang, and Tianmen (Lu 2019). Moreover, the abnormality of the river channel being “wide at the upper section and narrow at the lower section” is widespread in the lower reaches of the HRB, for example, the riverbed near Qianjiang has a discharge cross-section of 2300m2, while near Xiantao it is only 1700m2, which is also an important reason for the serious floods in the lower reaches of the HRB, especially in the Qianjiang area (Institute of Geography

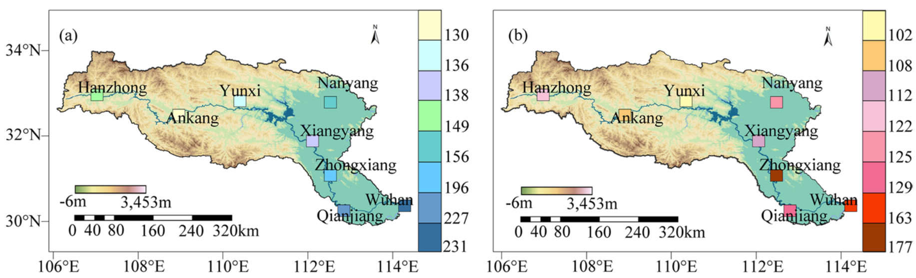

Fig. 8 Frequency of floods (a; Grade 1 and 2) and droughts (b; Grade 4 and 5) at eight sites in the HRB from 1426–2017

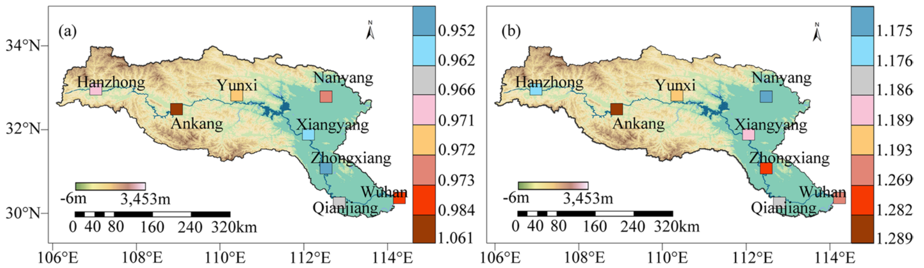

Fig. 9 Standard deviation of DFGs for eight sites in the HRB for 1679–1835 (a) and 1890–2017 (b)

of Chinese Academy of Sciences 1957). However, the abnormality of the river channel continued to exist in the time period after early 19th, and it only occurred in the very lower section of the middle and lower reaches of the HRB, which may not be a main reason for the century-scale DFG variability of the "two-end dry and middle wet" in the whole HRB and the upper reaches of the river as shown in Fig. 4. Furthermore, the water level of the Yangtze River' main stream is closely linked to the floods in the lower HRB. When the water level of the Yangtze River and HRB rise simultaneously, backflow may even occur in the lower HRB (Institute of Geography of Chinese Academy of Sciences 1957). The possible influence of the main stream water level needs to be investigated in future, but it may dominantly occur near the mouth of the Hanjiang River.

3.3 Cyclical characteristics of DF

Figures 11 and 12 show the intensity of the wavelet real and wavelet energy spectra, as well as the power spectra for the DFGs in the whole HRB, the upper HRB (1578–2017 was chosen for analysis because of the high number of missing values for DFGs in the upper HRB before 1578; 1729–1735 gaps are filled in with the average values of the 30 years before and after) and the middle and lower HRB, which reflect the characteristics of each DF cycle over time.

Figures 11 (a, d) and 12 (a) show that there were three main long cycles of 50 years, around 30 years and 80–100 years in the whole HRB. Specifically, the early fifteenth century to the end of the seventeenth century was dominated by high-energy oscillation cycles of 50 years (the fifteenth century was affected by the edge effect). From the end of the sixteenth century to the mid-nineteenth century, oscillation cycles of around 30 years were more stable but weak in overall energy, but relatively strong from the end of the eighteenth century to the early nineteenth century. From the mid-sixteenth century to the early

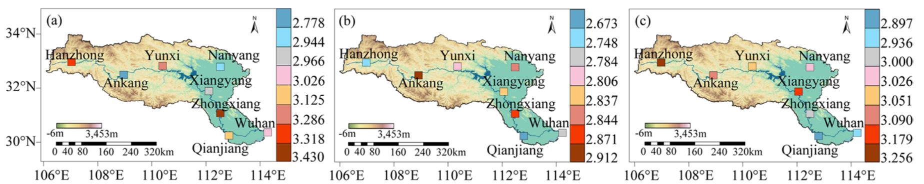

Fig. 10 Average values of DFGs at eight sites in the HRB for the periods 1426–1515 (a), 1516–1939 (b), and 1940–2017 (c)

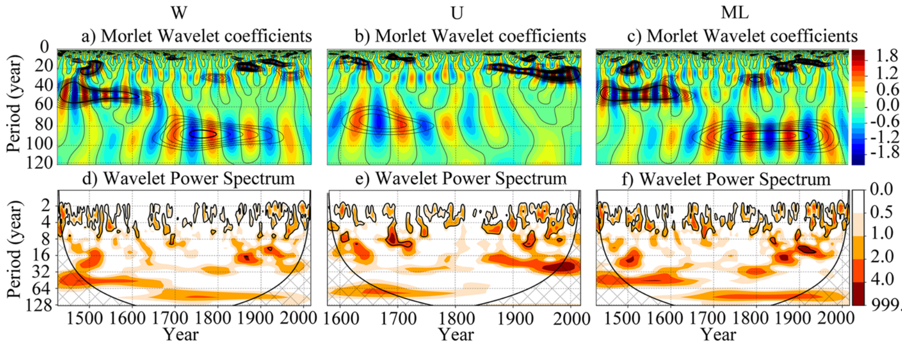

Fig. 11 Temporal characteristics of DF cycles in the whole HRB (a, d; W), upper HRB (b, e; U), and middle and lower HRB (c, f; ML) from 1426–2017 (the upper HRB from 1578–2017). (a, b, c) show the real part of wavelet coefficients; black contours indicate passing the 95% significance test of confidence, and larger color bar values indicate drier condition, and smaller values indicate wetter condition. (d, e, f) show the wavelet energy spectrum distribution; the grid line part indicates the area affected by the edge effect, and a larger value of the color bar indicates a stronger wavelet spectrum power

twenty-first century, a stable century-scale cycle of 80–100 years exists (the end of the nineteenth century onwards was affected by the edge effect). Meanwhile, significant interannual and interdecadal scale fluctuations of around 7–8 and 10–30 years were superimposed from the early fifteenth century to the mid-sixteenth century and from the mid-nineteenth century to the end of the twentieth century, with a large overall variation and basically all reaching a significance level of 5% (early fifteenth century affected by the edge effect). In addition, there are interannual cycles of 2–3 and 5 years. After the mid-twentieth century, 30-year cycle is again signaled (the end of the twentieth century was affected by the edge effect).

As a whole, the high-energy oscillation cycles of DF in the HRB were concentrated between the mid-fifteenth century and the early sixteenth century as well as mid-nineteenth century and late twentieth century. Combined with Fig. 4a, it is clear that, during the above two periods, the HRB was relatively dry.

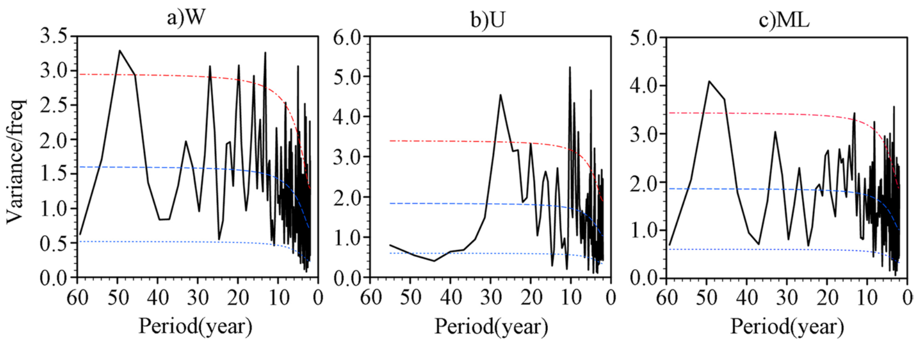

Fig. 12 Power spectra for the whole HRB (a; W), upper HRB (b; U), and middle and lower HRB (c; ML). Red dashed curves are the Markov red noise spectra. Blue dashed curves indicate upper and lower confidence bounds at 95% significance levels

Figure 11 (b, c, e, f) and (b, c) also shows that, overall, the cycle variation characteristics of the middle and lower HRB and the entire HRB as a whole are relatively similar, but there are relatively obvious differences in the upper HRB. There are two main long cycles of 70–80 years and around 30 years in the upper HRB. Century cycles of 70–80 years occurred mainly from the end of the sixteenth century to the mid-nineteenth century (affected by the edge effect before the eighteenth century). The cycle of around 30 years runs essentially throughout the entire period, with the overall energy being weak until the mid-nineteenth century (the energy in the early nineteenth century was at its weakest) but relatively strong in the eighteenth century. After the mid-nineteenth century, the high energy oscillation cycle is significant and shortens to around 20 years, and then after the mid-twentieth century it gradually lengthens to around 30 years again (the second half of the twentieth century to the beginning of the twenty-first century was affected by the edge effect). High energy interannual and interdecadal oscillatory cycles with large variability of around 10 and 5–20 years were superimposed from the late sixteenth century to the early eighteenth century and from the mid-nineteenth century to the early twenty-first century. In addition, there are also long-term interannual cycles of variation of 3–5 years.

Previous studies of historical records of DF, tree-ring, lake sediments, ice cores, and other proxy data found that the 11, 22, 35, and 80–100 year cycles of wet and dry variations are widespread in the eastern monsoon and western arid zones of China (Ge 2011; Qin et al. 2021). Previous reconstructions of the annual DFG series for the past 2000 years and the wet and dry grade series for the last 1000 years in central and eastern China found that there were significant wet and dry cycles of 2.5, 3.5–7, 22, 32, 45 and 70–80 years (Zhang et al. 1997; Ge 2011). Xu et al. (2010) reconstructed the recent 500 years wet and dry series in Hubei Province. They found that there were clear cycles of 3, 35, and 50 years of wet and dry variability in northern Hubei Province (including the middle HRB), while the eastern region (including the lower HRB) showed clear cycles of 11, 50–60, and 80–100 years. Yin (2015) found that there were 2–5 and 65–70-year cycles of drought variability, as well as 2–5 and 38–40 year cycles of flood variability, in the upper HRB. The study by Fang et al. (2007) on the cycles of flood frequency in China between 1644 and 2004 showed that floods were mainly manifested as century cycles before 1833, and from 1834 to 1920, and significant 20-year fluctuations were superimposed on the cycle of the century; then after 1921, 20–30-year cycles were most prominent.

In addition, previous studies on the factors of regional climate variability found that ENSO has interannual and interdecadal cycles of 2–7 years and 10–30 years (Fiedler 2002); PDO has interdecadal to multi-decadal oscillation cycles of around 15 years and 30 years (Han et al. 2012); frequent cycles of solar activity are around 20 and 50 years (Zhan et al. 2006); and century cycles of the East Asian monsoon are around 80–100 years Guo et al. (2004). The above-mentioned climate cycles are manifested to varying degrees in the DFG variation in the HRB. Yin (2015) associated ENSO and the East Asian monsoon with the DF variability in the upper HRB; Zhang et al. (2022) showed that the East Asian monsoon and El Niño played a role in influencing historical extreme DF in the HRB. Meanwhile, it was found that ENSO, PDO, East Asian monsoon and sunspot activity all have different degrees of influence on precipitation in the middle and lower Yangtze River basin (Hao et al. 2015; Ge et al. 2016a, b; Qin et al. 2021), reflecting that the HRB precipitation may be sensitive to changes in multiple climate factors.

However, the concrete link mechanisms of the DFG variability with the internal and extra climate factors need to be investigated in the future. Whatever the mechanisms, the quasi-cycles revealed in the analysis would be of reference to the long-term DF prediction of the HRB, which is very important to the planning and management of the water resources in the river basin and the efficient operation of the MSNWD project.

3.4 DF association with AMO

As mentioned above, previous studies showed that historical DF changes in the HRB were influenced by the East Asian monsoon and ENSO (Yin 2015; Zhang et al. 2022), but the factors influencing the variability of DF are numerous and complex. The AMO is a quasi-periodic warm and cold change of sea surface temperature in the North Atlantic (Kerr 2000), and its impact on climate change and variability is getting more and more attention. We calculated the correlations between the 11-year and 30-year sliding averages of DFGs in the HRB and AMO from 1567–1990 (Gray et al. 2004) and found that all the correlations were positive, and they all passed the 0.01 test of significance, indicating the possible impact of the AMO on the decadal to multi-decadal variabilities of DF in the HRB (Table 1; Online Resource).

There is, of course, still lots of uncertainty about the impact of AMO on climate change and variability in East Asia (Li et al. 2009). Some studies of the correlation between precipitation variability and AMO over historical periods in multiple regions of China found that AMO has a variable influence on precipitation variability in different regions; moreover, the correspondence between AMO and precipitation is unstable over time. For example, Wang et al. (2022) showed that the AMO was in anti-phase with precipitation changes in eastern China during 1500–1780 while in-phase during 1780–1980. Zhou et al. (2020) found that, during the Medieval Climate Anomaly (950–1250), when the AMO was in positive phases, more precipitation occurred in the Yangtze River basin and South China, and less in parts of North China; however, during the Little Ice Age (1450–1850), when the AMO was in positive phases, precipitation tended to be low in eastern China, especially in the Yangtze River basin. The study of tree-ring stable oxygen isotopes (δ18O) in Shanxi Province, China, from 1784–2013, showed that, at the decadal scale, the positive phase of the AMO may have contributed to summer precipitation in the region (Liu et al. 2022).

As this study focuses on characteristics of DF variability, and there is also a limit of words, here we only briefly discuss the one of the potential factors influencing the low-frequency variability of DF in the HRB; a specific analysis on the link of the regional DF with large-scale atmospheric and environmental factors is needed in the future.

4 Conclusions

The above analysis of DF variability patterns in the HRB from 1426–2017 leads to the following basic understanding:

1) Frequent droughts and floods occurred in the HRB during the historical period, and there is a relatively high consistency of DF variability throughout the basin. The HRB has roughly experienced two relatively dry climate stages lasting around 100 years and one relatively wet climate stage lasting around four centuries in the last 592 years. The

Table 1 Correlation coefficients between the AMO and the HRB's 11- and 30-year sliding averages, 1567–1990

	11-year sliding average	30-year sliding average
AMO	0.29**	0.35**

Significance level of Pearson test: **, $p < 0.01$

two relatively dry periods were from the early fifteenth century to the early sixteenth century and from the early twentieth century to the present; a long period of relative wet period lasted from the early sixteenth to the early twentieth centuries.
2) Droughts and floods in the HRB became more frequent, and climate instability increased since the early twentieth century. There was a high frequency of co-occurrence of severe floods and severe droughts during the recent 100 years. Severe floods increased more in the middle and lower HRB than in the upper reaches, severe droughts increased more in the upper HRB than in the middle and lower reaches, and the frequency of severe droughts in the upper HRB since the early twentieth century is the highest in nearly six centuries.
3) The characteristics of the spatial distribution of DF showed that the upper HRB, located in mountainous areas, has the greatest variability of DF.
4) There is a phenomenon of interannual quasi-cycles of 2–8 for DF in the whole HRB as well as middle and lower HRB, and interdecadal to century-scale quasi-cycles of 10–30, 50, and 80–100 years, and the upper HRB is dominated by 3–5-year quasi-cycles, as well as 10–30 year and 70–80 year quasi-cycles. The high-energy oscillation cycles of DF in the HRB were mainly concentrated between the mid-fifteenth century and the early sixteenth century, as well as the mid-nineteenth century and late twentieth century.

The findings reported in this paper would be of reference to the understanding, prediction and management of long-term DF risks in the HRB, which is an important river basin in central China. Further works should be made to recovery more historical documents, collect other proxy data including tree-ring records and high-resolution lake sediments, analyze the possible causes and mechanism of the drought/flood periodical variability, and simulate the multi- to centennial variability of DF with regional climate model.

Author contribution GR and HB designed the research and guided the writing; TM and JM guided the development of the methods; XZ conducted the analysis, PZ and GY guided the technical part; XZ reconstructed the DF grade series, analyzed the data, and drew the figures the manuscript.

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Data availability The "China National Ground Meteorological Station Homogenized Precipitation Data Set (V1.0)" is non-public.

Declarations

Competing interests The authors declare no competing interests.

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