Yangtze floods recorded on Mt. Mufu and Swallow Cliff in Nanjing, China

Huachun He a,b and Haiyu Lee a,b

aSchool of Geographic and Oceanographic Sciences, Nanjing University, Nanjing, China; bKey Laboratory of Coast and Island Development, Nanjing University, Ministry of Education, Nanjing, China

ABSTRACT

The Yangtze drainage basin is the most densely populated and prosperous area of China; however, it is frequently threatened by floods. The Holocene flood lines of the Yangtze River have been preserved on Mt. Mufu and Swallow Cliff in north-eastern Nanjing, and they are characterised by the presence of particular colour tones and the horizontal arrangement of erosional pits and holes. Four major paleo-flood lines at altitudes of 8.51, 9.43, 10.47, and 12.84 m were identified via a field survey along the river bank. Historical literature and instrumental flood records extend the paleo-flood stage to the contemporary era and indicate that the highest flood line of 12.84 m represents a maximum limit for future floods. Besides, the flood line at 10.47 m can be regarded as a foreseeable extreme flood risk level with a recurrence interval of 100–200 years, especially considering the current circumstances of rising sea levels and decreasing flood storage capacities caused by human activities.

1. Introduction

The Yangtze River is one of the largest rivers in the world in terms of river length, water discharge and drainage area. This river originates from the Tibetan Plateau, crosses the country from the west to the east, and finally debouches into the East China Sea at Shanghai. Nearly 440 million people live in the Yangtze drainage basin, which has an area of $1.94 \times 10^6$ km$^2$ (Chen et al. 2001). The annual precipitation in this basin is approximately 1070 mm, and it is dominated by the eastern Asian subtropical monsoon climate. Because of the highly uneven spatio-temporal distribution of rainfall, with values ranging from 500 mm in the west to 2500 mm in the east and more than 70% of the rainfall occurring in summer, annual floods in this basin are inevitable. These floods usually occur from June to July (Xu et al. 2008) and only vary in their magnitude, frequency, and impact on modern human societies (Ding et al. 2008; Yu et al. 2009; Ge et al. 2011; Deng et al. 2016).

Long flood series are essential for understanding the local climate, projecting future changes, and managing and assessing the safety of infrastructure along rivers, such as artificial levees and series of locks and dams, especially in the most densely populated and prosperous areas. However, instrumental flood records of the Yangtze River only extend 150 years into the past, which was when the earliest gauging station was established at Hankou in 1865 (Qian & Zhu 2001; Jiang et al. 2007; Zhang et al. 2008; Guan et al. 2015). However, because of the prevailing ancient custom of writing local chronicles, abundant historical records of flood events are valuable resources for reconstructing...
longer flood series (Jiang et al. 2006). Other paleo-flood records can be derived from slackwater sediments in bedrock gorges, from boulder berms in upland areas (Macklin & Rumsby 2007), and from layers of sand or gravel strata in floodplain sediments through the identification of textural reversals in the sedimentary sequences (Goman & Leiph 2004; Li et al. 2013). These methods have been deployed successfully in temperate catchments and semiarid or arid environments (Sheffer et al. 2008).

In the 1990s, the Yangtze River experienced extraordinary flooding that caused billions of dollars’ worth of damage. Many of these extreme floods were larger than expected or predicted. During the summer of 1998, a heavy flood caused more than one thousand deaths and rendered millions homeless. The economic damage of this flood event was estimated at 20 billion dollars (Zong & Chen 2000). Knowledge of prior floods of similar or larger magnitude in this area might have improved the flood hazard estimations and prevention and preparation strategies for such events. In this research, we explored a series of caves and eroded watermarks recorded naturally on Mt. Mufu and Swallow Cliff as proxy records of the major Holocene flood stages of the lower Yangtze reach in the Nanjing section. Common sense dictates that what has really happened may happen again; therefore, investigating this paleo-flood state has many practical ramifications for studies of the lower Yangtze reach as well as for local economic development.

2. Geological setting

The Yangtze River can be divided into the upper, middle, and lower reaches based on the geology, geomorphology, and regional climate (Figure 1(a)). The upper section is more than 4300 km long from the source to Yichang. The middle section is 950 km in length from Yichang at the end of the Three Gorges reach to Hukou, which is an outlet of the Yangtze to the Poyang Lake. The final 930 km below Hukou constitutes the lower section (Chen et al. 2001; Xu et al. 2008).

The study site is located in the northeast section of the city of Nanjing, which is in the lower reach of the Yangtze River (Figure 1(b)) and well known for its cultural and historical significance as an ancient capital of six dynasties with its recorded history spanning over 2000 years. The Yangtze River flows through Nanjing from the southwest to northeast. The north bank is 98 km in length, and the south bank is 88 km (Figure 1(c)). The width of the water surface is 1.1 to 2.5 km; the average water depth is −20 to −30 m; and the deepest trough is −72 m. Several sand islets and shoals are scattered throughout this section because of the tidal backwater caused by the river-tide interaction, and the average annual discharge is $2.88 \times 10^4$ m$^3$/s (Pan 1990; Chen et al. 2012).

Since the Middle Pleistocene, the river course in this area has been quite stable along the valley between two groups of mountains and hills. Two major mountains occur on the northern bank: Mt. Laoshan, which is mantled by forest and underlain by Sinian neritic sedimentary rock dated ca. 600 Ma BP; and Mt. Lingyan, which is composed of a set of Pleistocene sandy gravels overlain by basalt rock. One mountain occurs on the southern bank: Mt. Mufu (6 km long, 1 km wide, and 205 m high), which consists of ancient Lunshan limestone of Ordovician age (Xia 1998).

A series of limestone caves similar to small rock shelters is distributed along Mt. Mufu. Three bigger caves have been well preserved as historical and scenic spots: Toutaidong (1st cave), Ertaidong (2nd cave), and Santaidong (3rd cave), from east to west. The 3rd cave has the most scenic view and consists of three smaller caves layered vertically at altitudes of 7.56 – 25.1 m. The average annual lowest water stage of the Yangtze River here is 2.98 m. Larger floods have inundated these caves for a long time and are believed to have formed all the caves.

Swallow Cliff (alt. 36 m) is located on the river channel to the northeast of Mt. Mufu. A series of clear flood marks is shown on this vertical cliff that appear similar to strokes on a wall, and this series is an ideal source of information for flood studies.
3. Material and methods

The instrumental flood data were collected from local meteorological stations and hydrological gauging stations; and historical data were collected from various records, including local chronicles. Documentary entries on hydrographic events used in this paper were critically reviewed to ensure the reliability of the reconstructed flood records.

Field surveys were conducted to identify paleo-flood stages along the riverside. Total station surveying and D-GPS technologies (Leica TCR702/SR510, Leica Geosystems Ltd., Swiss) were deployed to collect feature data at the field sites, and they provided detailed relative elevation data for constructing continuous paleo-flood lines. Sediment samples were collected from caves, erosional pits, and river flats.

A Mastersizer 2000 particle size analyser (Malvern Instruments Ltd., UK) was used to measure the sediment samples, and their consistency was verified by frequency curve characteristics.

Figure 1. The Yangtze catchment and study site. (a) Map of conterminous China showing the location of the Yangtze River and (b) the study area; and (c) a portion of the Nanjing composite image illustrating the major geographical features.
used to authenticate the flood lines. The designed size range was 0.02–2000 μm, and the reproduc-
ibility was better than 2%. Each of the surficial samples was thoroughly mixed, and about 1 g was
selected, placed into a 25 ml glass beaker, and then stirred with distilled water for 2 min; subse-
quently, 10 ml of 5% hydrogen peroxide (H₂O₂) was added and stood for 24 h to eliminate organic
matters. The sample was then treated by adding 10 ml of sodium hexametaphosphate ((NaPO₃)₆,
0.5 mol·L⁻¹) and standing for 24 h to aid dispersion. The computer program GRADISTAT (Blott & Pye 2001) was run to obtain the statistics for the grain size data exported from the laser granulom-
er. The statistical parameters, i.e. mean, standard deviation (sorting), skewness, and kurtosis were
calculated using the logarithmic method of moments.

Pieces of flowstone collected in two caves were transported to the Stable Isotope Lab of the
Department of Geology and Geophysics, University of Minnesota, USA for U-series dating, which
confirmed that the old cave-generation period ended at ca. 400–500 ka BP (Tan et al. 2010).

4. Results
4.1. Characteristics of the flood lines

The flood lines, which are represented on the limestone rock and wall along the south river-side of
Mt. Mufu and Swallow Cliff, have a particular dark tone with several small eroded pits distributed
horizontally, and these features demonstrate that Mt. Mufu has experienced heavy
floods over a long period.

We found four clear paleo-flood lines preserved in the 3rd cave (Figure 2) and unclear flood
marks in other caves. In the 2nd cave, which is 200 m east of the 3rd cave, paleo-flood lines are diffi-
cult to identify because this cave was once used as a residential shelter. In the 1st cave, which is
270 m east of the 2nd cave, the light-grey paleo-flood lines are faint and blurred, and they are hori-
zontally discontinuous because of the anthropogenic interference. The reason for the relatively good
preservation of flood lines in the 3rd cave is mainly because of its superior scenic view, which made
it an ideal location for monks to practice. Therefore, we studied the flood marks first in the 3rd cave
and then traced them into other locations.

(1) The first flood line (FL1) is deep-grey coloured at an altitude of 8.5 m, which is 5 m higher
than the present river surface and the bottom line in this cave. Small erosional pits and holes
are developed along this flood line. Although hydrological records indicate that modern
floods frequently reach this level, the erosional indentation in the surface of limestone rock
shows that the flood line was initiated a long time ago.

(2) The second flood line (FL2) is dark grey at an altitude of 9.4 m and characterised by horizon-
tal tiny erosional holes, and it is not as clear as FL1 because of rock collapse.

Figure 2. Flood lines on the rock of the 3rd cave.
(3) The third flood line (FL3) is the clearest line, and it is coloured deep grey at an altitude of 10.5 m. Small erosional pits are distributed horizontally, and small embryonic caves in the form of vaults and uprights along the line show that the formation period was longer and earlier than those of FL1 and FL2.

(4) The fourth flood line (FL4) is grey at an altitude of 12.8 m. Small vault caves developed at this level, thus reflecting changes in the flood stages. An unclear flood line with smaller erosional pits (FL4-3) between FL3 and FL4 is observed at an altitude of 11.7 m. The altitude of FL4-3 is at the bottom of a small vault cave, which was subsequently dug through by an upright cave, thus forming a water tunnel into FL3. This relationship indicates that FL3 formed later than FL4 and was more stable than FL4-3 and FL4.

Based on these remnant paleo-flood lines in the 3rd cave, further investigations were conducted in the upstream and downstream regions to consolidate the results. Certain findings are described below.

(1) In the 1st cave (450 m downstream), several flood lines are identified on the rock cliff, and two are clear and coloured dark grey at altitudes of 12.68 m and 12.34 m, which are approximately equal to FL4 in the 3rd cave.

(2) At Swallow Cliff (1.5 km downstream), four flood lines characterised by a discontinuous horizontal grey colour on the limestone wall are present at altitudes of 5.5 m (FL1), 7.5 m (FL2), 10.5 m (FL3), and 12.5 m (FL4) (Figure 3), and these lines can be divided into two groups by elevation. The lower group, FL1 and FL2, is characterised by a dark grey colour and lies above the water surface by 2–5 m; and the higher group, FL3 and FL4, is characterised by a whitish-grey colour and lies above the water surface by 10–12 m.

(3) At Caishiji Cliff (67 km upstream in Anhui Province), four flood lines are also observed at altitudes of 8.6, 9.5, 14.1, and 16.6 m on the cliff wall (alt. 50 m), which is composed of Jurassic quartz sandstone and silty limestone. The local river surface is at approximately 4 m. Furthermore, a few muddy imprints composed of yellow clay and silt are preserved on concrete.
pillars constructed in 1997, one of which corresponds to the 1998 Yangtze flood and has an altitude of 10 m.

Particle size analyses of the sediment samples collected from the 3rd cave (N32°8.255’, E118°47.590’, alt. 10.38 m), the river flat (N31°38.961’, E118°27.044’, alt. 4.8 m), and the erosional pit (N31°38.958’, E118°27.052’, alt. 8.2 m) show that their substance composition is the same as that from the Yangtze River. The major component is silt (≥80%) with an average diameter of 5.97–6.46 μ and a unimodal symmetrical frequency curve (Table 1, Figure 4). This result also reveals that FL1 is the remnant water mark of Yangtze River floods.

The characteristics of the water marks preserved in the limestone rock and cliff provided a preliminary confirmation that they represent the fading relics of paleo-floods, and four distinct paleo-flood lines were distinguished by their horizontal continuity (Figure 5, Table 2).

### 4.2. Documentary entries on hydrographic events

After the last glacial maximum, the water level of the Yellow Sea (into which the Yangtze River debouches) presented the lowest level at ca. 15 ka BP and the highest level in the Holocene Megathermal at ca. 6.5 ka BP, and since then, the water level has been decreasing gradually with several fluctuations. At the epoch of the high sea level, the riverbed was rising, the runoff was increasing, and the river valley was widening via enhanced lateral erosion. Rising waters cascaded through a hierarchically arranged system in an efficient flood distribution network that was stable for all but the heavy floods. The overarching Holocene history of the lower Yangtze River represented a metamorphosis from a Late Pleistocene braided floodplain into an anastomosed river system. Along the riverside from Yichang, Anqing, to Nanjing, scores of buried subtropical broadleaf paleo-trees were excavated and 14C dated to 6–5 ka BP (Yang & Xu 1980), which represented the first peak of the

---

**Table 1. Grain size parameters of the surficial sediment samples.**

| Site           | Mean (m) | Sorting (σ_v) | Skewness (Sk_v) | Kurtosis (K_v) | Sand (%) 63–2000μm | Silt (%) 2–63μm | Clay (%) ≤2μm |
|----------------|----------|---------------|-----------------|---------------|---------------------|----------------|---------------|
| 3rd cave       | 5.97     | 1.92          | 0.30            | 3.02          | 12.3                | 80.0           | 7.7           |
| River flat     | 6.46     | 1.75          | 0.31            | 2.74          | 11.1                | 81.0           | 7.9           |
| Erosional pit  | 6.12     | 1.87          | 0.14            | 3.00          | 11.5                | 81.3           | 7.2           |

---

**Figure 4.** Grain size frequency distributions.
frequent large flood events. In the second terrace on the north bank in Nanjing, buried paleo-trees and alluvial sandy gravel dating to 4.2–3.6 ka BP (Zhu et al. 1997) revealed the second flood peak.

From 190 BC to 1999, 240 flood disasters in the lower Yangtze reach were recorded in various historical literature; thus, heavy floods occurred on average every nine years. The dates of these floods were accurate in the Chinese lunar calendar along with the traditional reign titles, which we converted to the current international Gregorian calendar by the Academia Sinica Department of Information Technology Services. The flood depths indicated in the literature were usually imprecise because of the lack of datum reference, ambiguity or exaggeration in the flood descriptions, and variations of the length unit (Chinese ruler) throughout the long history of the region. Table 3 shows several of the historical flood entries related to the Nanjing area.

### 4.3. Instrumental flood record

Continuous instrumental hydrographic monitoring began at Xiaguan gauging station in Nanjing in 1912, and it recorded 12 heavy floods above 9.0 m (the warning level is 8.5 m). The altitudes of these floods corresponded to the flood line between FL2 and FL3. The largest recorded flood occurred in 1954 and had a peak of 10.22 m and maximum runoff of $9.26 \times 10^4$ m$^3$/s, and this flood persisted...
for 62 days above the high stage of 9.5 m (Table 4). The statistics of the maximum flood stages grouped by decades show an upward trend after the 1960s that continued into the 1990s (Figure 6).

5. Discussion

5.1. Causal factors of the high flood stages

(1) The lower reaches of the Yangtze River include an enormous alluvial plain and many tributaries, and the elevation is only 2–7 m above mean sea level in 95% of this region, thus flash floods tend to come after short periods of heavy rain and most often affect small streams and flood prone areas. In the Plum Rain Season, usually from June to July when a slowly drifting cold front meets a moist and stable subtropical air mass to form the Jianghuai Quasi-stationary Front that fluctuates over the lower Yangtze reach, general flooding tends to affect major rivers and the whole region. Additionally, Jiangsu Province is one of the targets of typhoon storms in summer, which bring extraordinary rainfall within a short period. Furthermore, the periodic spring tide produces stagnant flood discharge and raises the high water stage along the tideway. Moreover, the storm surge and astronomical spring tide may

| Table 3. Historical flood entries related to Nanjing. |
|-------------------------|----------------------|
| Date   | Flood description                                                                 |
| Aug 251 | Yangtze flood overflowed Nanjing; depth of 8 feet.                               |
| Aug 351 | Yangtze flood attacked Nanjing; hundreds of people drowned.                      |
| Feb 404 | Yangtze flood surged into Nanjing; tens thousands of merchant fleets drifted off; dead bodies were everywhere. |
| Aug 1028 | Flood overflowed into Nanjing, Yangzhou, Yizheng, and Zhenjing; public and private houses were damaged. |
| Jun 1170 | Heavy flooding in Nanjing, water depth of 10 feet or more on the south bank; private houses drifted; dykes burst. |
| Aug 1298 | Yangtze River overflowed; Nanjing experienced a serious disaster; water height up to 40–50 feet; houses and huts were submerged or drifted. |
| Aug 1502 | Yangtze flood inundated Nanjing with depth of up to 5 feet; more than a thousand private and military houses collapsed; part of the city wall and some bridges were destroyed. |
| Aug 1560 | Yangtze flood reached the Sanshan gate; several feet of water in the Qinhuaui residential area. |
| SU 1589 | Yangtze River overflowed; in Nanjing, the water reached heights of tens feet on the ground; houses in farmlands were submerged. |
| Jul 1608 | Heavy rain lasted nearly 20 days in Nanjing, ‘the flood was extremely abnormal, people drowned,..., this is a disaster that hasn’t happened for 200 years’. |
| SU 1755 | Heavy rain in Jiangsu; high water stage lasted more than 40 days. |
| SU 1848 | Rainy in many provinces along the middle and lower reaches of Yangtze River; ‘Rivers and lakes rose together, bank breached at many places in Jiangsu, flood overflowed on both sides of the Yangtze River at depths of several feet’. |

| Table 4. Rank of floods (≥9.0m) at Xiaguan gauging station in the twentieth century. |
|-------------------------|-------------------------|
| Year   | Max stage | Date | Days (≥9.0 m) | Days (≥9.5 m) |
| 1 | 1954 | 10.22 | 8.17 | 87 | 62 |
| 2 | 1998 | 10.14 | 7.29 | 42 | 17 |
| 3 | 1983 | 9.99  | 7.13 | 27 | 11 |
| 4 | 1991 | 9.69  | 7.13 | 17 | 6 |
| 5 | 1977 | 9.30  | 7.20 | 6 | – |
| 6 | 1931 | 9.29  | 9.15 | 45 | – |
| 7 | 1969 | 9.20  | 7.80 | 9 | – |
| 8 | 1980 | 9.20  | 8.28 | 9 | – |
| 9 | 1973 | 9.19  | 7.20 | 7 | – |
| 10 | 1949 | 9.17  | 7.25 | 1 | – |
| 11 | 1989 | 9.08  | 7.21 | 3 | – |
| 12 | 1992 | 9.05  | 7.16 | 4 | – |
act together in the rainy season to form an extraordinarily high water stage that persists over a long time, and such events constitute disasters for human beings. In the Nanjing section, the flood discharge from the upper reaches is the main reason for the high water stage, according to the flood records. The highest water stage at the Xiaguan station in Nanjing exhibits an excellent correlation with the Datong station upstream in Anhui Province ($r = 0.97$) but a poor correlation with the tidal stage of the Wusong station downstream at the river mouth ($r = 0.2$) (Rui 1994).

(2) The flood storage capacity has decreased at this river section, which is a primary reason for the persistently high water stage. From Mt. Mufu to Zhenjiang, the river bed has suffered the most severe siltation in the middle-lower reach of the Yangtze River, which is accompanied by a gentle slope of $0.5 - 1.0 \times 10^{-5}$ (Xu 1999). Shallows along the river channels function as water barriers and dam the downstream flow, thereby extending the time of flood discharge, raising the high water stage, and eventually enhancing floods events (Hu & Luo 1992).

(3) The tributary Huaihe River plays a backwater role when its flood meets the Yangtze flood between Datong and Nanjing, especially when it coincides with heavy rainfall in this area. A hydrological model shows that the water stage at the Xiaguan station of Nanjing could rise 0.15 m once the flood discharge of the Huaihe River reaches $1.2 \times 10^4$ m$^3$/s (Rui 1996).

(4) Current anthropogenic changes in land use and land cover are expected to enhance the risk of forming the high water stage, especially when the lake reclamation in this region has significantly decreased the flood storage capacity (Yin & Li 2001; Nakayama & Watanabe 2008; Yang et al. 2016).

5.2. Implications of the flood lines

(1) The paleo-flood lines at different altitudes are preserved in caves and cliffs along the Yangtze River bank, and they are characterised by horizontally distributed small eroded holes and pits. The highest flood line is at approximately 12.8 m (FL4), and the most distinct flood line is at approximately 10.5 m (FL3), where mini-vaults and vertical caves originated. Flood relics of these two flood stages are widespread along Mt. Mufu, which may indicate that this area suffered from frequent heavy floods over an extended period. Lateral erosion created the continuous horizontal lines in the limestone rocks. In addition, the minor blurred flood lines between FL4 and FL3 reveal flood fluctuations of 0.3–1.0 m.

![Figure 6. Statistics of the maximum flood stages grouped by decades at the Xiaguan station.](image-url)
(2) Major flood fluctuation can be identified by comparing the altitude change of these flood lines. The differential values are 0.92 m between FL1 and FL2, 0.95 m between FL2 and FL3, and 2.37 m (in the 3rd cave) and 2.0 m (on Swallow Cliff) between FL3 and FL4. The minimal change is 0.33 m between FL4 and FL4-3 in the 1st cave, and the maximal change is 2.37 m as noted above. Therefore, the flood stage change is mainly between 1 and 2 m for a given period over the long run.

(3) The rock caves and cliff consist of the Lower Ordovician Lunshan limestone, which is a stable bedrock bank and an ideal medium to preserve vestiges of ancient floods. The local flood control standard for dyke projects is 12.8 m (10.8 m of designed water level plus 2 m for additional safety) based on a recurrence interval of 100 years. This specification is approximately equal to the paleo-flood line FL4, which we estimated could not recur. Therefore, the investigation of paleo-flood lines provides scientific evidence for local protection works against Yangtze floods.

5.3. Recurrence implied in the flood lines

The flood lines are consistent in the three caves along Mt. Mufu and on the rock wall of Swallow Cliff, and they are represented by clear horizontal colours and obvious textures of tilt or cross-cutting in the limestone as well as the tiny serried erosional pits and pinholes. The highest paleo-flood line exceeds the highest instrumental flood stage recorded in 1954 by 2.65 m. The elevations of the other three flood lines are from 8.5 m to 10.5 m, which lie within the range of instrumental flood records. Therefore, we regard FL4 as the maximum Yangtze flood stage in the local history. Although direct dating could not be performed, we roughly deduced the geological times and flood recurrence intervals of the individual flood lines as follows.

(1) The highest flood line (FL4) is the earliest flood relic, and it corresponds to the Middle Holocene at 6–5 ka BP when the sea level was at its high stage. On the second terrace at an altitude of 10 m on the north bank, the stratigraphic record shows rapid alluvial sedimentary facies, peat bogs, and buried paleo-trees with coarse sand and gravel, which indicates a warm moist environment as well as the prevalence of floods in the lower Yangtze reach. The particle size analysis also reveals a higher proportion of medium and fine sand and a lower proportion of clay, which indicates flood activities during this period. In the Middle Holocene, the Yangtze River mouth was at Zhenjiang, which is 65 km downstream from Nanjing, and the water stage was −2 to −3 m (Li and Min 1981). The current average high water stage is 7.15 m between June and August, and the mean slope is 0.5–1.0 × 10−5 (Chen et al. 2001) from Nanjing to the river mouth at a distance of 480 km. Therefore, we can deduce that the water stage of Nanjing was approximately 6–8 m in the Middle Holocene, and paleo-floods frequently reached the altitude of FL4 when an extraordinary flood, storm surge and spring tide coincided, particularly considering the long geological span. However, it is nearly impossible for floods to reach this altitude at present because of the migration of the river mouth and the lower sea level.

(2) The second highest flood line (FL3) is consistent with several historical flood events in the literature. We can deduce the altitude of these flood stages to be approximately 12 m by their imprecise description in ancient Chinese, such as ‘depths of more than ten feet’, ‘five feet in the city’, ‘houses submerged in farmlands’, etc. The corresponding time series of 1170, 1298, 1502, and 1589 may indicate that the flood recurrence interval at this stage is approximately 100 to 200 years. The extraordinary flood recorded in 1298 has a counterpart event in the Old Walled City of Shibam, Yemen, which is inscribed on the World Heritage List by UNESCO. At this site, torrential rains and floods are rare except for two disastrous floods in 1298 and 1532.
(3) The lower flood lines (FL2 and FL1) are within the range of instrumental flood records. Although they are currently disengaged from the river flow, heavy floods could still reach these altitudes. For example, the flood stages in 1954 and 1998 surpassed these lines. Horizontal flood lines with dark grey tones were found in the rock bank eroded as linear dented marks. The current average highest water stage is approximately 9.3 m, and the flood recurrence interval at this stage is 10–50 years.

5.4. Flood lines under the scenario of global warming

Since the industrial revolution, the global average surface temperature has increased with a 100-year warming trend (1906–2005) of 0.74 °C, and the global average sea level has risen at an average rate of 1.8 mm/a since 1961 (IPCC 2007). Such global climate change enhances ocean dynamics and causes incremental increases of climate extremes, such as storm surges, torrential rainfall, and floods. Although many dams, dykes, and reservoirs have been constructed throughout the Yangtze catchment in recent decades to enhance flood control, including the project of Three Gorges Dam, their effectiveness for withstanding extreme events, such as a 100-year flood, has been largely weakened under the current circumstances (Zong & Chen 2000). Recently, sudden changes in drought/flood have frequently occurred in the middle and lower reaches of the Yangtze River (Tian et al. 2016), which may be related to environmental changes and could exacerbate the flood events.

The lack of relevant quantitative research as a basis for decision-making is a challenge for flood monitoring and risk mitigation. Holocene deposits that still retain primary sedimentary structures are rare in this region, thus demonstrating the importance of identifying more ground features that could reveal complex hydrodynamic processes, such as caves and cliffs, and utilising multiple sources to reconstruct long flood series. The results of the presented analysis highlight the potential for expanding available databases for the study area. The proposed methodology may be utilised in other regions with similar geological settings affected by flood risk and applied for environmental analyses, hydraulic engineering, and disaster mitigation.

6. Conclusions

The watermark archive preserved in the caves of Mt. Mufu and Swallow Cliff has recorded significant regional Yangtze River floods since the Middle Holocene. The overall stability of the Yangtze River in the Nanjing section and the characteristics of the Ordovician Lunshan limestone fostered the development of flood lines. Historical literature and instrumental flood records extend paleo-floods to the contemporary era and indicate that the highest flood line of 12.84 m (FL4) can be considered a maximum limit for floods in the foreseeable future. However, the level of 10.47 m (FL3) could still be reached, which indicates the threat of extraordinary floods, especially under circumstances that heavy rainfall, storm surges, and astronomical spring tide act together. The development of more detailed flood recurrence intervals depends on the precise dating of paleo-flood lines, which will be conducted in further studies.

Acknowledgements

We would like to thank the authors' advisor, Academician Ying Wang, for her great insights into this research. Thanks to Prof. Xinqing Zou for the fruitful discussions. Many thanks to Prof. Ramesh Singh and the anonymous reviewers for their valuable and constructive comments and suggestion.

Disclosure statement

No potential conflict of interest was reported by the authors.
Funding

National Natural Science Foundation of China [grant number 41206092]; National Science and Technology Support Program, China [grant number 2013BAC03B0408].

ORCID

Huachun He http://orcid.org/0000-0002-4747-3097
Haiyu Lee http://orcid.org/0000-0003-3126-3594

References

Blott SJ, Pye K. 2001. GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments. Earth Surface Process Landforms. 26:1237–1248.
Chen J, Wang ZB, Li MT, Wei TY, Chen ZY. 2012. Bedform characteristics during falling flood stage and morphodynamic interpretation of the middle–lower Changjiang (Yangtze) River channel, China. Geomorphology. 147:18–26.
Chen ZY, Li JF, Shen HT, Wang ZH. 2001. Yangtze River of China: historical analysis of discharge variability and sediment flux. Geomorphology. 41:77–91.
Deng JL, Shen SL, Xu YS. 2016. Investigation into pluvial flooding hazards caused by heavy rain and protection measures in Shanghai, China. Nat Hazards. 83:1301–1320.
Ding YH, Wang ZY, Sun Y. 2008. Inter-decadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part I: Observed evidences. Int J Climatol. 28:1139–1161.
Ge Y, Xu W, Gu ZH, Zhang YC, Chen L. 2011. Risk perception and hazard mitigation in the Yangtze River Delta region, China. Nat Hazards. 56:633–648.
Goman M, Leigh DS. 2004. Wet early to middle Holocene conditions on the upper Coastal Plain of North Carolina, USA. Quat Res. 61:256–264.
Guan YH, Zheng FL, Zhang P, Qin C. 2015. Spatial and temporal changes of meteorological disasters in China during 1950–2013. Nat Hazards. 75:2607–2623.
Hu M, Luo C. 1992. [Chinese historical large floods (V.II)]. Beijing: China Book Store Press. Chinese.
IPCC. 2007. Climate change 2007: synthesis report. In: Core Writing Team. Pachauri RK and Reisinger A, editors. Contribution of Working Groups I, II, and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland.
Jiang T, Su B, Hartmann H. 2007. Temporal and spatial trends of precipitation and river flow in the Yangtze River Basin, 1961–2000. Geomorphology. 85:143–154.
Jiang T, Zhang Q, Zhu DM, Wu YJ. 2006. Yangtze floods and droughts (China) and teleconnections with ENSO activities (1470–2003). Quat Int. 144:29–37.
Li C, Min Q. 1981. [Transgressive coast time and sea surface position of Yangtze River Delta in Holocene]. J Tongji Univ. 3:104–108. Chinese.
Li YF, Guo Y, Yu G. 2013. An analysis of extreme flood events during the past 400 years at Taihu Lake, China. J Hydrology. 500:217–225.
Macklin MG, Rumsby BT. 2007. Changing climate and extreme floods in the British uplands. Trans Inst Br Geogr. 32:168–186.
Nakayama T, Watanabe M. 2008. Role of flood storage ability of lakes in the Changjiang River catchment. Glob Planet Change. 63:9–22.
Pan F. 1990. [On the channel change taking place at Changjiang River Nanjing reach since mid-Holocene]. J Nanjing Normal Univ (Nat Sci). 13:81–88. Chinese.
Qian WH, Zhu YF. 2001. Climate change in China from 1880 to 1998 and its impact on the environmental condition. Clim Change. 50:419–444.
Rui X. 1994. [Hydrologic analysis of formation and changing trend of flood on Nanjing reach of Yangtze River]. Technol Water Resources Hydroelectricity. 10:130–131. Chinese.
Rui X. 1996. [Formation and change trend of large flood in the lower tidal reach of the Yangtze River]. Adv Water Sci. 7:221–225. [Chinese]
Sheffer NA, Rico M, Enzel Y, Benito G, Grodek T. 2008. The palaeoflood record of the Gardon River, France: a comparison with the extreme 2002 flood event. Geomorphology. 98:71–83.
Tan M, Wang Y, He H, Chen H. 2010. [Primary investigation of the relationship between formation of santai caves in Nanjing and paleo-water-table of Yangtze River]. Quat Sci. 30:877–882. Chinese.
Tian R, Cao CX, Peng L, Ma GR, Bao DM, Guo JH, Yomwan P. 2016. The use of HJ-1A/B satellite data to detect changes in the size of wetlands in response to a sudden turn from drought to flood in the middle and lower reaches of the Yangtze River system in China. Geomatics, Nat Hazards Risk. 7:287–307.

Xia B. 1998. [Pre-mesozoic tectonic evolution of the lower Yangtze region]. J Chengdu Inst Technol. 25:145–152. Chinese.

Xu H. 1999. [Flood and scientific & technological strategies in Yangtze River basin]. Beijing: Science Press. Chinese.

Xu J, Yang D, Yi Y, Lei Z, Chen J, Yang W. 2008. Spatial and temporal variation of runoff in the Yangtze River basin during the past 40 years. Quat Int. 186:32–42.

Yang H, Xu X. 1980. [Quaternary environmental changes in eastern China]. J Nanjing Univ (Nat Sci). 1:121–144. Chinese.

Yang L, Xu YP, Han LF, Song S, Deng XJ, Wang YF. 2016. River networks system changes and its impact on storage and flood control capacity under rapid urbanization. Hydrol Process. 30:2401–2412.

Yin HF, Li CG. 2001. Human impact on floods and flood disasters on the Yangtze River. Geomorphology. 41:105–109.

Yu F, Chen Z, Ren X, Yang G. 2009. Analysis of historical floods on the Yangtze River, China: characteristics and explanations. Geomorphology. 113:210–216.

Zhang Q, Xu CY, Zhang ZX, Chen YD, Liu CL, Lin H. 2008. Spatial and temporal variability of precipitation maxima during 1960–2005 in the Yangtze River basin and possible association with large-scale circulation. J Hydrol. 353:215–227.

Zhu C, Yu S, Shi W, Dai D, Zhao N. 1997. [Holocene deposits and paleo-floods on the north bank of the Yangtze River], Nanjing area. Geogr Res. 16:23–30. Chinese.

Zong Y, Chen X. 2000. The 1998 flood on the Yangtze, China. Nat Hazards. 22:165–184.