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Sediment characteristics of the Yangtze River during major flooding

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ABSTRACT

River sediment fluxes to the sea contribute to the morphological evolution as well as environmental and biological conditions of estuaries and their adjacent coasts. Especially for river basins that are dominated by a monsoonal climate, extreme high discharges can occur due to intense rainfall during the flood season, which will considerably affect the amount of sediment that is transported to the sea. In this paper, 4 major floods of the Yangtze River (2 extreme floods, one affecting most of the basin in 1954, and one more pronounced in the upper reach in 1981; and 2 large floods, one impacting mainly the middle reach in 1983, and one affecting most of the basin in 1998) are analyzed as these provide a unique opportunity to investigate fluvial sediment characteristics to the sea affected by major flooding. Results reveal that more sediments were delivered to the sea during the flood season when regional-sized major floods occurred, and this was even more pronounced when major floods occurred in the upper reach of the Yangtze River. Sediment retention in the middle reach of the Yangtze River during the major floods significantly reduced the amount of sediments reaching the sea. As for the flood season of 1981, the sediment size distribution to the sea was not significant different than that of the perennial average. However, coarser-grained sediments were delivered to the sea during July 1983 due to the remarkably high water discharges at that period. These findings can provide enlightenment regarding the timing of wetland restoration and interpretation of previous flood deposits in the deltaic zones of the Yangtze River.

1. Introduction

River systems provide freshwater and sediment to deltas, estuaries and continental shelves (Gao and Wang, 2008; Twilley and Rivera-Monroy, 2009; Morris et al., 2013; Nyman, 2014). Nearly 0.5 billion people live in these regions, of which many in mega-cities. However, most (71%) of the major deltas are sinking and this is partly attributed to sediment starvation resulted from human activities upstream (Syvitski et al., 2009). As such, mitigating coastal erosion and restoring coastal wetlands has become challenging for many deltas. Conservation and restoration of deltas and coastal wetlands are controlled by the quantity of sediment supply by the rivers (Fanos, 1995; Carriquiry et al., 2001; Chu et al., 2006; Blum and Roberts, 2009; Yang et al., 2011; Rosen and Xu, 2013). Flood events, especially major floods have played an important and active role in delta formation and coastal wetland restoration by replenishing large quantities of sediment (Shlemon, 1975; Rouse et al., 1978; Roberts et al., 1980; Rodriguez et al., 2000; McManus, 2002; Fabre, 2012; Falcini et al., 2012; Khan et al., 2013; Rosen and Xu, 2013; Day et al., 2016). What these aforementioned studies have in common is that they focus on the deposition patterns in river deltaic plains and the response of the evolution of deltas to water discharge or sediment supply during a large flood event. Similar can be concluded for the wave-dominated Brazos delta, Texas, as it is dominantly fluvially influenced during four major floods of 1941, 1957, 1965, and 1992 and mostly wave influenced during intervening periods (Rodriguez et al., 2000). In regard to sediment transported by large floods, less than a handful of studies have been conducted on the larger river systems. The Yangtze River, for instance, delivered much more sediment to the estuary during the 1998 large flood event (Xu et al., 2005). Horowitz (2009) and Meade and Moody (2010) studied the relation between the flood of 1993 in the upper Mississippi and observed stepwise decreases in decadal sediment loads prior and post 1993 for the lower Mississippi. In addition, small rivers along the California coast transported greater quantities of sediment to the Pacific Ocean during the three major flood years compared to annual sediment fluxes during the previous drier years (Inman and

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Jenkins, 1999). This illustrates that sediment fluxes to the ocean during major floods on a regional scale or for large rivers have so far received little attention.

Sediment records in the estuary, subaqueous delta, and the nearby shelf have been used to interpret historic flood magnitude and frequencies associated with climatic change for specific drainage basins (Sommerfield et al., 2002; Liu et al., 2010; Wang et al., 2011; Young, 2014). Grain size, or grain size related features of flood deposits are generally key indexes to identify a flood event (Liu et al., 2010; Zhan et al., 2010; Wang et al., 2011). For example, the formation and preservation of sediment deposits offshore of north California induced by several major floods of the Eel River were studied by Sommerfield et al. (2002) and Sommerfield and Wheatcroft (2007). And for the deltaic wetlands of Louisiana, Khan et al. (2013) demonstrated the limitations of lithological characteristics in identifying large flood event deposit. And based on the shallow wetland sediment cores of the Mississippi River, retrieved after the 2011 major flooding event, the sediment resulted from the 2011 flood event could be distinguished from underlying deposits in terms of biological characteristics. However, there were no discernible differences in the lithological characteristics including bulk density, organic matter content and grain size between the flood and earlier deposits (Khan et al., 2013). Researchers have found a correlation between large flood events and the transportation of coarse-grained load (Nittrouer et al., 2008; Rosen and Xu, 2013). However, the characteristics of the grain size of sediments to the sea delivered by large floods need further investigation in order to improve the precision of interpretation of previous flood events, based upon recognizable deposit features associated with flooding events.

The Yangtze Delta, one of the world's mega-deltas, is subsiding 10 mm/yr due to accelerated compaction and significantly decreased aggradation rates (Syvitski et al., 2009). Furthermore, the Yangtze subaqueous delta and the wetland along the coast of the Yangtze estuary have begun to show signs of erosion (Liu et al., 2011; Yang et al., 2011; Han et al., 2019). This will bring new challenges for the development and utilization of the coastal zone assuming accelerated global sea level rise and an even more reduced sediment supply of the Yangtze River (Liu et al., 2011). As a large river impacted by the East Asian monsoon regime, water and sediment transport patterns of the Yangtze River demonstrate obvious seasonal variation. Seventy percent of the annual water discharge and eighty-five percent of the annual sediment flux flows into the sea during the flood season (May to October). Every so often, major flood events occur. During the 20th century alone three basin-wide major floods occurred, in 1931, 1954, and 1998, as well as two regional-sized major floods in 1981 and 1983.

Extensive and intensive research has been conducted on the long-term trends of river sediment of the Yangtze River to the sea (e.g. Zhang et al., 2006; Dai et al., 2008, 2016; Gao and Wang, 2008; Yang et al., 2002, 2006, 2018). Furthermore, some work has been conducted on the interpretation of previous flood events based on sedimentary characteristics associated with subaqueous Yangtze delta and adjacent subaqueous sediment bodies (Liu et al., 2010; Zhan et al., 2010; Wang et al., 2011). However, less is known on the grain size of sediment transported by the Yangtze River and its sediment flux to the sea during major floods. Therefore, the objectives of this study are to investigate: (1) if the Yangtze River is delivering more sediments to the sea during major flooding, and (2) if more coarse-grained sediment is transported to the sea during these floods.

2. Regional setting

The Yangtze River is the longest river of China and the third longest in the world with a 1.8×10^6 km^2 watershed encompassing part of the Qinghai-Tibet, Sichuan Basin, and the middle and lower reach plains. The entire watershed can be divided into three reaches: the upper (above Yichang), the middle (Yichang to Hukou), and the lower (Hukou to Datong) reach (Fig. 1). The Yangtze basin encompasses mountainous and hilly regions, covered by pre-Cambrian to Quaternary strata. In the upper reach the strata are well developed, with Proterozoic to Quaternary strata exposed. The western part is dominated by metamorphic rocks. The eastern part is more dominated by sedimentary rocks. Quaternary deposits are exposed in the basins and valleys, with the thickest deposition of > 400 m within the Chengdu Basin (Yang, 2004). Thick Quaternary deposits dominate the middle and lower reach plains, decorated by exposed Paleozoic to Tertiary strata in some places (Yang, 2004). The main gauging stations in the upper and middle Yangtze River are Cuntan and Hankou stations, respectively, and the Yichang station is situated at the junction of the upper and middle reaches. Datong gauging station is the most downstream gauging station along the mainstream, so water and sediment measurements at this station represent the flux of the Yangtze River to the sea. The main sediment source of the Yangtze River was the upper reach, prior to the impoundment of the Three Gorges Dam in 2003 (CWRC, 2003). Average annual water, sediment flux and suspended sediment concentration (SSC) to the sea from 1953 to 2002 are 8.98×10^{11} m^3, 4.24×10^{11} kg and 0.48 g/l, respectively. The water flux during that period does not change significantly, whereas the sediment flux shows a decreasing trend since as early as the 1980s due to human activities such as dam construction, and soil and water conservation practices (Gao and Wang, 2008; Dai et al., 2016; Yang et al., 2002, 2018). Suspended load accounts for > 99% of the sediment flux to the sea (Yang et al., 2002). Therefore, when referring to "sediments", from here on, we mean suspended sediments. Annual average median grain size of the suspended load at Datong varies between 6 and 13 μm with an average of 10 μm (CWRC, 2000–2018).

Most of the Yangtze River Basin is dominated by a typical subtropical monsoon climate, except for a small portion situated at the Tibet plateau. The mean annual precipitation of the Yangtze drainage basin increases from the western region (270–500 mm) to the southeastern region (1600–1900 mm) (Gemmer et al., 2008). The maximum precipitation reaches 1800 mm/yr in the southern-central Dongting sub-drainage basin of the middle Yangtze Reach. The Yangtze Basin receives approximately 80% of its annual precipitation during the flood season. Rainstorms often cause flooding in the Yangtze River basin (Zhang et al., 2005). Furthermore, the main water source for the Yangtze River was the upper reach. The Yangtze flood season lasts approximately 6 months. Large flooding of its branches occurs between early April and early October, while mainstream flooding occurs typically in July and August. Generally, the flood season is gradually delayed spatially, starting in the lower reach and then progressing towards the upper reach, avoiding becoming one large hazard. During years of abnormal precipitation, the floods from upper, middle and lower reaches can overlap to form a basin-wide major flood. To study the grain size distribution of sediments and how much sediment gets delivered to the sea during flooding, the following four major floods which all occurred since the early 1950s (HBMWRPRC, 2009) are used in this study: a) the basin-wide extreme flood of 1954, b) the regional extreme flood of 1981 in the upper reach, c) the regional large flood of 1983 in the middle reach, and d) the basin-wide large flood of 1998. These events are chronological described in more detail below.

2.1. The flooding of 1954

One of the deathliest river induced floods of the world (~30,000 fatalities) occurred during the last century and was caused by several long-lasting high-intense rainstorms that devastated large parts of the Yangtze basin. Water levels at Hankou station exceeded the highest watermark of the 1931 flood on July 18, 1954. In order to protect the levees of the middle Yangtze River and the city of Wuhan (Fig. 1), a water diversion was executed through Beizha for three times from late July to early August. In total 122.56×10^8 m^3 of water was diverted. An addition 602×10^8 m^3 of water was diverted at the same period due to enforced river diversions in the Hubei Province (Fig. 1).

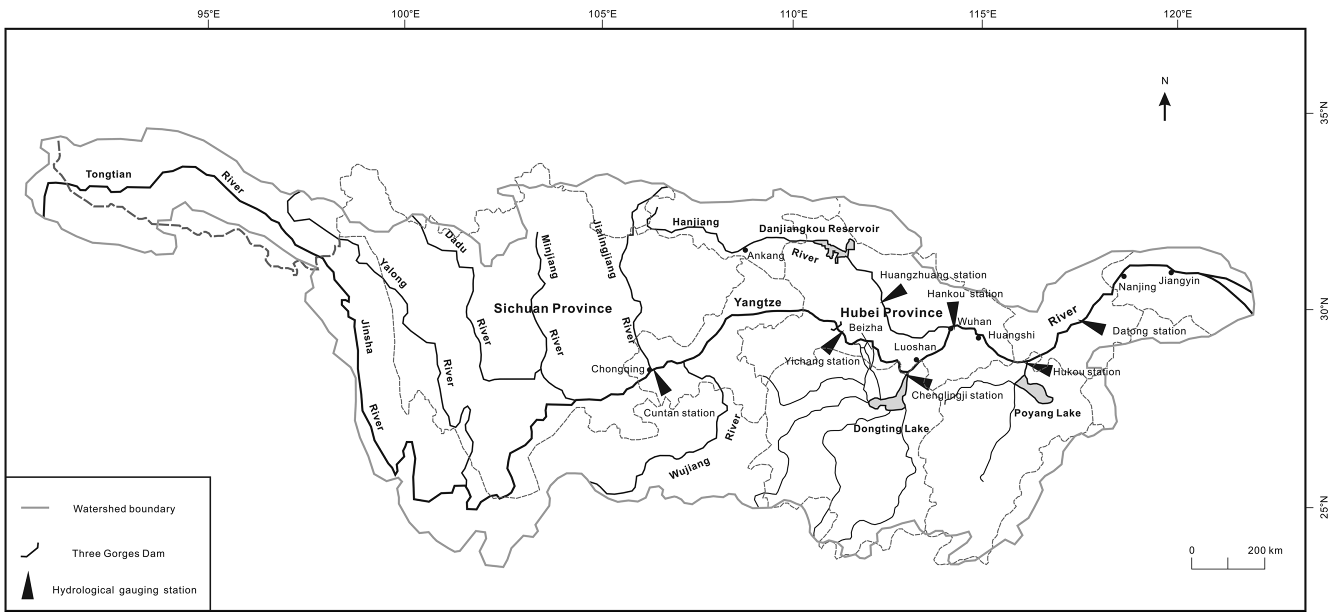

Fig. 1. Overview of the study area.

Subsequently, more water was diverted in six regions along the Yangtze of the Hubei Province in order to lower the water level of the Yangtze River and minimize the flooding. Despite the diversions which had a total volume up to 1.02×10^{11} m^3, historical high water level records were measured at Hankou and Hukou stations, reaching 29.73 and 21.68 m at the middle and lower reaches respectively.

2.2. *The flooding of 1981*

The province of Sichuan (Fig. 1) underwent its most devastating flooding of the last century in July 1981. Torrential rains overwhelmed Minjiang, Luojiang and Jialingjiang watersheds and lasted for almost one week (9 to 14th July 1981), with extreme precipitation on the 12th and 13th of July, which accounted for 80% of the total precipitation. These two days of intense rainfall were mostly responsible for the extreme flooding of the upper Yangtze River. Flooding occurred in Minjiang, Tuojiang, Jialingjiang from July 14 to July 16th, resulting in peak discharges of 85,700 m^3/s at Cuntan station, which is equivalent to a recurrence interval of ca. 70 years.

2.3. *The flooding of 1983*

A large flood occurred in the middle reach of the Yangtze River in 1983, that had a recurrence interval of 20 to 50 years based on discharge data of Hankou gauging station. The peak discharge at Hankou station was 63,800 m^3/s on July 18. An extreme flood also occurred in the upper Hanjiang River (a tributary to the middle reach of the Yangtze River) early August around Ankang (Fig. 1) and had a peak stage of 259.30 m, 1–2 m higher than the city walls of Ankang. As a result, the city of Ankang was completely inundated. A peak discharge of 31,000 m^3/s was recorded at Ankang station, ranking as the third largest flood since 1583.

2.4. *The flooding of 1998*

Exceptional precipitation resulted in another basin-wide large flood event in 1998, but was far less devastating (~3,700 fatalities) as the 1954 flooding. The total water volume that was diverted in 1998 (180×10^8 m^3) was much less than that of 1954 for the middle and lower Yangtze River (Sun et al., 2004). Compared to the 1954 flood, the 1998 flood showed a shorter duration during which the water level was higher than 26.30 m at Hankou, and overall lower maximum water volumes were measured during a 30-day period at Luoshan, Hankou, and Datong stations. It is therefore no surprise that the recurrence interval of the 1998 flood is shorter, which is estimated between 20 and 50 years, as compared to the flooding in 1954 (> 100 years) (HBMWRPRC, 2009).

3. Material and methods

Daily water discharge and water level data at major gauging stations along the Yangtze main channel, together with monthly grain size data of fluvial sediments during the 1980s at Yichang and Hankou stations, and during the 1970s, 1980s, and 2000s at Datong station were obtained from Annual Hydrological Reports P.R. China. Systematic hydrological measurements at the major gauging stations along the mainstream of the Yangtze River began in the early 1950s. Accordingly we explore the characteristics of sediment fluxes to the sea during the major floods post 1950. Hydrological data from the early 1950s are available for Yichang, Hankou, and Datong stations. For the sake of simplicity, we address the reach between Yichang and Hankou as the middle reach and the reach between Hankou and Datong as the lower reach (Fig. 1). Data on grain size distribution of sediments at Datong station have been obtained during the 1970s, 1980s, and 2000s. Our grain size analyzes during major flooding focuses on the 1980s, as this data is unavailable for the 1990s and no major floods occurred in the 1970s and 2000s. Sediment deposition and erosion rates for Dongting Lake and the middle and lower Yangtze River are estimated applying a sediment budget analysis. Sediment load for ungauged areas is estimated based on a similar method described by Dai and Lu (2010). It is determined by the difference in water discharge between upstream stations and the downstream station of a reach, times the minimum SSC among all the upstream stations of the reach. For example, for the middle reach of the Yangtze River, the water discharge supplied by ungauged areas is estimated as the difference between inflow of water discharge (upper reach through Yichang station, the Hanjiang River through Huangzhuang station, and Dongting Lake through Chenglingji station) and outflow of water discharge through Hankou station (Fig. 1). The SSC of ungauged areas is defined as the minimum SSC value measured at three upstream stations (Yichang, Huangzhuang, and Chenglingji stations). Thus, a first order estimation of sediment load can be provided for ungauged areas, and this will most likely be a

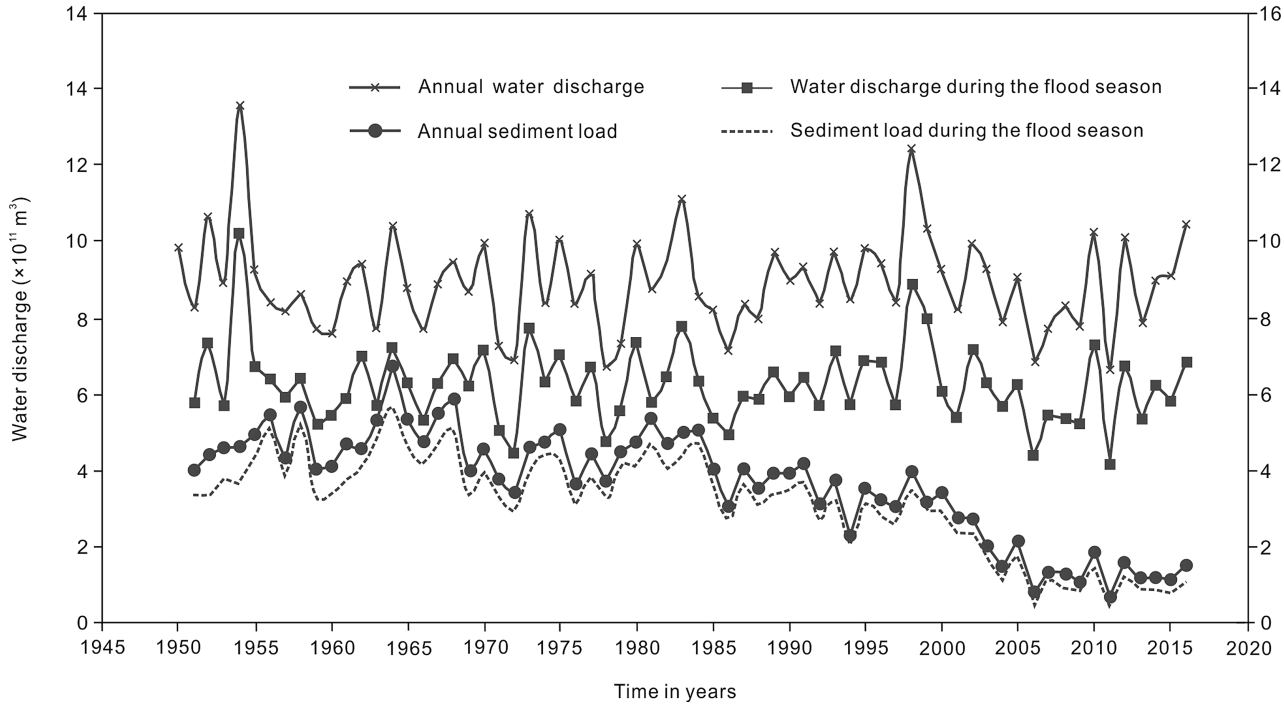

Fig. 2. Annual water discharge and sediment load, and flood seasonal water discharge and sediment load from 1951 to 2016 at Datong gauging station.

conservative estimation.

4. Results

4.1. Water and sediment fluxes to the sea during the flood season for major flood years

There is no significant change in the total volume of water during the flood season (TVWFS) at Datong station (Fig. 2). The flooding in 1954 and 1998 has been recorded as the largest and second largest events from 1951 to the present, with the TVWFS value of 10.27×10^{11} m^3 and 8.81×10^{11} m^3, respectively at Datong station, which is considerably larger than the perennial average (1951–2016) of 6.42×10^{11} m^3. The TVWFS is 5.87×10^{11} m^3 in 1981, smaller than the perennial average, whereas the TVWFS is 7.86×10^{11} m^3 in 1983, 1.22 times larger than the perennial average. Sediment observations during the flood season at Datong station in the period 1951 to 2002 exhibit a decreasing trend similar to the annual sediment flux with multiple abrupt changes in 1969, 1986, and 1991 (Dai, 2006). These changes divide the period into four stages: stage I: from 1951 to 1968, stage II: from 1969 to 1985, stage III: from 1986 to 1990, and stage IV: from 1991 to 2002. The average sediment flux during the flood season at stage I, II, III, and IV are 4.26×10^{11} kg, 3.92×10^{11} kg, 3.29×10^{11} kg, and 2.78×10^{11} kg, respectively. The sediment flux during the flood season in 1954 and 1998 are 3.69×10^{11} kg and 3.46×10^{11} kg, respectively, the former smaller than the perennial average of stage I and the latter larger than the perennial average of stage IV. For 1981 and 1983, the sediment flux during the flood season is 4.70×10^{11} kg and 4.37×10^{11} kg, respectively, both larger than the perennial average of stage II.

4.2. Average SSC to the sea during the flood season for major flood years

The perennial averaged SSC to the sea during the flood season of stage I, II, III, and IV is 0.67, 0.63, 0.56, and 0.42 g/l, respectively (Fig. 3). Average SSC of 1954 and 1998 is the smallest and the fourth smallest over the period from 1951 to 2002, at 0.36 and 0.39 g/l, respectively. The former is 54% of the perennial average of stage I and the latter is 93% of that of stage IV. Average SSC during the flood season in 1981 is 0.80 g/l, the third largest concentration during 1951 to 2002 and 1.27 times larger than its perennial average of stage II. Average SSC in 1983 is 0.56 g/l, smaller than the perennial average of stage II (Fig. 3). These demonstrate that average SSCs to the sea during the flood season, during major flood years, are lower than the perennial average SSC except for the year when a major flood occurred in the upper Yangtze River.

4.3. Monthly median grain size and bed material load content of sediments to the sea during the flood season for major flood years

Due to limited availability of data, only grain-sizes of sediments to the sea during the 1981 and 1983 major floods are described and discussed. Qian and Wan (2003) suggests to use the finest 5% or 10% of the riverbed sediment to distinguish between wash load and bed material load. Lai et al. (2017) adopted the finest 10% of the riverbed sediment to investigate river erosion downstream the Three Gorges Dam in the middle reach of the Yangtze River. We use the same grain size (0.100 mm) as Lai et al. (2017) to separate between wash load and bed material load for the sediment records obtained at Yichang and Hankou stations. The grain-size of riverbed sediment with cumulated proportion of 10% ranged from 0.050 to 0.080 mm measured from 2001 to 2008 at Datong station (Shen et al., 2011). This is similar (0.050–0.100 mm) to measurements obtained in 1980, at the same station. Accordingly, we use the grain-size of 0.050 mm to separate wash load and bed material load for data measured during the 1970s and 1980s at Datong station. The grain size of 0.062 mm is used to do such a separation from 2004 to 2008 at Datong station due to variation of grain size data statistics (cumulative probability of grain size being calculated based on 0.007, 0.010, 0.025, 0.050, 0.100, 0.250, and 0.500 mm during the 1970s and 1980s, whereas on 0.002, 0.004, 0.008, 0.016, 0.031, 0.062, 0.125, and 0.500 mm during the 2000s).

For the extreme flooding that occurred in the upper Yangtze River in July 1981, monthly median sediment grain sizes from July to September 1981 are close to the perennial average (1976–1984, 1986) and lower than that during October (Fig. 4a). Bed material load content to the sea from July to October 1981 is lower than the perennial

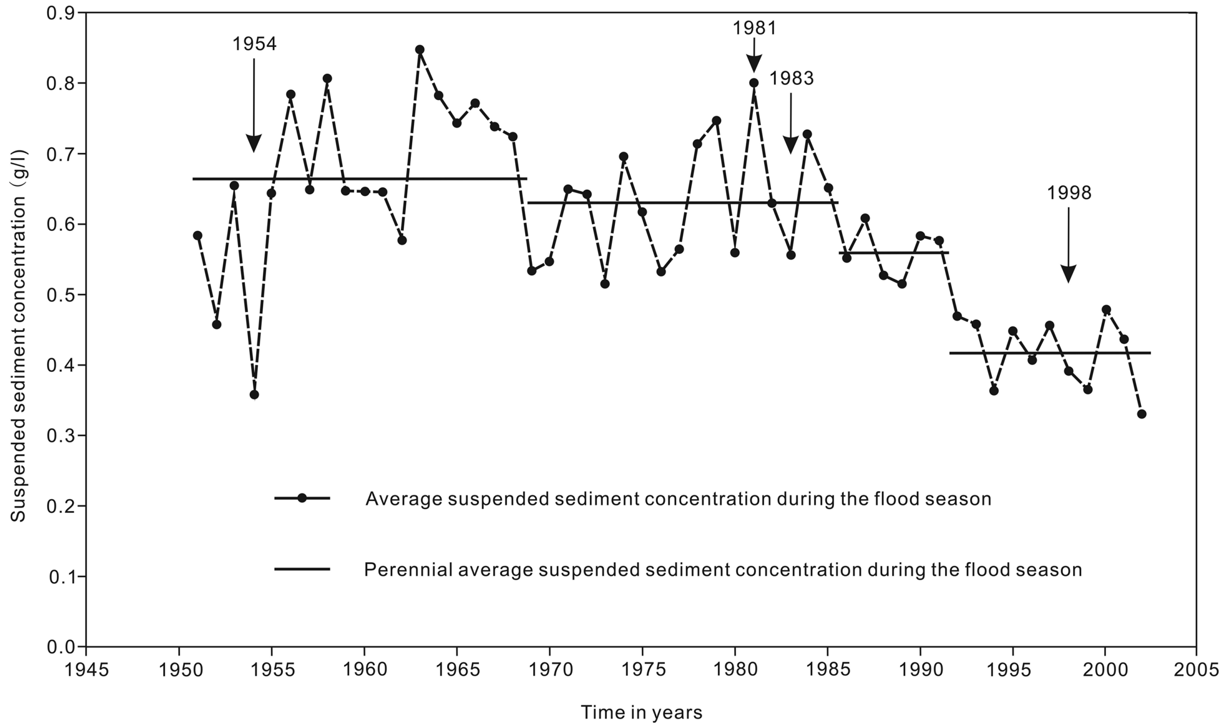

Fig. 3. Perennial average and flood seasonal average suspended sediment concentration (SSC) from 1951 to 2016 at Datong station.

average (1976–1984, 1986) (Fig. 4b). Monthly median sediment grain size from July to October 1981 is close to or equal to the perennial average (1980–1984, 1986) at Yichang station (Fig. 4c) and all lower than the perennial average (1980–1984, 1986) at Hankou station (Fig. 4d).

For the large flood that occurred in the middle Yangtze River reach in July 1983 and the extreme flood that occurred in the Hanjiang River in early August and October that same year, monthly median sediment grain size is the largest from July to September 1983 and the second largest during October 1983 during the period from 1976 to 1984, 1986, and from 2004 to 2008 (Fig. 4a). Monthly median sediment grain size is slightly deviating over time from the perennial average (1980–1984, 1986) from July to October at Yichang and Hankou stations (Fig. 4c and d). Bed material load content during the flood season of 1983 is the largest during July and the second largest during August, and almost similar to the perennial average during September (Fig. 4b). This demonstrates that the Yangtze River discharged similar sediment size distributions as is estimated for the perennial average to the sea during the flood season of 1981, despite the occurrence of an extreme flood in the upper Yangtze River. In contrast, coarser-grained sediments were delivered to the sea during 1983 when a large flood occurred in the middle Yangtze River, together with an extreme flood in the upper Hanjiang River.

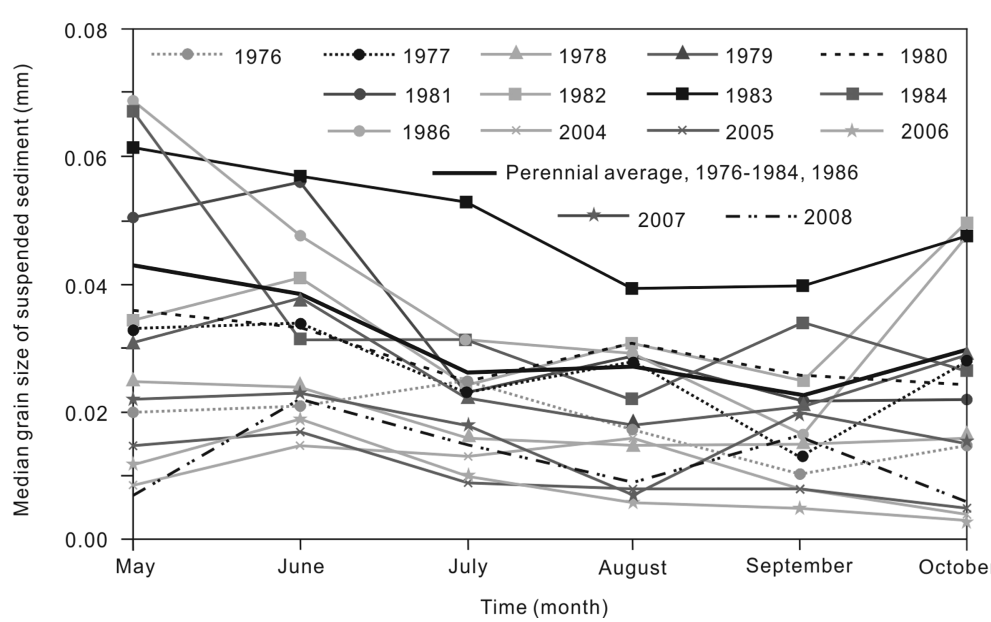

Fig. 4a. Monthly median grain size of suspended sediment during the flood season from 1981 to 1984, 1986, and from 2004 to 2008 at Datong station.

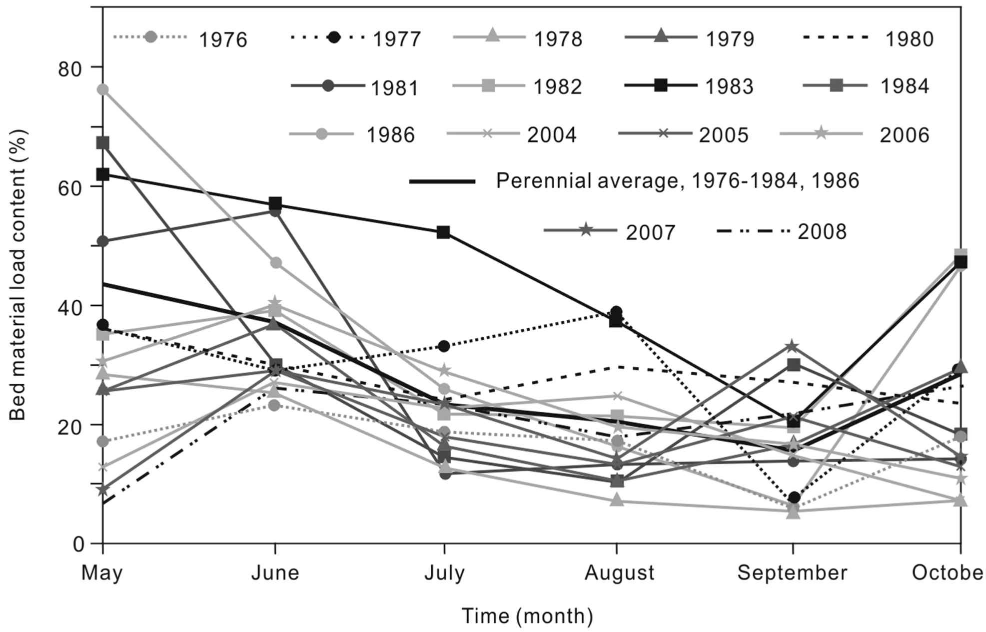

Fig. 4b. Monthly bed material load content of suspended sediment during the flood season from 1976 to 1984, 1986 (grain size > 0.050 mm), and from 2004 to 2008 (grain size > 0.062 mm) at Datong station.

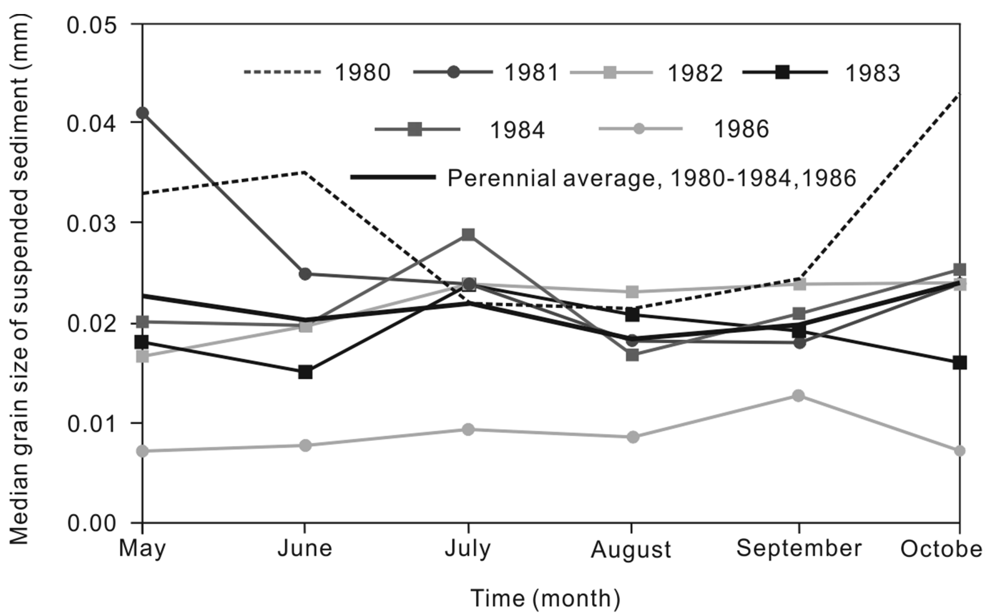

Fig. 4c. Monthly median grain size of suspended sediment during the flood season from 1980 to 1984 and 1986 at Yichang station.

5. Discussion

5.1. Sediment retention in the middle reach of the Yangtze River during years of major flooding

Significant sediment deposition occurred between Yichang and Hankou gauging station during years of major flooding as illustrated in Fig. 5 and Table 1. This indicates sediment retention in the middle reach of the Yangtze, which includes Dongting Lake and the main Yangtze channel. Furthermore, sediment retention increased remarkably during years when there was basin-wide major flooding (Fig. 6 and Table 1). Generally, during none major flood years, deposition in the middle reach channel was less than that of Dongting Lake. However, during basin-wide flooding more sediments are deposited in the middle reach; ~ 4.0 times more during the 1954 flood and ~2.3 times more during the 1998 flood (Fig. 6). Whereas the deposition rates of Dongting Lake and the middle reach were much more comparable during the flood years 1981 and 1983. This means that sediment retention in the middle reach of the main channel is more significant during basin-wide major floods. Sediment deposition in Dongting Lake has kept relatively stable during the four years of major flooding (Table 1). However, deposition in the main channel of the middle reach has changed significantly (Table 1). This clearly indicates that the main channel of the middle reach retains more sediment during the year of basin-wide major flooding.

Sediment deposition for the main channel occurred mainly between the cities of Luoshan and Huangshi, with the reach around Wuhan being the depocenter where sediments are deposited mostly on the floodplains and bar islands (Yin et al., 2004). Most of the sediment deposition on the floodplains and bar islands is wash load due to its

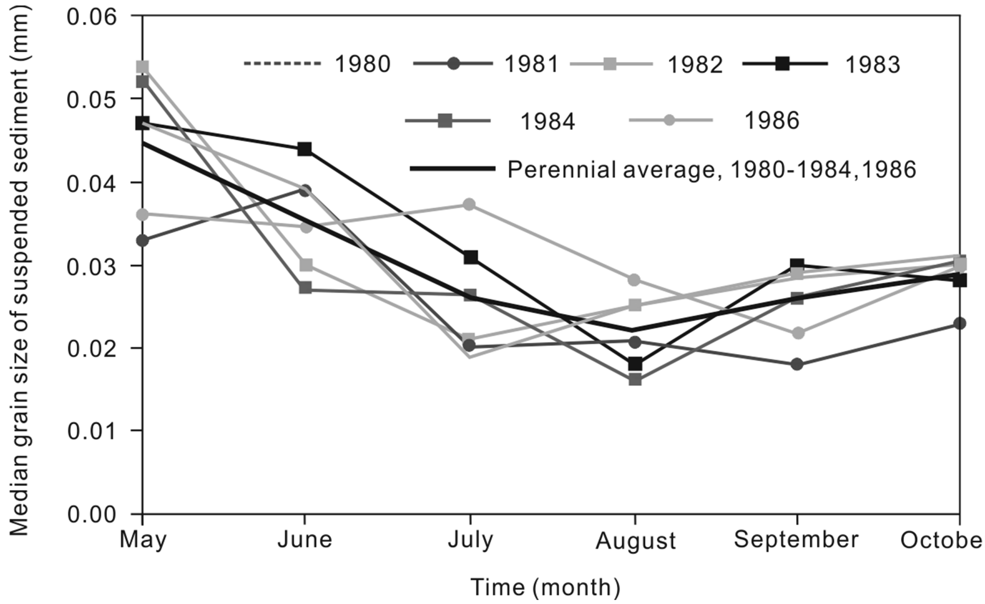

Fig. 4d. Monthly median grain size of suspended sediment during the flood season from 1980 to 1984 and 1986 at Hankou station.

dominance in sediment transported (Zhan et al., 2010; Liu et al., 2019). As a result, a remarkable reduction in wash load transport rate can be observed during the flood season at Hankou station compared with Yichang station (see section 5.3). The amount of sediment deposition on the floodplains and bars is controlled by peak flood discharge, inundation period, and the water depth. Generally, large peak flow, long inundation periods, and deep inundation waters favor a thick deposition layer (Magilligan et al., 1998; Li and Zhang, 2004; Knox, 2006; Toonen et al., 2015; Omengo et al., 2016; Moody, 2019). Sedimentation rates analysis of sediment cores over different periods prove that major floods can accelerate the floodplain sedimentation rates in the middle and lower reaches of the Yangtze River (Liu et al., 2019). In-situ measurements at 18 transections along the mainstream of the middle Yangtze River show that the deposit layer of 1998 is the thickest, followed by smaller layers of 1999 and 2000 (Yin et al., 2004). Moody (2019) made a long-term topographical survey (38 yr) of transects of floodplains and point bars along the Powder River in Montana, USA and found a linear relation between sediment deposition volume and peak flow.

Furthermore, we analyzed the key influencing factors of flood deposition during the flood years of 1954, 1981, and 1998, using data obtained at Hankou station as an example. The peak discharge of 75,900 m^3/s in 1954 is slightly larger than that of 71,000 m^3/s in 1998 (Fig. 7a). Inundation durations in 1954 and 1998 are 127 days and 91 days respectively and water level during the inundation period of 1954 was overall higher than during 1998 (Fig. 7b). The water level from June 27 to September 14 in 1954 had been higher than that in 1998 except for one week. However, daily water discharges in 1954 have been lower than in 1998, except during the period from August 3 to August 17 (Fig. 7a and b). This demonstrates that daily flow velocity in the period in 1954 was lower compared to1998 during ca. a two months period. Lower flow velocities are favorable for deposition on

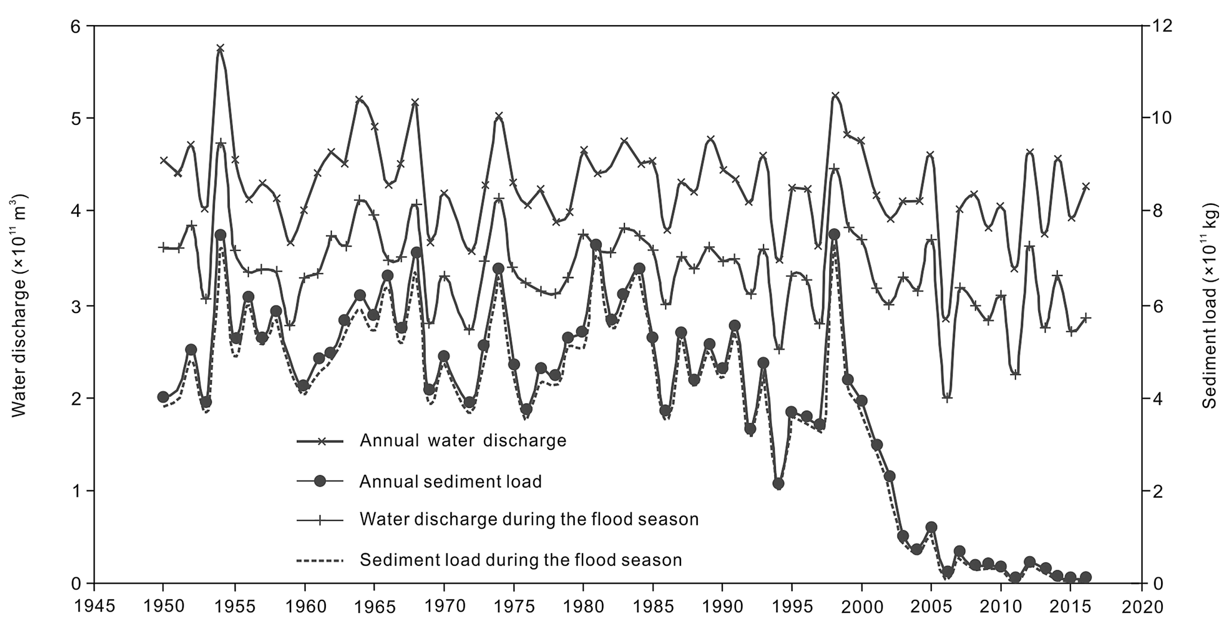

Fig. 5a. Annual water discharge and sediment load, and flood seasonal water discharge and sediment load from 1950 to 2016 at Yichang station.

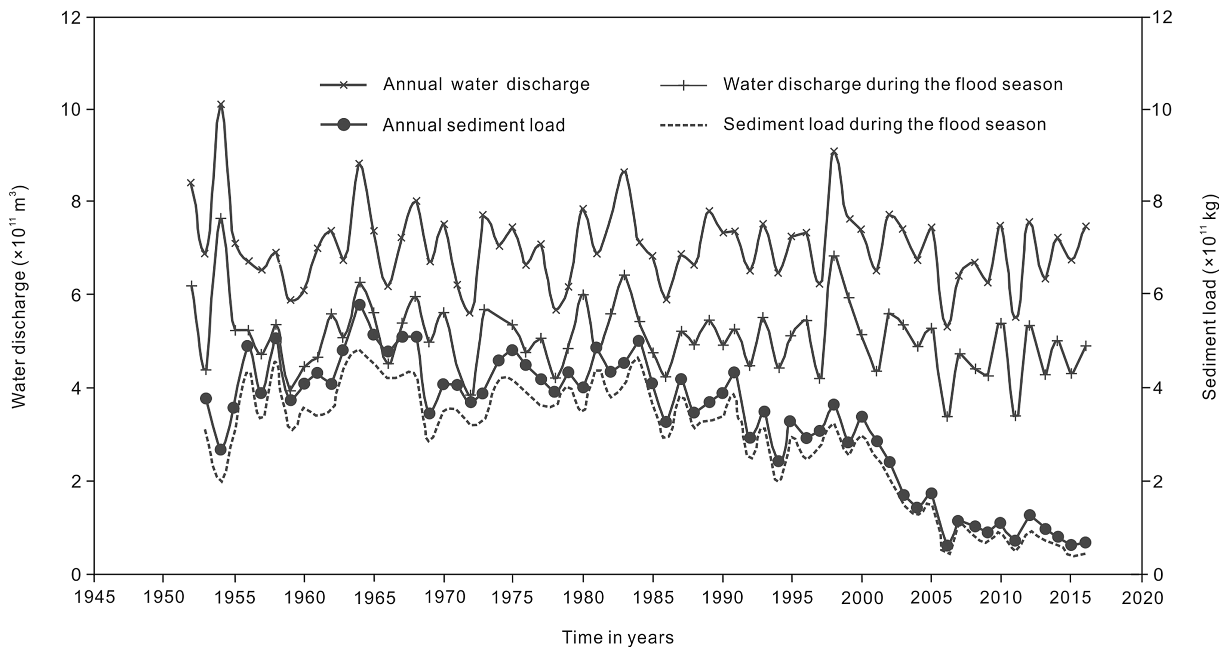

Fig. 5b. Annual water discharge and sediment load, and flood seasonal water discharge and sediment load from 1953 to 2016 at Hankou station.

bars and floodplains. Thus, the combination of a longer inundation duration, higher water levels and lower flow velocities results in more sedimentation of the middle reach of the Yangtze River in 1954 compared to flooding during 1998.

Peak flood discharge at Wuhan in 1981 was 52,800 m^3/s, much smaller compared to 1954 and 1998 (Fig. 7a). The inundation at Wuhan in 1981 lasted 6 days, much shorter compared to 1954 and 1998. In addition, water levels over the inundation period were considerably lower than during the flooding of 1954 and 1998 (Fig. 7b). This led to less deposition in 1981 compared to the flooding of 1954 and 1998 (Fig. 6). Peak flood discharge at Wuhan in 1983 was 63,800 m^3/s and the inundation lasted 69 days, both ranking between the flooding of 1981 and 1998, similar to the water level (Figs. 7a and b). This resulted in less deposition in 1983 compared to the flooding events of 1954 and 1998 (Fig. 6).

Due to a combination of large quantities of sediments from the upper reach, less sediment retention in the middle reach, and TVWFS smaller than the perennial average (1951–2016), the flood of 1981 delivered more sediment with significantly high SSC to the sea during the flood season than the perennial average (1969–1985). The effect of wetland restoration projects depends directly on availability of sediments (Blum and Roberts, 2009, 2012; Bentley et al., 2014). The best period to divert suspended sediment for coastal restoration in the Mississippi Estuary is during intermediate and high flow stages in the limb of floods due to high SSC and suspended sediment load (Rosen and Xu, 2014). Accordingly, we infer that the major flood of the upper reach with significant high SSC would offer a good opportunity to capture sediments efficiently for coastal restoration in the Yangtze River Estuary.

5.2. Median grain size distribution of sediments to the sea during major flood events

The median grain size of sediments at Datong station is larger in May than in the summer (Fig. 4a). Shen et al. (2000) also found that coarse-grained sediment is mostly transported from the Yangtze River to the sea during April and May rather than in the summer. Contents of bed material load are relatively high during these two months at Datong station (Fig. 4b). However, the contribution of sediment load during April and May to the annual sediment load from 1976 to 2010 ranges between 4.8% and 22.6%, with an average of 11.5%. Whereas, the contribution of sediment load during July and August to the annual sediment load varies from 30.3% to 54.2%, with an average of 41.4% (Table 2). This indicates that a little lower than half the annual sediment load is transported during July and August, and ca. 10% of annual sediment load is transported during April and May before and after the emplacement of the Three Gorges Dam in 2003. So, the coarse-grained sediments that are transported during April and May do not dominate the annual sediment budget. Therefore, we infer that coarse-grained sediments delivered during April and May do not dominate the annual grain size due to its low contribution.

The median grain size of sediments is the largest during July, August, and September, with the second largest (slightly lower than that of 1982) being observed during October at Datong gauging station in 1983. Obviously, the characteristics of the median grain size of sediment during July to September from 1976 to 1984, and 1986 are not

Table 1
Sediment deposition in the middle reach of the Yangtze River, Dongting Lake, and main channel of the middle Yangtze River during years of major flooding.

Year	Annual sediment load at Yichang station $\times 10^{11}$ kg	Annual sediment load at Huangzhuang station $\times 10^{11}$ kg	Annual sediment load provided by ungauged areas $\times 10^{11}$ kg	Annual sediment load at Hankou station $\times 10^{11}$ kg	Sediment deposition in the middle reach $\times 10^{11}$ kg	Sediment deposition in Dongting Lake $\times 10^{11}$ kg	Sediment deposition in the main channel of the middle reach $\times 10^{11}$ kg
1954	7.53	1.69	0.18	2.68	6.72	1.33	5.39
1981	7.30	0.20	0.01	4.88	2.42	1.21	1.42
1983	6.21	0.51	0.08	4.55	1.66	1.14	1.10
1998	7.43	0.10	0.03	3.64	3.79	1.19	2.73

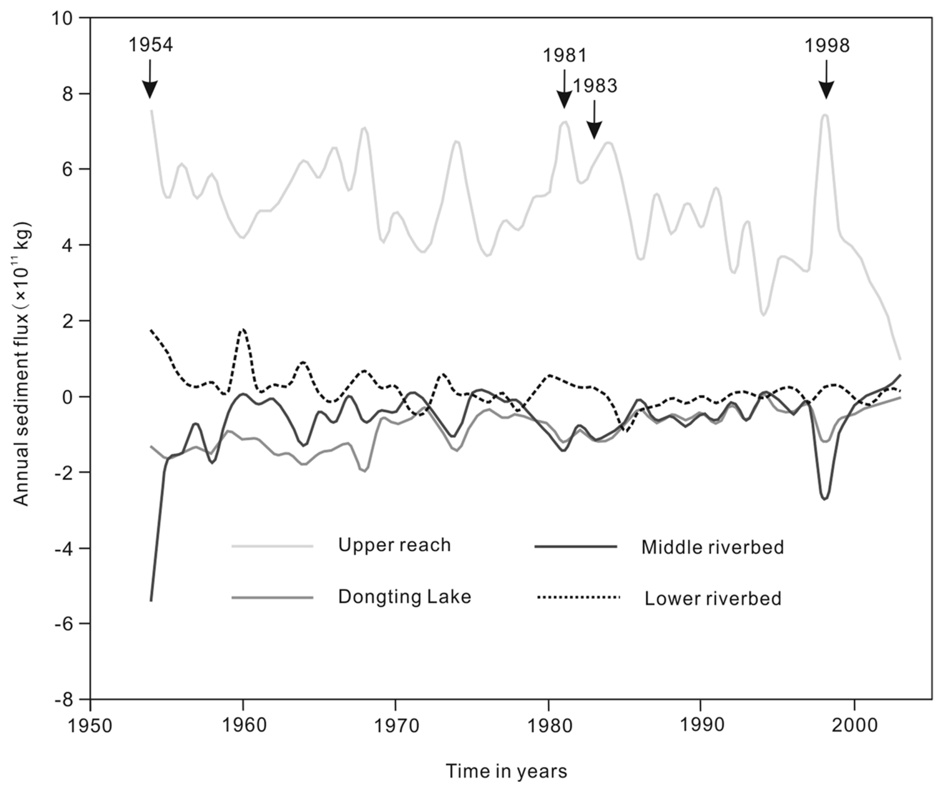

Fig. 6. Annual sediment flux provided by the upper reach, Dongting Lake, middle riverbed deposition (-), and lower riverbed erosion (+).

in accordance with the monthly water discharge during that same period (Figs. 4a and 8). Whereas the characteristics of bed material load transport rates from July to September are consistent with the monthly water discharge of that same period, i.e., high monthly water discharge results in high transport rate of bed material load. For example, the maximum monthly water discharge of 66,238 m^3/s during July 1983 corresponds to the maximum bed load transport rate of 21,234 kg/s. Monthly water discharge of 45,261 m^3/s during July 1981, being the largest in that year, corresponds to bed material load transport rate of 6,799 kg/s (Fig. 9a). Monthly wash load transport rates from May to

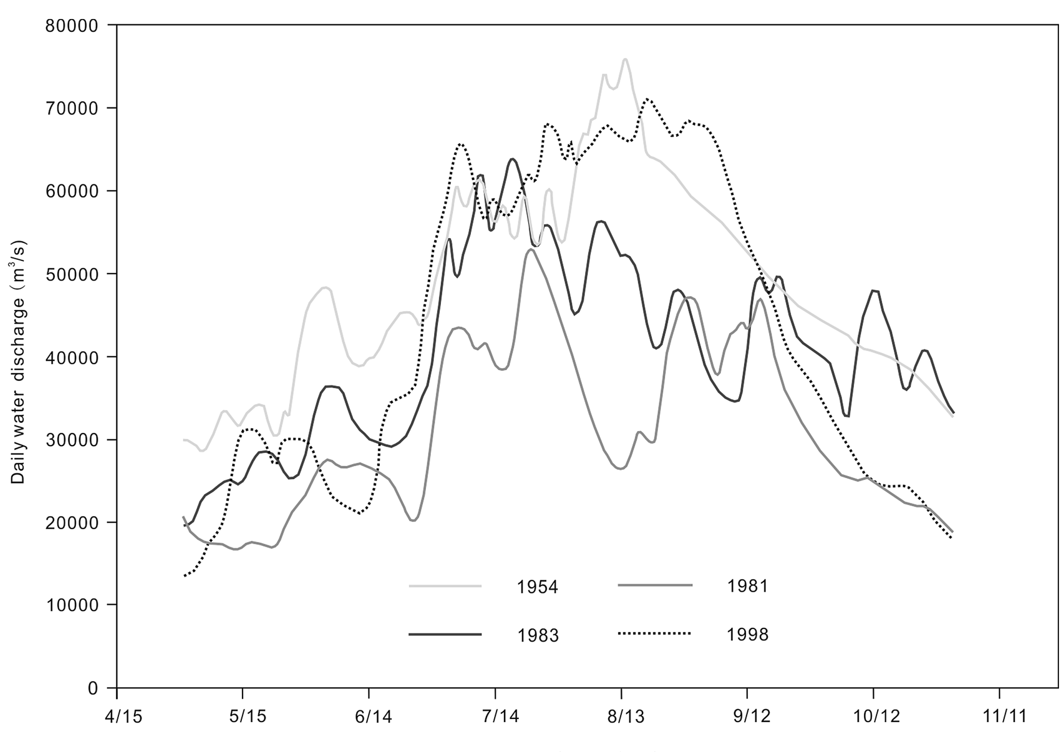

Fig. 7a. Daily water discharge during the flood season in 1954, 1981, 1983, and 1998 at Hankou station.

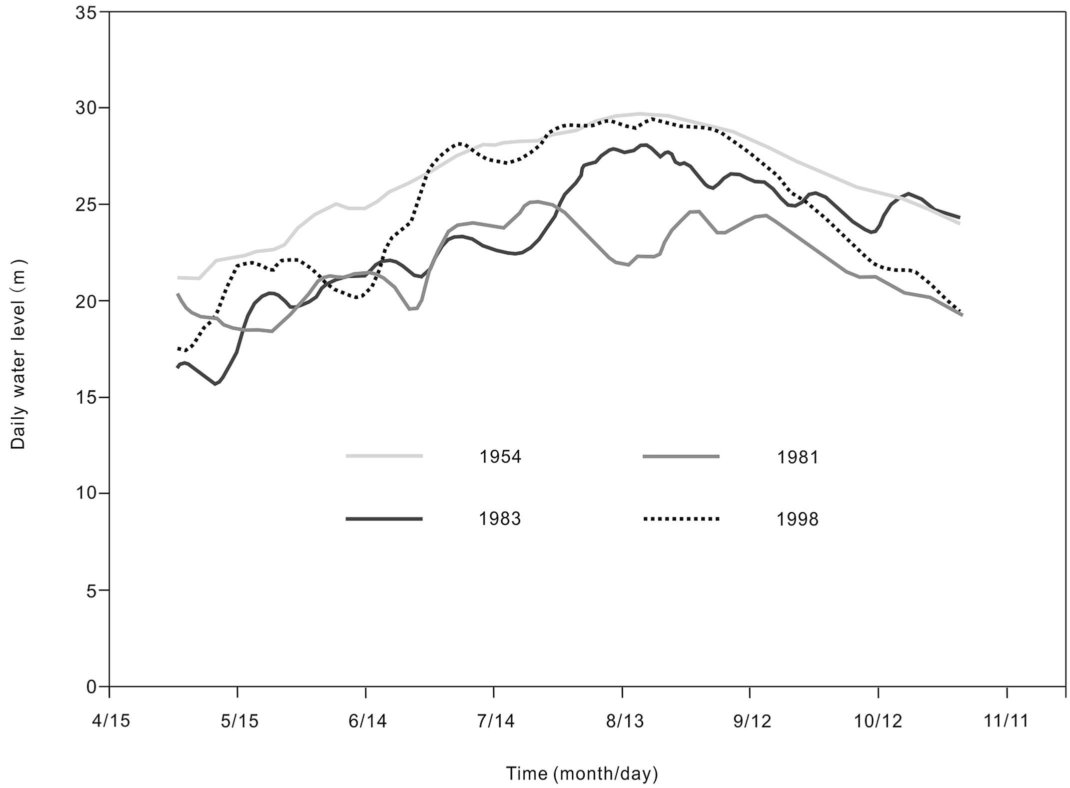

Fig. 7b. Daily water level during the flood season in 1954, 1981, 1983, and 1998 at Hankou station.

October during the period of 1976 to 1984, 1986, and from 2004 to 2008 show no such correlation to the monthly water discharge at Datong station. Obviously, the highest five wash load transport rates which range between 38,814–52,838 kg/s correspond to the monthly water discharge of 42,276–49,064 m^3/s. Among them, the maximum wash load transport rate of 52,838 kg/s occurred when the monthly water discharge reached 45,261 m^3/s during July 1981. However, the maximum monthly water discharge caused only a wash load transport rate of 19,444 kg/s during July 1983 (Fig. 9b). Furthermore, no significant changes in wash load transport rate could be observed during the flood season from 1980 to 1984 and 1986 from upstream Hankou station to downstream Datong station (Figs. 10a and 9b). We can detect extreme high wash load transport rates during July and August in 1981 at Yichang station due to the occurrence of an extreme flood during the middle of July in the upper Yangtze River (Fig. 10b). Due to significant sediment deposition in the middle reach during the flood season in 1981, the transport rate of wash load reduced significantly especially for July and August as can be observed when comparing gauging records of Yichang and Hankou stations (Figs. 10a and b). A similar reduction in wash load transport can be observed for July 1983 when comparing gauging records of Yichang to Hankou stations, followed by high wash load transport rates during August and September (Figs. 10a

Table 2
Sediment loads for April, May, July, August and their contribution to annual sediment load.

Year	Sediment load in April $\times 10^{10}$ kg	Sediment load in May $\times 10^{10}$ kg	Sediment load in July $\times 10^{10}$ kg	Sediment load in August $\times 10^{10}$ kg	Annual sediment load $\times 10^{10}$ kg	Contribution of sediment load for April and May to annual sediment load %	Contribution of sediment load for July and August to annual sediment load %
1976	1.47	3.07	9.82	4.08	36.30	12.5	38.3
1977	3.21	5.29	10.89	8.43	44.18	19.2	43.7
1978	0.56	2.08	9.62	7.60	36.99	7.1	46.6
1979	0.46	2.07	9.84	10.04	44.90	5.6	44.3
1980	1.49	3.57	11.39	8.69	47.40	10.7	42.4
1981	3.45	1.60	15.97	9.50	53.65	9.4	47.5
1982	0.87	1.38	9.98	10.46	46.74	4.8	43.7
1983	1.66	2.49	10.90	8.58	50.07	8.3	38.9
1984	1.56	1.63	13.51	13.86	50.52	6.3	54.2
1986	1.00	1.10	8.71	5.30	31.12	6.8	45.0
2002	0.91	4.33	4.89	7.09	27.50	19.1	43.6
2003	0.92	2.10	5.35	1.81	20.64	14.6	34.7
2004	0.55	1.39	2.57	1.96	14.67	13.2	30.9
2005	0.51	1.20	2.77	5.29	21.68	7.9	37.2
2006	0.86	1.06	1.72	0.85	8.48	22.6	30.3
2007	0.35	0.48	3.11	4.01	13.76	6.0	51.7
2008	0.72	0.52	1.58	2.85	13.00	9.5	34.1
2009	0.62	1.07	1.79	3.07	11.33	14.9	42.9
2010	1.67	2.00	3.82	2.94	18.28	20.1	37.0

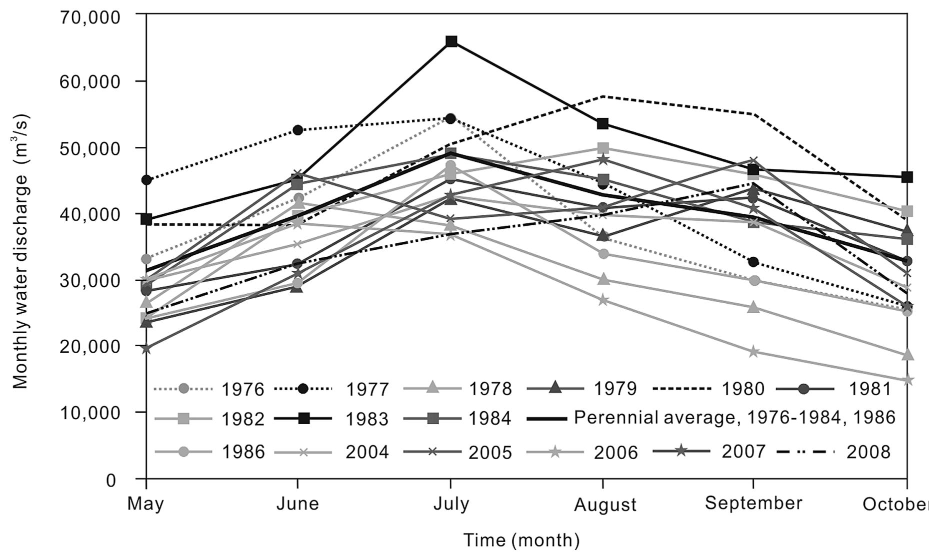

Fig. 8. Monthly water discharge during the flood season from 1976 to 1984, 1986, and from 2004 to 2008 at Datong station.

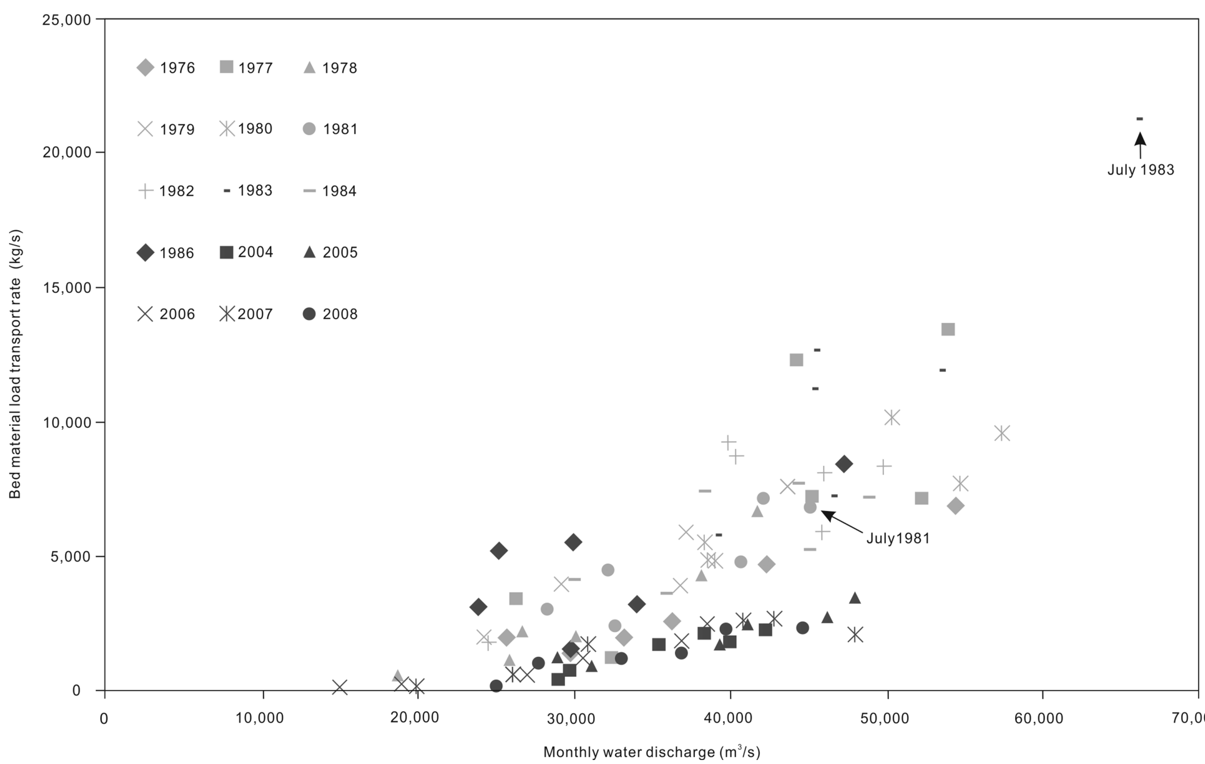

Fig. 9a. Monthly bed material load transport rate during the flood season from 1976 to 1984, 1986, and from 2004 to 2008 at Datong station.

and b), due to an extreme flood in the upper reach of the Hanjiang River during early August that year. This implies that variation of monthly wash load transport rate mainly depends on the inflow upstream rather than on monthly water discharge at the same station. However, the monthly bed material load transport rate is controlled by monthly water discharge of that same period. Furthermore, wash load is the dominant component of sediments transported from July to September (Figs. 4b and 9). This leads to an inconsistent correlation between bed material load content and water discharge (Figs. 4b and 8).

The monthly median grain size (< 0.030 mm) from July to September in most years is much smaller than the smallest grain size of bed material load (0.050 mm) (Fig. 4a). This implies that increased transport rates of bed material load due to increased water discharge hardly impacts the distribution characteristics of wash load of sediments. For example, monthly water discharges during August and September 1980 are the largest for the studied period and show nearly highest transport rates of bed material load at that period (Figs. 8 and 9a). However, monthly median grain size during these two months is just slightly higher than the perennial average (Fig. 4a). With a median grain size of 0.053 mm, July 1983 shows to be an exception (Fig. 4a). Monthly water discharge during July 1983 is the largest, much higher than the perennial average, and this results in exceptional high transport rate of bed material load (Figs. 8 and 9a). These two examples show the sensitivity of median grain size of sediments entering the estuary to water discharge, i.e., the sensitivity significantly increases when water discharge is high, propelling the median grain size of sediments to that of bed material load.

Quantities of bed material load transported during July from 2004

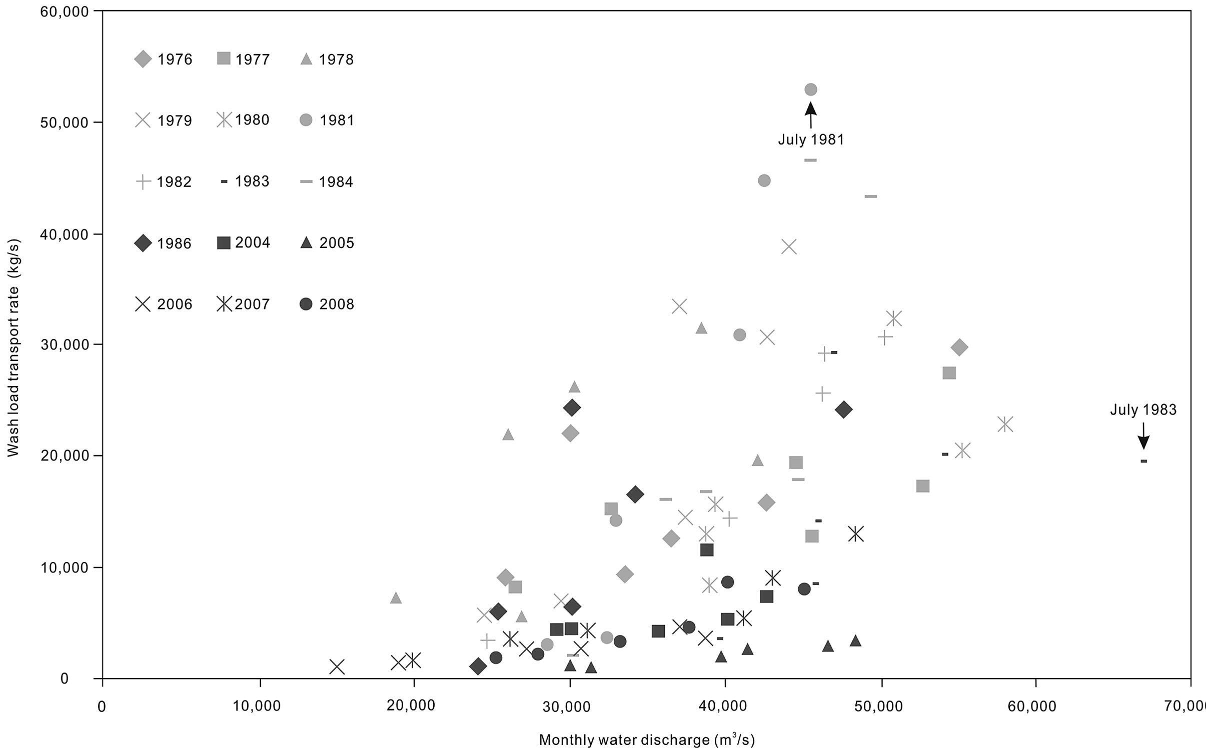

Fig. 9b. Monthly wash load transport rate during the flood season from 1976 to 1984, 1986 (grain size < 0.050 mm), and from 2004 to 2008 (grain size < 0.062 mm) at Datong station.

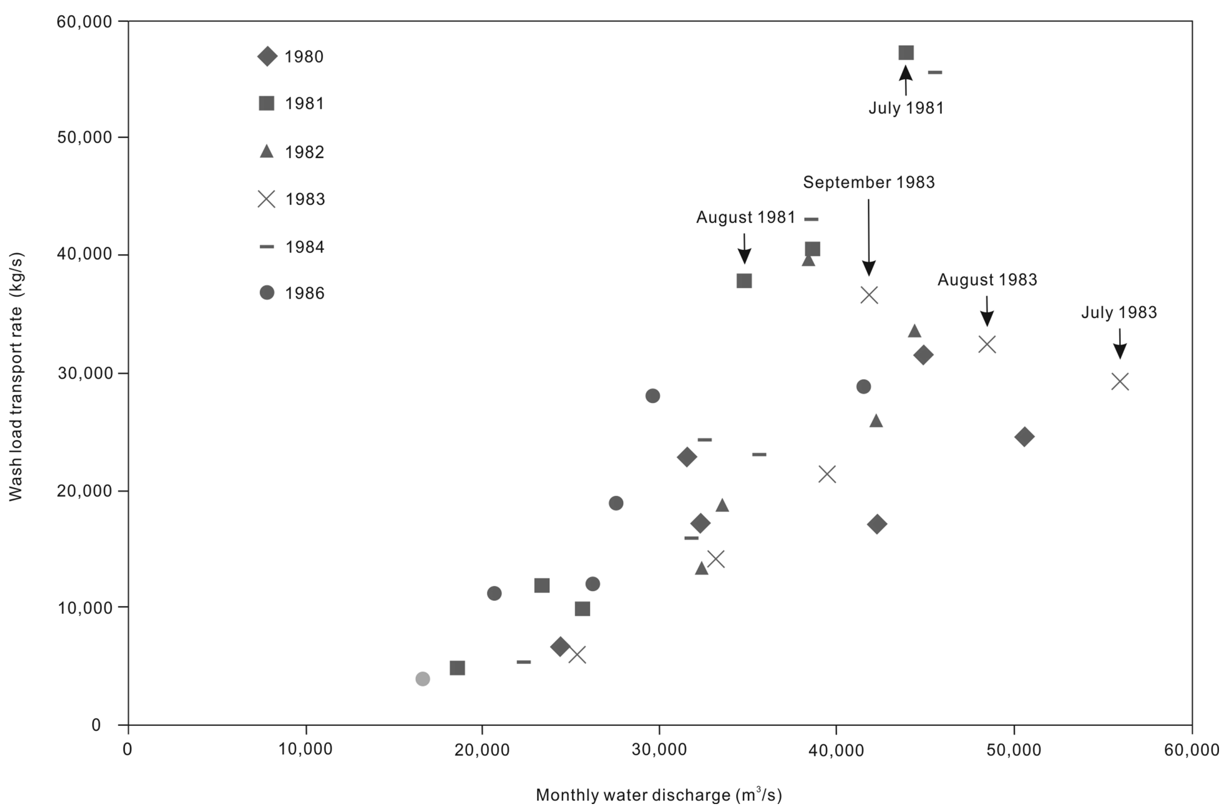

Fig. 10a. Monthly wash load (grain size < 0.100 mm) transport rate during the flood season from 1980 to 1984 and 1986 at Hankou station.

to 2008 at Datong station are significantly lower than those transported during July from 1976 to 1984, 1986 (Fig. 11). We infer that this is partly attributed to an increase from 0.050 to 0.062 mm in grain size for separating between wash load and bed material load since 2004 and partly to a decrease in monthly water discharge (from an average of 49,360 m^3/s from 1976 to 1986 to that of 44,047 m^3/s from 2004 to 2008) during July after the closure of the Three Gorges Dam in 2003 (Figs. 8 and 11). The quantity of bed material load transported during

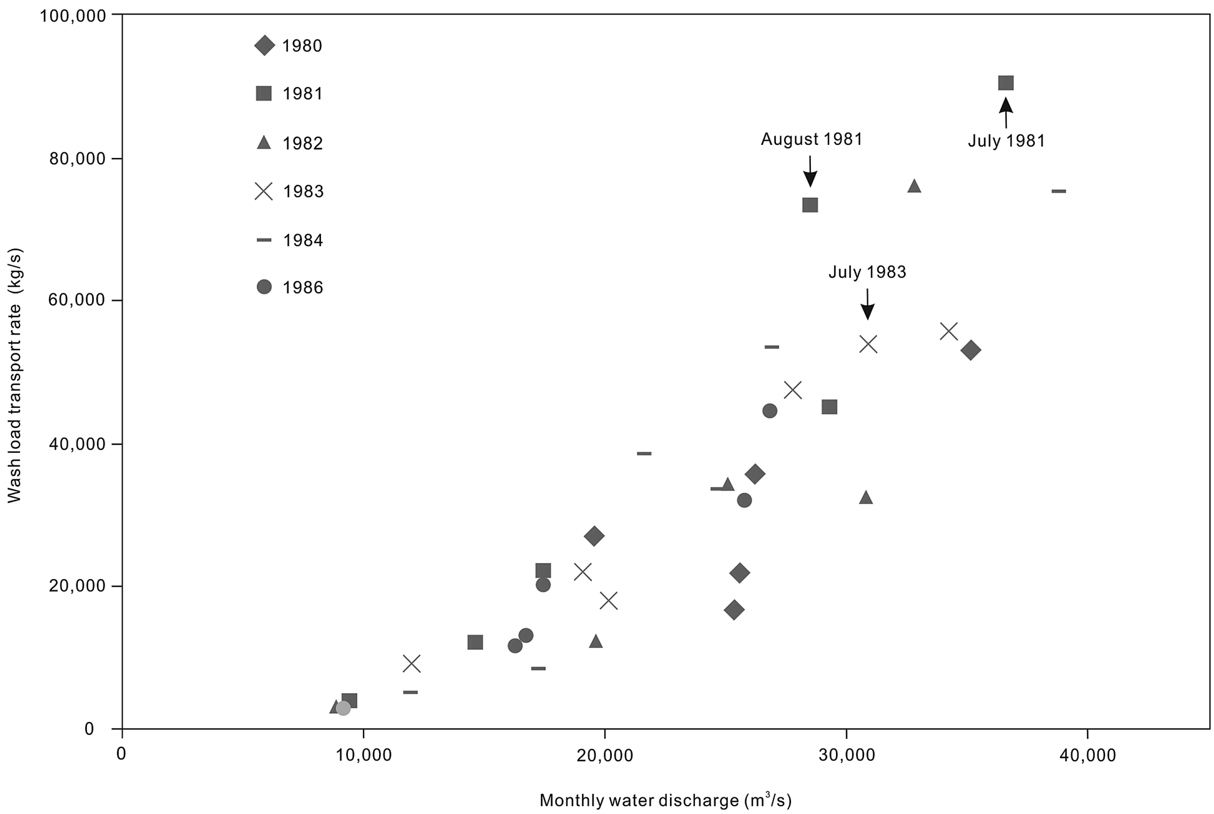

Fig. 10b. Monthly wash load (grain size < 0.100 mm) transport rate during the flood season from 1980 to 1984 and 1986 at Yichang station.

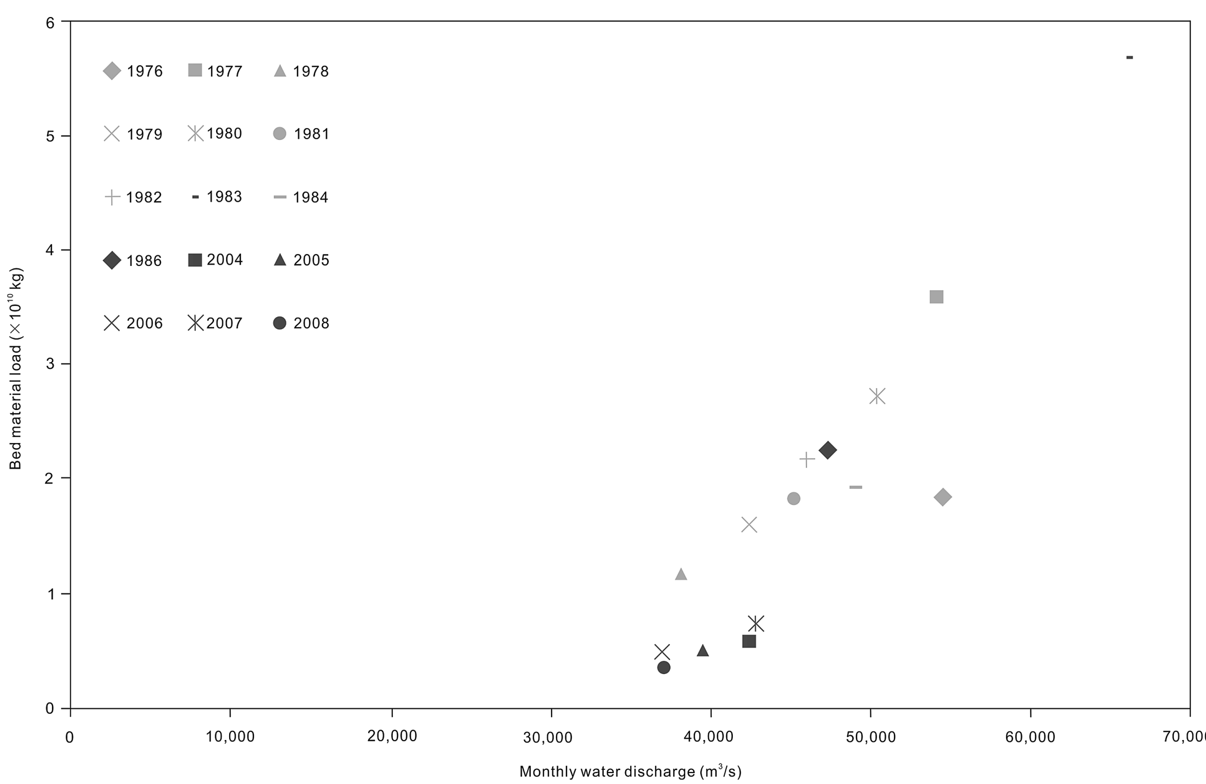

Fig. 11. Bed material load for July from 1976 to 1984, 1986, and from 2004 to 2008 at Datong station.

July 1983 at Datong is 5.69×10^{10} kg, and larger compared to loads from 1976 to 1984 and 1986 (Fig. 11). This indicates that the large flood of 1983 in the middle Yangtze delivered much coarser-grained sediment to the sea. The quantity of bed material load is 1.82×10^{10} kg during July 1981 at Datong station, slightly higher compared to July in 1978 and 1979, except for the period of 2004 to 2008 (Fig. 11). This shows that the extreme flood of 1981 in the upper Yangtze River did not deliver much coarser-grained sediments to the sea compared to years when no large flood occurred. This indicates that the extreme flood that occurred in the upper reach of the Yangtze River in 1981 couldn't carry its imprint as an extreme flood downstream, when entering the estuary. Previous flood events are identified mainly in terms of grain size and/or grain-size related characteristics of flood event deposits in the stratigraphic record in the estuary, subaqueous delta, and adjoining coastal zones of the Yangtze River (Liu et al., 2010; Zhan et al., 2010; Wang et al., 2011). Our findings provide insight regarding the identifiability of major flooding in the upper reach of the Yangtze River, based on grain size of suspended sediments to the sea during the flood season.

6. Conclusions

(1) A more than average sediment load was delivered to the sea from the Yangtze River during the flood season of 1981 with a higher than average SSC. Similar results were found for the floods of 1983 and 1998 but then with a lower SSC than average, whereas less sediment load than average was delivered during the 1954 flood, with a significantly lower SSC.
(2) Sediment retention in the middle Yangtze reach during the major floods substantially reduced the sediment flux to the sea. The upper Yangtze River provided significantly more sediments during the 1954, 1981, and 1998 major floods than the perennial mean of the corresponding stage. However, the sediment flux to the sea during the flood season were lower than the perennial mean of the corresponding stage in 1954 and not much higher than that in 1981 and 1998 due to the deposition of large quantities of sediment in the middle reach.
(3) Retention of sediments in the middle Yangtze reach is attributed to sedimentation in both Dongting Lake and the floodplains and bars of the main channel. The amount of deposition in Dongting Lake remained stable during the four described floods, whereas deposition in the main channel of the middle reach significantly increased due to an increase of peak flood discharge, inundation duration and water depth and a decrease of flow velocity. This led to more sediment deposition in the middle reach of the Yangtze River during the 1954 and 1998 floods, and consequently less sediments reached the Yangtze outlet.
(4) No significant change in the grain size distribution was observed at the Yangtze River outlet during the flood season for the extreme flood of 1981 in the upper reach of the Yangtze River. However, coarser-grained sediments were delivered to the sea due to the remarkably high-water discharges during the July 1983 large flooding of the middle reach of the Yangtze River and the extreme flooding in the upper Hanjiang River.

CRediT authorship contribution statement

Xiu Juan Liu: . **Albert J. Kettner:** . **Jun Cheng:** Writing - review & editing. **S.B. Dai:** .

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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