Climatic control of upper Yangtze River flood hazard diminished by reservoir groups

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Abstract

Over recent decades, concern has grown regarding the effects of climate change and artificial river projects on the variability of river floods. Specifically, it has been demonstrated that the Mississippi River flood hazard has been amplified by river engineering. In contrast, the world’s largest reservoir group with the Three Gorges Reservoir at its core has been built along the upper reaches of the Yangtze River, but the question of whether there has been a positive effect on flood control is worthy of discussion. Here, we revisit nine paleofloods from the ancient stone inscriptions for the first time and show that while annual peak discharge in the upper reaches of the Yangtze River is dominated by sunspot numbers and the North Atlantic Oscillation, the magnitude of flooding has been decreased by the reservoir group, which diminished flood hazard through reversing or strengthening the direction of climate control on the flood.

1. Introduction

The Yangtze River is a large river that contributes considerably to the economic development of central China but also exposes the population to severe natural hazards (Nilsson et al 2005, Lu et al 2011, Zhou et al 2016, Best 2019). For example, the flooding of the Yangtze River in summer 1998, which persisted from mid-June to the end of August, caused several thousand fatalities and direct economic losses of RMB 255 billion (Zong and Chen 2000). This flooding was one of three severe all-basin flood events that occurred in the twentieth century. At the Yichang hydrological station, located at the exit of the upper reaches of the Yangtze River, the peak discharge during these three major events that occurred in 1931, 1954, and 1998 was 64 600, 66 100, and 61 700 m\(^3\) s\(^{-1}\), respectively. The frequent occurrences of flood disasters prompted the Chinese government to organize comprehensive effective engineering measures for flood control to safeguard lives and property. Reservoirs constitute one of the most efficient infrastructure components in integrated water resource development and management (Liu et al 2015, Li et al 2018). According to the International Commission on Large Dams, China is the country with the highest number of large dams (i.e. a dam with a height of 15 m or greater from the lowest foundation to the crest, or a dam with height of 5–15 m impounding more than 3 \(\times\) 10\(^6\) m\(^3\)). Specifically, China’s 23 841 large dams account for approximately 40% of the global total. Since 1956, numerous reservoirs have been constructed along the upper reaches of the Yangtze River, forming the world’s largest reservoir group with the Three Gorges Reservoir at its core (figure 1). Reflecting the availability of sufficient capital and the progress of technology, the storage capacities of most reservoirs built since 2000 are much larger than those of earlier constructions (figure 2(A)). These reservoirs realize comprehensive utilization benefits by changing the spatial and temporal distribution characteristics of the natural streamflow (Gao et al 2012).

Although water resource projects transform hydrological regimes directly, the climate also modulates dynamic changes of streamflow over...
Figure 1. Construction and locations of reservoirs in the upper reaches of the Yangtze River. (A) Upper reaches of the Yangtze River, divided into seven hydrological areas: the Jinsha River basin, Yalong River basin, Dadu River basin, Mintuo River basin, Jialing River basin, Wujiang River basin, and the main stream of the Yangtze River basin. The 21 large reservoirs marked include the Liyuan, Ahai, Jinanqiao, Longkaikou, Ludila, Guanyinyan, Jinping, Ertan, Xiluodu, Xiangjiaba, Pubugou, Zipingpu, Bikou, Baozhusi, Caojie, Tingzikou, Goupitan, Silin, Shatuo, Pengshui, and Three Gorges reservoirs. (B) Number of large dams in each tributary and the construction time period.

decal–centennial timescales through complex processes (Winsemius et al 2016, Yin et al 2018). The Yangtze River basin is located in southeastern Eurasia, and the regional climate dominated by the perennial western Pacific subtropical high is characterized by the subtropical monsoon (Wei et al 2019). The drainage area of the upper Yangtze River covers approximately $1 \times 10^6 \text{ km}^2$. It has complex underlying surfaces and is exposed to various climatic conditions. Flooding of the Yangtze River is caused by rainstorms triggered by the combination of air–sea interactions in the Pacific and Indian oceans (and even the Atlantic Ocean), air–solar interactions associated with solar activities, and air–earth interactions on the Tibetan Plateau (Feng 2003). Hence, identification of the dominant factors that reflect climatic
control on streamflow is challenging (Immerzeel et al. 2010). Understanding the mechanisms of climatic control on streamflow is of considerable importance for the prediction of future trends of streamflow and the implementation of adaptive management through artificial hydraulic projects.

Here, we quantitatively evaluate the contributions of both climatic control and water resource projects (i.e. reservoirs) to the variation in the magnitude of floods in the upper reaches of the Yangtze River, and we verify whether the construction of the reservoir group has reduced flood magnitude. The attribution analysis assumes streamflow was modulated only by climatic factors prior to the start of the construction of the reservoir group and that the impact of the reservoir group began after its construction (see Methods for details). The discharge measured at the Yichang hydrological station, which is at the boundary point of the upper and middle reaches of the Yangtze River, is the export discharge of the upper Yangtze River basin. In particular, the Jingjiang reach located downstream of the Yichang station is an important reach for flood control on the Yangtze River; hence, the discharge measured at the Yichang station represents the effectiveness of the reservoir group on flood control (Yang et al. 2015). The peak discharge, which is a typical indicator of flood characteristics, is chosen for evaluation of the degree of change in flood magnitude.

2. Results

2.1. Paleoevents and the variation of annual peak discharge

The multiproxy dataset used in this study, which extends the record of annual peak discharge at the Yichang station back to the early twelfth century, includes nine paleofloods that occurred in 1153, 1227, 1560, 1613, 1788, 1796, 1840, 1860, and 1870 and observed data acquired during 1882–2012. The paleoflood information had been demonstrated in the hydrological data compilation, and was adopted in the design of the Three Gorges Reservoir (Commission 1996). The main process of derivation included estimation of water level based on ancient stone inscriptions (figure 3) and the derivation of discharge according to stage–discharge relation curves.

It is evident that the magnitudes of the nine paleofloods are much larger than the observed annual peak discharge (figure 2(B)). The magnitude of observed annual peak discharge presents a decreasing trend over the past 130 years. However, the decreasing trend has been more drastic since 1956, following intensive dam-building activities, and multiple small-scale floods have been observed during the past 50 years. By contrast, flood magnitude exhibits an increasing trend before the start of dam-building activities. Thus, flood magnitude presents two contrasting trends before and after the start of dam-building
Figure 3. Stone inscriptions relating to paleofloods (Commission 1996). (A) Stone inscription from 1153, found in Zhong County, Chongqing, which reads ‘the water level arrived here on June 27 in the 23rd year of Shaoxing.’ (B) Stone inscription from 1227, found in Jiangbei District, Chongqing, which reads ‘the water level on June 8 in the 3rd year of Baoqing.’ (C) Stone inscription from 1560, found in Zhong County, Chongqing, which reads ‘the water trace on July 23 in the 39th year of Jiajing.’ (D) Stone inscription from 1788, found in Fengdu County, Chongqing, which reads ‘the water level arrived here in the 33rd year of Qianlong.’ (E) Stone inscription from 1796, found in Zigui County, Hubei Province, which reads ‘water levels in the 1st year of Jiaqing.’ (F) Stone inscription from 1860, found in Zhong County, Chongqing, which reads ‘the water level arrived here on May 21 in the 10th year of Xianfeng.’ (G) Stone inscription from 1870, found in Fengjie County, Chongqing, which reads ‘the water level arrived here in the 9th year of Tongzhi.’ It should be noted that only one of many stone inscriptions found for each paleoflood is shown here.

activities, while previous studies have found that an abrupt change of discharge at the Yichang station appeared around 1960 using the changepoint test (Xiong and Guo 2004, Zhang et al 2006). However, we cannot assert that the observed decreasing trend in peak discharge since 1960 is attributable to reservoir construction. The construction and operation of reservoirs could potentially strengthen the role of climatic control or reverse it.

2.2. Identification of climate control factors
To assess the effects of climatic control on flood magnitude, we inspected the relationships between annual peak discharge and possible climatic factors (figures S1 and S2 available online at https://stacks.iop.org/ERL/15/124013/mmedia). Based on multiproxy data from 1749–1955 that included five paleofloods with 79 pairs of samples ($r = 0.433, p < 0.01$), sunspot numbers (SSNs) in
March were found to be highly correlated with annual peak discharge. Using multiproxy data from 1840–1955 that included three paleofloods with 77 pairs of samples ($r = -0.288, p < 0.05$), the second most highly correlated factor was the North Atlantic Oscillation (NAO) in December. The SSN is one of the most striking signs of solar activity and it is used widely as an index to describe solar activity strength (Clette et al. 2014). The NAO is an irregular fluctuation of atmospheric pressure over the North Atlantic Ocean that has a notable effect on winter weather in Europe, Greenland, northeastern North America, North Africa, and northern Asia (Gu et al. 2009). The tendency and strength of the correlative relationships confirm the hypothesis regarding the driving forces of floods in the Yangtze River basin. Solar radiation is the most important source of energy for Earth’s climatic system and it determines Earth’s energy budget. Solar activity affects the distribution of sea surface temperature, and the years with maximum and minimum SSNs often coincide with El Niño events that influence the position of the western Pacific subtropical high (Ye and Wu 2018). Consequently, this influence extends to the East Asian summer monsoon (Zhang et al. 2016), mid–low-level height fields, sea-level pressure field, and 850 hPa wind field, all of which are factors that influence precipitation over the Yangtze River basin (Zhang et al. 2007b). In particular, it has been proven that the East Asian summer monsoon is positively correlative with SSNs (Xiao et al. 2006). In addition, solar activity, which is the external driving force of climatic change, also exerts considerable influence on precipitation and flooding in the Yangtze River basin through solar radiation and energy particles, especially the occurrence of sunspots, solar eclipses, and eclipses at perihelion. Snowmelt and earthquakes on the Tibetan Plateau, which contribute to the flood magnitude of the Yangtze River, are also related to solar activities (Zhang et al. 2007a). Over the past 300 years, SSNs have exhibited an increasing trend with an average 11-year cycle. Solar activity was reasonably intense during both the 1840s–1870s and the 1930s–1960s when large flood events occurred (figure 4(A)). Besides, the sea surface temperature (SST) anomaly in the North Atlantic, western North Pacific and Indian oceans affects the extension of the western North Pacific Subtropical High (Tian and Fan 2013). The phase transition of the NAO is found to be able to influence the East Asian summer monsoon, which may be related to a wave train pattern originating from the North Atlantic (Sung et al. 2006). The precipitation variability in the Yangtze River basin is related to upper-tropospheric midlatitude perturbations that are part of a Rossby wave pattern with its origin in the North Atlantic (Stephan et al. 2018). However, the trend of the NAO presents violent oscillation without any obvious cycle (Goodkin et al. 2008) (figure 4(B)).

2.3. Attribution of climate control and reservoir group

We compared the differences in magnitudes of floods with different recurrence intervals and the magnitudes of 10-, 100-, 1000-, and 10,000-year floods (i.e., $Q_{10}$, $Q_{100}$, $Q_{1000}$, and $Q_{10000}$; a flood with a 10%, 1%, 0.1%, and 0.01% chance of exceedance in any year) estimated statistically based on observed discharge data after the construction of the reservoir group (1956–2012); the derived differences were $(7.16 \pm 2.46)%$, $(7.91 \pm 4.13)%$, $(8.49 \pm 6.12)%$, and $(8.97 \pm 7.99)%$ lower, respectively, compared with the period before reservoir construction (1153–1955). To separate the influences of natural and human activities on the change in discharge, the reconstructed discharge during 1956–2012 was derived based on univariate ($R^2 = 0.187, p < 0.01$) and bivariate ($R^2 = 0.223, p < 0.05$) linear regression models that relate annual peak discharge to the SSN in March and to the NAO in December over the period before the construction of the reservoir group (figure 4(C) and tables S3 and S4). In the absence of human modification of the river, the ‘SSN-only’ regression predicts that $Q_{10}$, $Q_{100}$, $Q_{1000}$, and $Q_{10000}$ would have increased by $(1.42 \pm 1.97)%$, $(2.03 \pm 3.10)%$, $(4.08 \pm 5.31)%$, and $(6.52 \pm 7.56)%$, respectively, over the same period, accounting for approximately $-72.60\%$ to $-19.84\%$ of the observed decrease in discharge. This implies that the remainder (approximately $119.84\%$ to $172.60\%$) of the decline in flood magnitude is the result of human modification of the river. However, the ‘SSN–NAO’ regression demonstrates that $Q_{10}$, $Q_{100}$, $Q_{1000}$, and $Q_{10000}$ would have decreased by $(1.24 \pm 1.91\%)$, $(3.22 \pm 3.05\%)$, $(3.35 \pm 4.54\%)$, and $(2.84 \pm 6.03\%)$, respectively, indicating that climatic control and reservoir operations contribute $(17.31-40.73\%)$ and $(59.27-82.69\%)$, respectively, to the observed decrease in discharge (figure 5). Hence, human modification of the river, specifically the construction and operation of the reservoir group, has played a significantly positive role in reducing flood magnitude, irrespective of the recurrence intervals and magnitude of the flood in the two regression results. The contributions of climatic control and the reservoir group are inconsistent in the results of the two linear models (table 1), which implies that the teleconnection results of a similar contribution analysis conducted on the lower Mississippi River (USA) are suspicious (Munoz et al. 2018).

3. Discussion

Although the mechanisms of runoff generation and concentration, as well as the routing time to Yichang station in the hydrological subareas, are complex and nonlinear, the maximum precipitation in 6 d and total precipitation in July and August over the upper
reaches of the Yangtze River are highly correlated with annual peak discharge, and did not present a significant variation trend during the past 100 years or more. The variation in peak discharge was not a result of the variation in regional precipitation which is often the first-order control on streamflow (figure S5 and table S6). The total potential evapotranspiration in flood season and the whole year both present a significant decreasing trend (figure S6). Furthermore, hydrological modeling has also been implemented to illustrate the impact of climate variables. Concretely, the daily areal average precipitation and potential evapotranspiration data for the upper reaches of the Yangtze River were adopted to run the Xinanjiang hydrological model. The parameters were calibrated using the data before 1956 to represent the basin conditions controlled by climate variables. The annual peak discharge after 1956 was reconstructed by the Xinanjiang model, and was overall larger than the observed flood magnitude (table S8 and figure S9), which also demonstrates the positive effect exerted by reservoir groups in diminishing upper Yangtze River
flood hazard. However, it should be emphasized that the climate variables cannot represent the climate states fully, because these variables are influenced by human activities through changing the land use and land cover, increasing carbon emission. The attribution analysis based on teleconnection factors like SSN is more objective and convincing, in which the basin and even the Earth are an independent system influenced by the teleconnection factors and the teleconnection factors vary in line with its own principles.

The time at which the magnitude of the annual peak discharge presents a decreasing trend is close to the time at which the construction of the reservoir group expanded. Thus, the contribution analysis proves the crucial role of reservoirs in flood control through their capability of peak-flood clipping. On the basis of streamflow forecast, the grouped large reservoirs, which are subject to the joint operation schemes of the Changjiang Water Resources Commission, have successfully defended against floods in 2016 arising in association with a super El Niño event (Ma et al. 2018). In addition to the benefit of flood control, the reservoir group generates approximately 330 billion kWh of hydropower annually, supplying electricity throughout the central regions of China (Zhou et al. 2015), and the waterway shipping volume between the eastern and western parts of China reaches 2.69 billion tons annually. The upper reaches of the Yangtze River basin have undergone massive agriculturalization and urbanization over the previous few decades, which have exerted an indirect influence on local water cycle processes but a lagged and subtle influence on streamflow (Piao et al. 2010, Zhang et al. 2020). In short, reservoir groups that directly modify streamflow magnitude represent the most important form of human modification of rivers and basins for reducing floods.

Similarly, the change in streamflow under the combined influence of climate and anthropogenic activities also exists in other big rivers all over the world, but the specific conditions of each river present unique characteristics. In Africa, for the Nile river which is modulated by the El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole, the construction of dams such as Aswan have prevented floods while the increasing irrigation activities have further promoted the decline of streamflow (Awange et al. 2014). In South America, the ongoing unprecedented increase in flooding in Amazonia has been attributed to a strengthening of the Walker overturning circulation, while the impacts of low-elevation, large-reservoir dams on hydrological alternation were largest among the nearly 200 dams in the Amazon and the hydrologic regimes downstream of dams were significantly more affected than those upstream (Timpe and Kaplan 2017). In North America, the anthropogenic engineering in the Mississippi River are in part offsetting one another. Although the flood mitigation reservoirs along the tributary can decrease peak discharges (up to 28%) according to basin-scale
hydrologic modeling, a magnitude increase (up to 25%) is caused by the levees in the mainstream (Pinter et al 2010). About 75% of the increase in 100-year flood was attributed to artificial channelization, and the rest was rooted in the ENSO and Atlantic Multidecadal Oscillation (Munoz et al 2018). In Asia, although decreasing precipitation and increasing temperature in the Yellow River basin associated with the global ENSO events increase evapotranspiration (Zhao et al 2014), human activity including agricultural irrigation and damming is the main reason for the decrease in streamflow, with a mean fractional contribution of 73.4% during 1980–2000 and 82.5% during 2001–2014 (Li et al 2017). In terms of flood, the number of days with daily runoff exceeding 4000 m$^3$ s$^{-1}$ was reduced sharply in response to the operation of dams and reservoirs since 1950, according to records at the Huayuankou gauge (Wang et al 2006).

Our main conclusion is that the construction of the reservoir group along the upper reaches of the Yangtze River has reversed or strengthened the influence of climatic control through regulation of flood magnitude, resulting in the declining magnitude of flood. The joint application of the reservoir group and floodplain management will offer increased potential for flood control, and a flood insurance system will be implemented to protect communities and industries in the future (Mei et al 2018, Richler 2019). However, it must be acknowledged that dam construction blocks migratory channels for aquatic organisms and can induce geological disasters around reservoir areas. Meanwhile, flow downstream of the dams is artificially controlled by reservoir operations, which changes the stage–discharge rating curve of downstream channels, the river–lake interaction between the Yangtze River and Dongting and Poyang lakes (Wang et al 2017). Concurrent with flow regulation, a considerable amount of sediment is retained in the reservoirs, leading to a decrease in sediment load released from the dams and long-term geometric morphological changes to the downstream channels (Wang et al 2013). The future importance of such negative impacts remains unpredictable. It is hoped that the conclusions presented in this paper will help elucidate the interactive controlling mechanisms of climatic control and human activities in the upper reaches of the Yangtze River basin, and provide a potent reference in support of comprehensive river management.

4. Materials and methods

4.1. Study design

The contributions of climatic control factors and human activities (especially the construction of the reservoir group) to the variation of floods were assessed quantitatively based on the following procedures. (1) According to the time at which dam-building activities commenced, the entire study period was divided into two phases: the period before 1956 (defined as the ‘baseline period’) when only climatic control factors were relevant, and the period after 1956 (defined as the ‘modern period’) when the influence of the reservoir group was considered. Correspondingly, the observed discharge was also divided into two: the observed discharge during the baseline period and that during the modern period. (2) During the baseline period, the climatic control factors that modulated the variation of discharge were identified by conducting successive trial correlation analyses with all possible options. Thus, simple linear regression models between discharge and the dominant climatic factors were established to reconstruct the discharge during the modern period based on the values of the climatic control factors in the modern period. The reconstructed discharge in the modern period represents the natural discharge with the effect of the reservoir group removed. (3) The contributions of the climatic control factors and the reservoir group to the variation of floods were determined based on the following: (i) the difference between the observed discharge in the baseline period and the reconstructed discharge in the modern period, and (ii) the difference between the reconstructed discharge in the modern period and the observed discharge in the modern period, respectively.

4.2. Streamflow data

The observed discharge data used in this study were recorded at the Yichang hydrological station and obtained from the Changjiang Water Resources Commission of the Ministry of Water Resources. The Yichang Customs Office was established in 1877 by the United Kingdom, and a water gauge was installed in the same year; however, subsequent measurement of the water level was not continuous for multiple reasons. After the Yichang hydrological station was established in 1946, continuous measurements of water level and discharge were recorded. The discharge of the years prior to 1946 was derived based on the stage–discharge relation, and missing discharge data were estimated based on the correlation between the stage of the Yuyang station further upstream and the discharge at the Yichang station. Hence, observed daily discharge data for the Yichang station during 1882–2012 were derived and the annual maximum discharge in each calendar year was selected to develop the annual peak discharge series.

In addition to the observed discharge data, information relating to paleoflood events that happened long before the establishment of modern hydrometric systems was also derived from historical documents. Adding the paleofloods into frequency analysis can increase the length of flood series, which contributes to the precise estimation of parameters of the frequency distribution function, the reliability of frequency curve fitting and the extension of
frequency curves to obtain the extreme flood with a rare recurrence period (Guo and Cunnane 1991). The application specifications of paleoflood information have been explicitly stipulated in multiple industry norms of China, including ‘Regulation for calculating design flood of water resources and hydropower projects’ and ‘Technical code of hydrology for electrical power projects’. Estimation of paleoflood magnitudes was based on reliable flood tracing, stone inscriptions, and literature (e.g. local chronicles and historical records) obtained throughout the entire basin, instead of the water deposits or isotope elements in fashion. The investigative work on paleofloods in the Yangtze River basin was conducted as part of the design process of the Three Gorges Reservoir (Commission 1997). The estimation process of paleoflood includes two steps: the first step is to determine the flood elevation through the long and short gradient lines drawn based on the flood trace points (e.g. flood elevation in 1788 and 1860 was determined through the reliable inscriptions in the Huangling Temple) or interpolation according to the correlation between water levels of each section along the river (e.g. flood in 1153, 1227, 1560, 1613 and 1796, the inscriptions of which were found in Zhong county, 400 km upstream of Yichang), while the second step is to determine the peak discharge by extension of the water level–discharge relation curve in the observed flood year when the flood, rainfall, disaster information and water surface lines are similar with the paleoflood year (e.g. floods in 1560, 1788, 1860 were determined using the rating curve which is between the curve of 1954 and the curve of 1956 in Yichang station, flood in 1870 was estimated using the curve of 1956) or extension of one specified compromise rating curve due to the limited reference to judge the flood, rainfall, or disaster information (e.g. floods in 1153, 1227, 1613 and 1796 were estimated using the curve of 1956) (Yang 1989, 1992). In terms of scale, geological characteristics, neotectonic signs, deformation rate and geological age, the characteristics of the river channel in the Yichang area, where the cross section is based on granite, have been stable during the thousands of years of paleofloods (Yang 1997). Exhausting all available references and field visits, these nine paleoflood are the complete records of the largest floods since 1153 (Shi 1987). Hence, information on the nine acknowledged paleoflood events (i.e. 1153, 1227, 1560, 1613, 1788, 1796, 1840, 1860, and 1870) was used to expand the annual peak discharge series.

4.3. Climate data

The Yangtze River basin is located in southeastern Eurasia. To its east lies the Pacific Ocean, to the south is the Indian Ocean, and to the west is the Atlantic Ocean. SST anomalies in the eastern Pacific not only affect the location of the western Pacific Subtropical High, which influences the distribution of rain bands in the Yangtze River basin (Yu et al 2015), but also affect spring SST in the Indian and northwestern Pacific oceans, which influences the availability of moisture for precipitation over the Yangtze River basin (Zhu et al 2003). In particular, the East Asian monsoon is responsible for the four distinct seasons that are representative of the monsoon climate of the Yangtze River basin. Winters in the Yangtze River basin are cold and dry with northerly winds, whereas summers are hot and wet with southerly winds (Zheng et al 2014). In short, the mechanism of climatic control on the Yangtze River basin is too complex to dissect. Hence, it is important to collect as much climate data as possible to support future attempts.

To identify the major climatic factors that affect the trend of variation in discharge of the upper reaches of the Yangtze River, various types of meteorological data were downloaded from multiple data centers. These included the National Oceanic and Atmospheric Administration (NOAA), National Climate Center (NCC) of the China Meteorological Administration, and College of Global Change and Earth System Science (GCES) of the Beijing Normal University. Diverse indices were downloaded including SST, climate variability mode, atmospheric circulation indices, monsoon indices, and other relevant indices (table S2). It should be noted that the lengths of the series of climatic factors are disparate and that only public and recognized data were adopted. Although the availability of data prior to 1956 is limited, the Pearson correlation coefficient between peak discharge and each climatic factor was calculated considering all possible combinations. Finally, the selected indices fulfilled the following three requirements: maximal correlation coefficient, high significance level, and long series length.

4.4. Statistical analysis and flood frequency estimation

The magnitudes of Q10, Q1000, Q10000, and Q100000 were estimated statistically by fitting a Pearson type III distribution (recognized as a suitable distribution type for Chinese river basins) to the discharge data during the baseline period and the modern period respectively. The probability distribution function is expressed as follows:

$$ f(I) = \frac{\beta^\alpha}{\Gamma(\alpha)} (I - a_0)^{\alpha-1} e^{-\beta(I-a_0)}, $$

where $f(I)$ denotes the probability of streamflow; $\alpha$, $\beta$, and $a_0$ denote the shape, scale, and location parameters, respectively, of the Pearson type III distribution ($\alpha > 0$ and $\beta > 0$); and $\Gamma(\alpha)$ denotes the gamma function of $\alpha$.

The specific processes included calculation of the empirical frequency of the discharge samples, determination of the values of the parameters in the probability distribution function, and derivation of
the discharge for the prescribed recurrence intervals. Admittedly, the magnitude of paleofloods is much higher than those of observed floods, and their recurrence period is even longer than the length of the observation discharge series, so special treatment is needed in frequency analysis (Zhan 1988). Notably, the calculation method of empirical frequency differed for the discharge in the baseline period and that in the modern period.

(a) For the discharge in the baseline period, given the nine investigated large paleofloods, the empirical frequency of the paleofloods was calculated as follows (England et al. 2003):

\[ P_M = \frac{M}{N+1}, \quad (2) \]

where \( M \) denotes the rank in the paleoflood sequence (\( M = 1, 2, \ldots, a \); \( a \) denotes the number of large paleofloods); \( N \) denotes the length of the entire period, which covers the paleofloods and observed floods; and \( P_M \) denotes the empirical frequency of the \( M \)th paleoflood.

The empirical frequency of observed floods in the baseline period was calculated as follows:

\[ P_m = P_{M,a} + (1 - P_{M,a}) \frac{m - l}{n - l + 1}, \quad (3) \]

where \( P_m \) denotes the empirical frequency of the observed floods; \( m \) denotes the rank in the observed flood sequence; \( n \) denotes the number of observed floods; and \( l \) denotes the number of large floods in the observed flood sequence, which was zero here.

(b) For the observed or reconstructed discharge in the modern period, the empirical frequency of floods was calculated as follows:

\[ P_m = \frac{m}{n + 1}, \quad (4) \]

where the denotation of each variable is the same as for equation (3).

In addition, interval estimation values of \( Q_{10}, Q_{100}, Q_{2000}, \) and \( Q_{10000} \) were derived to deal with the uncertainty in the representativeness of the discharge samples using the bootstrap method (Hu et al. 2015). The implemented bootstrap procedures were as follows. (1) Sampling with the return from the original samples was implemented repeatedly to produce a new sequence with the same length as that of the original sequence. This process was repeated 1000 times to produce 1000 new sequences with lengths equal to the lengths of the original samples. (2) The 1000 sets of parameters in the probability distribution function for the 1000 new sequences were estimated using the linear moment method. (3) For each given recurrence interval, the 1000 design discharge values were acquired based on the probability distribution function under the 1000 sets of parameters. (4) For each given recurrence interval, the 1000 design discharge values were considered subject to the normal distribution, and the mean and variance of the normal distribution were calculated to obtain the point and interval estimations. The uncertainty in the representativeness of the discharge in both the baseline and the modern periods was analyzed separately by repeating the above processes.

The process of calculating the design floods involves multiple uncertainties. For the choice of distribution type, the Pearson type III distribution, which is considered applicable for Chinese river basins, was adopted to provide estimations of the magnitudes of the 10-, 100-, 1000-, and 10 000-year floods in this study. Regarding the estimation of parameters, the linear moment method, which generally produces robust results, was adopted to estimate the parameters of the distribution; however, its precision is inferior to that of the maximum likelihood estimation method. With regard to the sampling, the information of the nine paleofloods was retrieved from historical inscription records, the authenticity of which has been demonstrated repeatedly and is openly recognized by Chinese hydrologists. The annual peak discharge during 1882–2012 was sampled from daily observations because records with higher resolution are not available; therefore, the value adopted might not reflect the real peak discharge in practice.

**Data availability statement**

The large dam data sets are available from the International Commission on Large Dams website (https://www.icold-cigb.org/). The irrigation area data of the upper Yangtze River reach are available from the National Bureau of Statistics of China website (https://www.stats.gov.cn/tjsj/). The climate control factor data sets are available from the National Oceanic & Atmospheric Administration (NOAA) website (https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/), National Climate Center (NCC) of the China Meteorological Administration website (https://cmdp.ncc-cma.net.cn/index.htm), and College of Global Change and Earth System Science (GCess) of the Beijing Normal University (http://flp.gcess.cn/dct/page/1). The meteorological data are available from the Natural Environment Research Council’s Data Repository for Atmospheric Science and Earth Observation (http://data.ceda.ac.uk/badc/cru/data/cru_jra/cru_jra_2.0/data).
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Conflict of interest

The authors declare no competing interests.

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Author contributions

H.L. and P.L. designed the study. S.G. contributed with data. H.L. performed the simulations and the analyses, and wrote the manuscript with contributions from all other authors. L.C. designed the figures. The results were synthesized by J.Y.

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