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RESEARCH ARTICLE

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Modulation of sediment load recovery downstream of Three Gorges Dam in the Yangtze River

Chunyan Zhu¹, Yuning Zhang¹, Dirk Sebastiaan van Maren^{1,2,3}, Weiming Xie¹, Leicheng Guo¹, Xianye Wang¹ and Qing He^{1*}

Abstract

The sediment load in the Yangtze River downstream of the Three Gorges Dam (TGD) has substantially declined in recent decades. The decrease is more profound below the TGD, e.g., a 97% decrease at Yichang, compared with that at the delta apex, 1200 km downstream, e.g., a 75% decrease, implying along-river sediment recovery. Two large river-connected lakes, i.e., Dongting and Poyang Lakes, may play a role in the re-establishment of the river's morphodynamic equilibrium, but a quantitative data-based understanding of this interaction is not yet available. In this work, we collected a series of field data to quantify the sediment gain and loss in the river-lake system in the middle-lower Yangtze River, and evaluate the lake's response to the reduction in riverine sediment supply. We find that Dongting Lake and Poyang Lake shifted from net sedimentation to erosion in 2006 and 2000, and back to a sedimentation regime again after 2017 and 2018, respectively. Natural morphodynamic adaptation and sand mining play an important role in the regime changes in the Dongting Lake whereas sand mining dominates the abrupt changes in the Poyang Lake. The Dongting and Poyang Lake contributed maximum by 38% (2015) and 17% (2006) (respectively) to the sediment recovery in the erosion regime, whereas the riverbed erosion dominates the main sediment source. These changes in the relative contribution of sediment sources also indicates a response time of ~20 years in the lakes towards a new equilibrium state. It is noteworthy that the lakes' buffer effects may be overestimated as the supplied sediment from the lakes is rather small compared to the significant dam trapping in the upstream basin and sediment source from downstream degradation. The results imply that river management and restoration should take into account of the river-lake interactions and feedback impact at decadal time scales.

Highlights

- Two lakes provided a sediment buffer to the declining sediment load of the Yangtze River for a 20-year period.
- The Dongting Lake has shifted from sink to source in 2006 due to both natural and human-driven morphological adaptation.
- The Poyang Lake has shifted from sink to source in 2000, mainly because of sand mining.

Keywords Sediment supply, Middle-lower Yangtze River, Dongting Lake, Poyang Lake, Three gorges dam

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1 Introduction

Sediment transport in alluvial rivers is critical to the morphodynamic changes in the channels, lakes, estuaries and deltas (Milliman and Syvitski, 1992; Syvitski et al., 2005, 2022). Worldwide rivers are experiencing a reduction in sediment supply by over 50% on average in the past decades (Syvitski et al., 2005; Besset et al., 2019; Li et al., 2020). The reduced riverine sediment supply will inevitably influence the morphology in the river and estuaries, and therefore it is essential to better understand its morphological impact on downstream reaches. The Yangtze River is the longest river in China (around 6300 km), which is usually divided into the upper, middle, lower reaches and its estuary with section boundaries at Yichang, Hukou, and Datong with a distance of 4500, 955, 338 and 600 km, respectively. The sediment load in the Yangtze River has been decreased gradually since the mid-1980s and accelerated to the present-day reduction by ~75% due to the Three Gorges Dam (Yang et al., 2011; Zhu et al., 2019; Guo et al., 2021). The morphodynamic responses to reduced sediment supply in river and estuaries have attracted much attention.

One of the great concerns is that the morphodynamic adaptation of the river-estuary system is controlled by several buffers, leading to time lags in response to human interventions. Such time lags introduce uncertainties in the overall period that the system requires to adapt to major interventions (such as the Three Gorges Dam). Previous studies have found that reduced sediment supply leads to channel degradation in the downstream Yangtze River and the upper estuary. In contrast, the mouth zone of the Yangtze Estuary sustained accretion and high suspended sediment concentration (SSC) for a long term, thus triggering studies exploring the mechanisms behind the limited impact on downstream SSC (Zhu et al., 2019, 2021a, b; Guo et al., 2021; Lin et al., 2021). The upstream 1893-km long riverbed becomes a sediment source, which is evidenced by channel degradation in the middle-lower reaches and the upper estuary (Wang et al., 2013; Zhou et al., 2016, 2019; Luo et al., 2017; Gao et al., 2018). Moreover, sediment has been coarsened and the organic content has been changed due to channel degradation in the riverbed (Guo and He, 2011; Bao et al., 2014). Thus far, the buffer effects are mainly focused on the main channel of the Yangtze river and its estuary. However, the lakes in the river basin are also suggested to exchange river and sediment discharges with the channel in a magnitude similar to or even larger than the mainstream (Griffiths and Topping, 2017); however, the buffer effects of lakes are less known.

The 1293-km long reach between Yichang and Datong in the Yangtze River is connected with the Dongting and Poyang Lakes. These river-connected lakes can store

and regulate river floods as well as sediment (Hooke, 2003; Croke et al., 2013; Leibowitz et al., 2018). For the Dongting and Poyang Lakes, many studies have investigated the basin-scale sediment regime and river-lake interaction in the middle-lower Yangtze River under the impacts of both climate change and human interferences (Yin et al., 2007; Nakayama and Watanabe, 2008; Dai and Lu, 2014; Tian et al., 2017). However, knowledge on the buffer effects of the lakes in response to reduced sediment supply is still inconsistent. Not knowing the role of the lakes on providing sediments to the main channel of the Yangtze river implies that it is difficult to quantify the total impact of the TGD, but also the timing when maximal impact will be achieved. For instance, Dai et al. (2005) and Chen et al. (2008) documented that the effect of lakes on sediment flux in the Yangtze River has decreased since the closure of the Three Gorges Dam (TGD) and would be further reduced. In contrast, Yang et al. (2007) found that the sediment from the lakes and riverbed erosion keeps the sediment load in the Yangtze River maintained high at ~100 Mt/yr. Moreover, previous studies mainly evaluated the changes in water and sediment discharges either in the Dongting or Poyang Lake (Zhang et al., 2012; Lai et al., 2014; Mei et al., 2015). However, an integral water and sediment budget of the Yangtze River and its lakes requires simultaneous analysis of the responses of both lakes and the Yangtze River.

In this study, we collected a series of water and sediment discharges in the middle-lower Yangtze River and main tributaries to evaluate the response of the river-lake system to reduced sediment supply in the middle-lower Yangtze River (Yichang-Datong). Section 2 introduces the Yangtze river-lake system and the data and methods. Section 3 evaluates the decadal changes in river and sediment discharges followed by the sediment budget and the sediment source contributions. The uncertainties and the buffer effects of the response in the two lakes are discussed in Section 4 whereas Section 5 summarizes the main findings.

2 Study area

2.1 Yangtze River-Lake system

The middle-lower Yangtze River in this study refers to the reach between Yichang and Datong which is 1293 km in length with a drainage area around 0.8 million km² (Fig. 1). Since the 1950s, more than 52,000 dams (until 2016) have been built in the Yangtze River basin, with a total storage capacity of 360 billion m³, accounting for one third of the annual streamflow from the Yangtze River to the sea. The largest dam, the TGD, was built in 2003 and has a storage capacity of ~40 billion m³. The large amount of dam construction has strongly reduced sediment supply to the middle-lower Yangtze River.

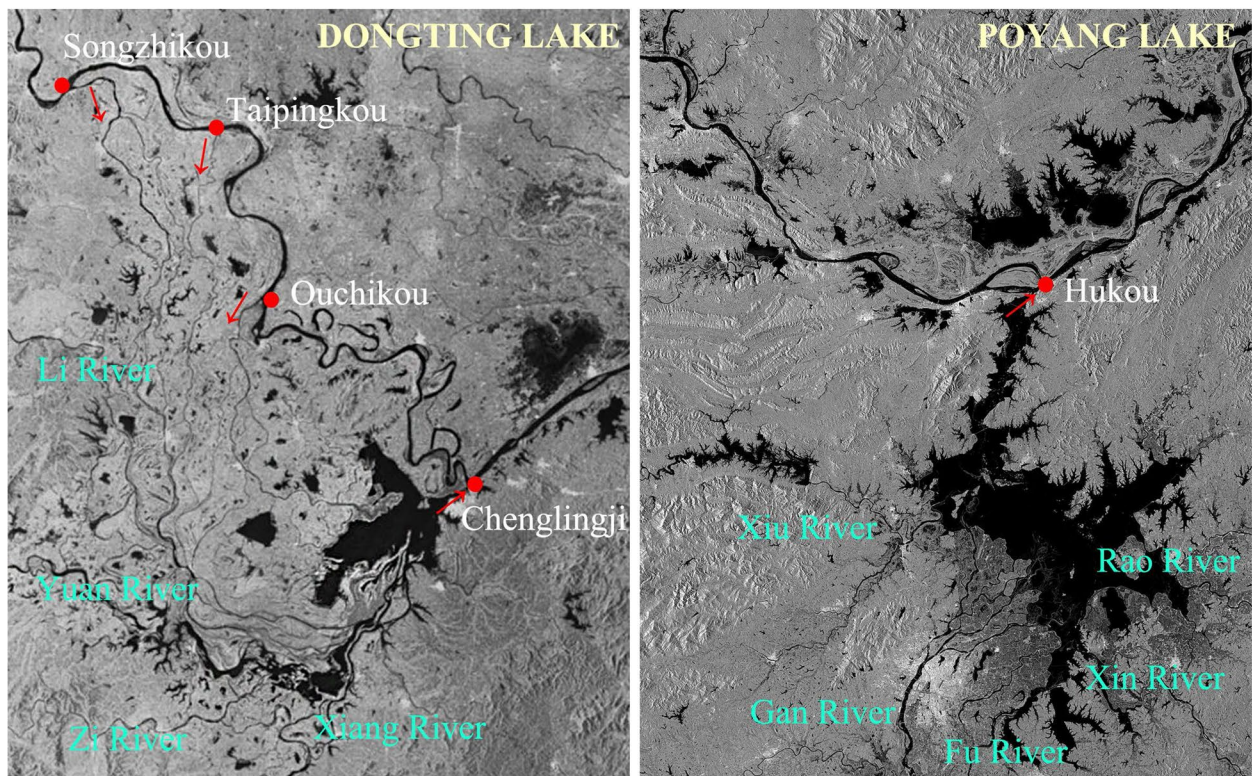
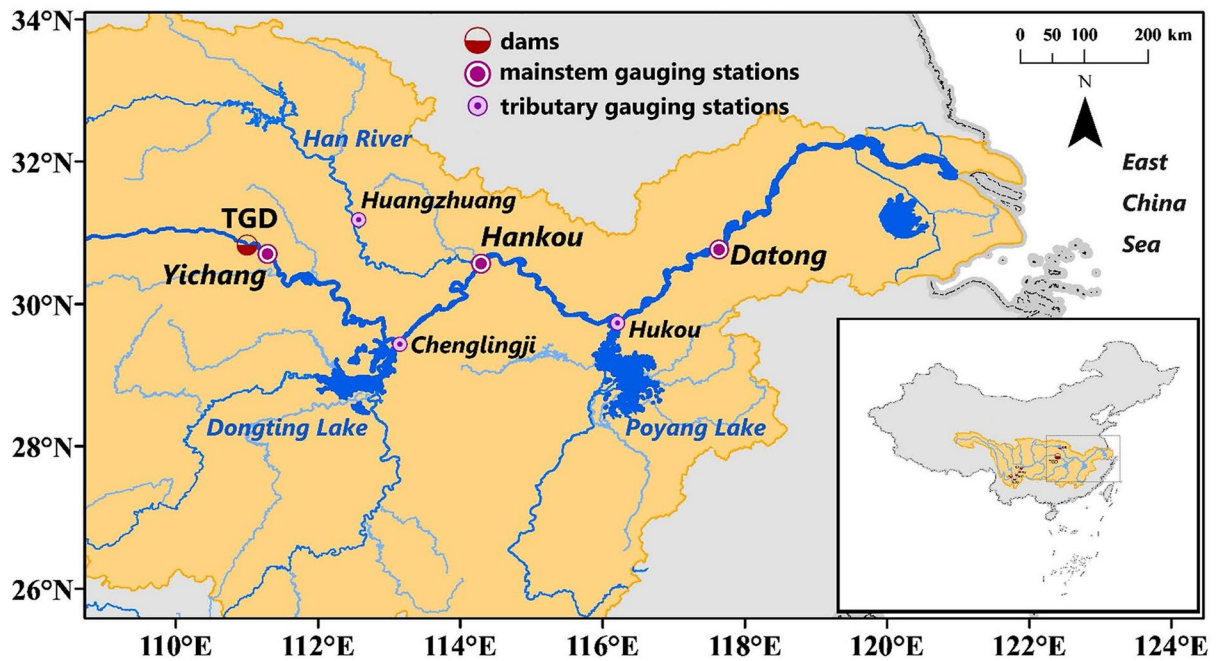


Fig. 1 Location of the hydrologic stations in the middle-lower Yangtze River, Dongting Lake and Poyang Lake

Within the middle-lower Yangtze River, there is a complicated river-lake system with three main tributaries, i.e., Han River, Dongting Lake and Poyang Lake. The Han River is the largest tributary (1577 km long)

exchanging water and sediment with the Yangtze River (Hankou gauging station). The main gauging station in Han tributary is at Huangzhuang. Since the operation of the Danjiangkou Dam in 1986 in the Han River, sediment

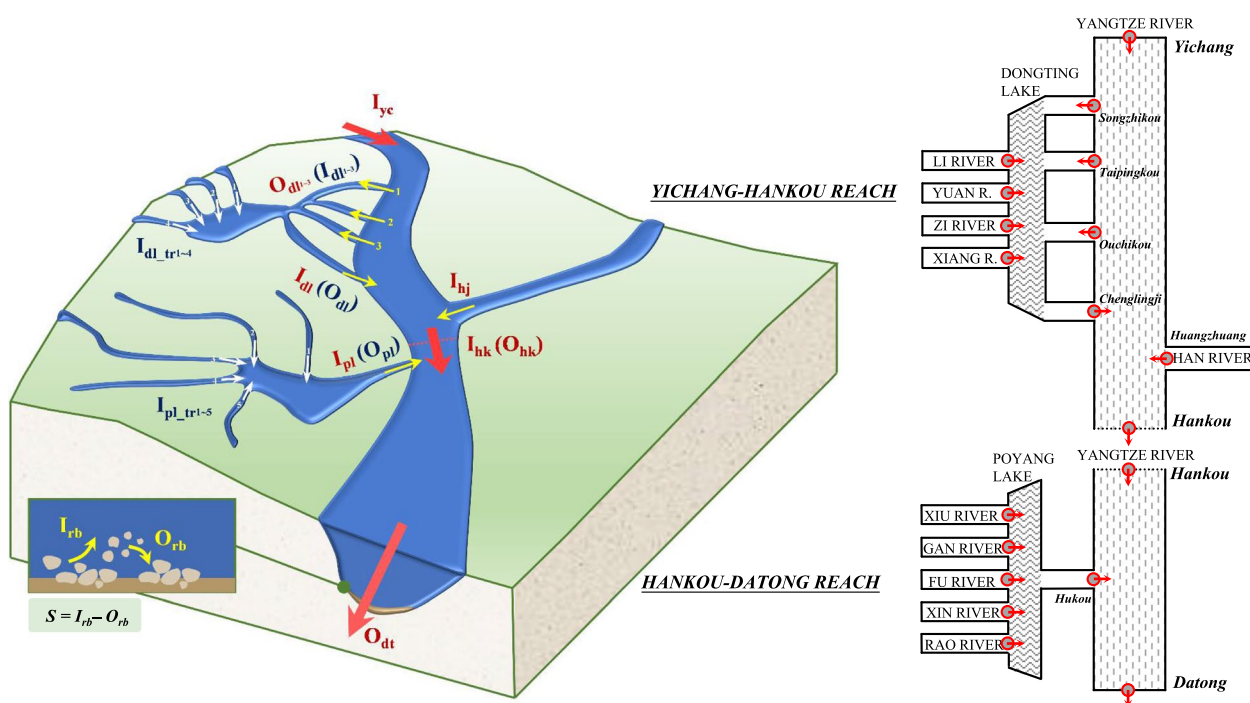


Fig. 2 A sketch showing the box model of sediment budget in the middle-lower Yangtze River

discharge has been reduced by >80%, shifting the Han River from a high to low turbidity state. Dongting Lake, the second largest freshwater lake in China (with an area of approximately 2600 km² during the summer high water), is connected with the Yangtze River via four connections, i.e., Songzikou, Taipingkou, Ouchikou, and Chenglingji channel. The first three (Songzikou, Taipingkou, Ouchikou) are inlets (with water and sediment flowing from the Yangtze River to Dongting Lake) whereas water and sediment flows back into the Yangtze River via Chenglingji channel. Four other small rivers (Yuan, Li, Zi and Xiang Rivers) supply water and sediment to the Dongting Lake. Poyang Lake is the largest freshwater lake in China (with an area of approximately 4000 km² during the summer high water) and receives water and sediment from five main rivers (Gan, Fu, Xin, Xiu and Rao Rivers) and exchanges water and sediment with the Yangtze River through a single channel joining at Hukou. The averaged water depth in both lakes is approximately 5 m with the maximum depth over 20 m. The depth of Poyang Lake varies greatly throughout the year, with an interannual difference up to 13 m.

2.2 Data and methods

We analysed yearly water discharge and suspended sediment load at Yichang, Hankou and Datong stations in the middle-lower Yangtze River and at the confluences

of Dongting Lake (three inlets and Chenglingji), Poyang Lake (Hukou), and Han River (Huangzhuang) between 1960 and 2019.

The sediment source and sink pattern between the lakes and the middle-lower is evaluated with a sediment budget method (Walling and Collins, 2008; Parsons, 2012). The segment sediment budget consists of three components: input (*I*), output (*O*) and storage (*S*). We evaluated the sediment budget in the Yichang-Hankou and Hankou-Datong Reaches and two lakes using the following formulations (Fig. 2):

$$\begin{aligned} \text{Reach} & \qquad \qquad \qquad \text{Yichang-Hankou:} \\ (I_{yc} + I_{dl} + I_{hj}) - (O_{dl^{1-3}} + O_{hk}) &= S \\ \text{Reach Hankou-Datong: } (I_{hk} + I_{pl}) - O_{dt} &= S \\ \text{Dongting Lake: } (I_{dl_{tr^{1-4}}} + I_{dl^{1-3}}) - O_{dl} &= S \\ \text{Poyang Lake: } I_{pl_{tr^{1-5}}} - O_{pl} &= S \end{aligned}$$

Where *I_{yc}*, *I_{dl}*, *I_{hj}*, *I_{hk}*, *I_{pl}* are the discharges at Yichang, Chenglingji, Huangzhuang, Hankou, and Hukou stations, respectively. *O_{hk}*, *O_{dt}*, *O_{dl}*, *O_{pl}* are the discharges at Hankou, Datong, Chenglingji, and Hukou stations, respectively. *O_{dl¹⁻³}* and *I_{dl¹⁻³}* are the same, representing the discharges from the mainstream to Dongting Lake. *I_{dl_{tr¹⁻⁴}}* and *I_{pl_{tr¹⁻⁵}}* are the discharges from 4 tributaries into Dongting Lake and from 5 tributaries into Poyang Lake, respectively. The storage (*S*) indicates the net deposition and erosion in the specified reaches and lakes. We also introduced the *O* to *I* ratio to indicate the change rate of the sediment deficit (*S* < 0) and surplus (*S* > 0).

Note that errors may occur because of limited data on bank collapse, sand mining, and ungauged tributaries; however, these uncertainties are regarded as acceptable. Bank collapse was frequently detected between Dongting Lake and the mainstream but later mitigated by the construction of dikes and levees (Xia et al., 2016). This methodology ignores sand mining (large-scale removal of sediment from the lakes). However, while sand mining was executed on a large scale in the 1990's it decreased after it was made illegal in 2001. The ungauged tributaries accounts for less than 5% of the sediment load of this river basin, which has been evaluated for the effects to be small in the middle-lower Yangtze River (Xu and Milliman, 2009).

3 Results

3.1 Decadal changes in river and sediment discharge

The river and sediment discharges of the mainstream Yangtze River changed markedly different over time in the period 1960 to 2019 (Fig. 3). The river discharges do not increase or decrease over time, but inflow from tributaries results in a downstream increase of the mean river discharges at Yichang, Hankou and Datong of 428, 702, and 888 m³/s, respectively. In contrast, the suspended sediment load is overall decreasing since 1965 and accelerated after 2003. The mean sediment loads are

485, 396, and 419 Mt before 2003 and 34, 97, and 132 Mt after 2003 at Yichang, Hankou, and Datong, respectively. Therefore, the mean sediment load has decreased by 93%, 76% and 68% from 1960 to 2002 to 2003–2019 at Yichang, Hankou, and Datong, respectively. The observation that the station immediately downstream of the TGD (Yichang) has a larger reduction in sediment load than stations further downstream is proof of sediment recovery in the downstream direction. In addition, before 2003 the sediment load at the upstream station Yichang is 18% larger than that at the downstream station Hankou whereas after 2003 the sediment load at Yichang is 65% smaller than that at Hankou. This suggests that the reach Yichang-Hankou shifted from accretion to strong erosion around 2003.

The river and sediment discharges at the inlet and outlet of Dongting Lake and Poyang Lake vary in time (Fig. 4). At Dongting Lake, the river inflow from the Yangtze is decreasing and as discharge from the tributaries remains relatively stable, the outflow at Chenglingji is also decreasing since 1960 (Fig. 4a). Therefore, the exchange of water between the Yangtze River and Dongting Lake progressively decreases from 1960 to 2019. The main sediment source of Dongting Lake is the Yangtze, which is approximately 5 times larger than the combined sediment load of the

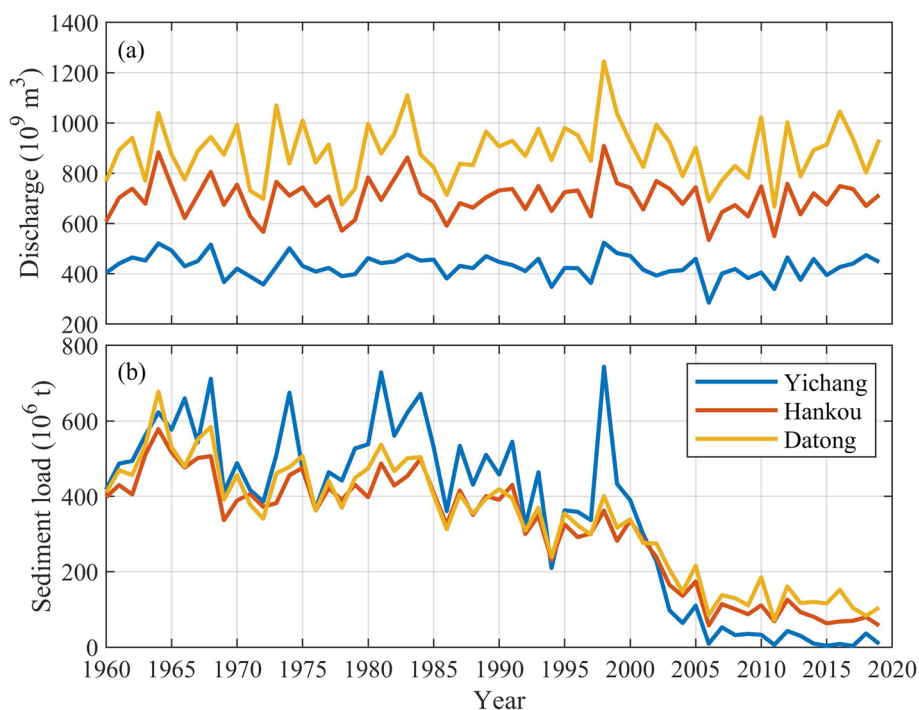


Fig. 3 Annual river discharge **a** and suspended sediment load **b** measured at Yichang (the gauging station immediately downstream of the Three Gorges Dam), Hankou and Datong (the most downstream gauging station) between 1960 and 2016

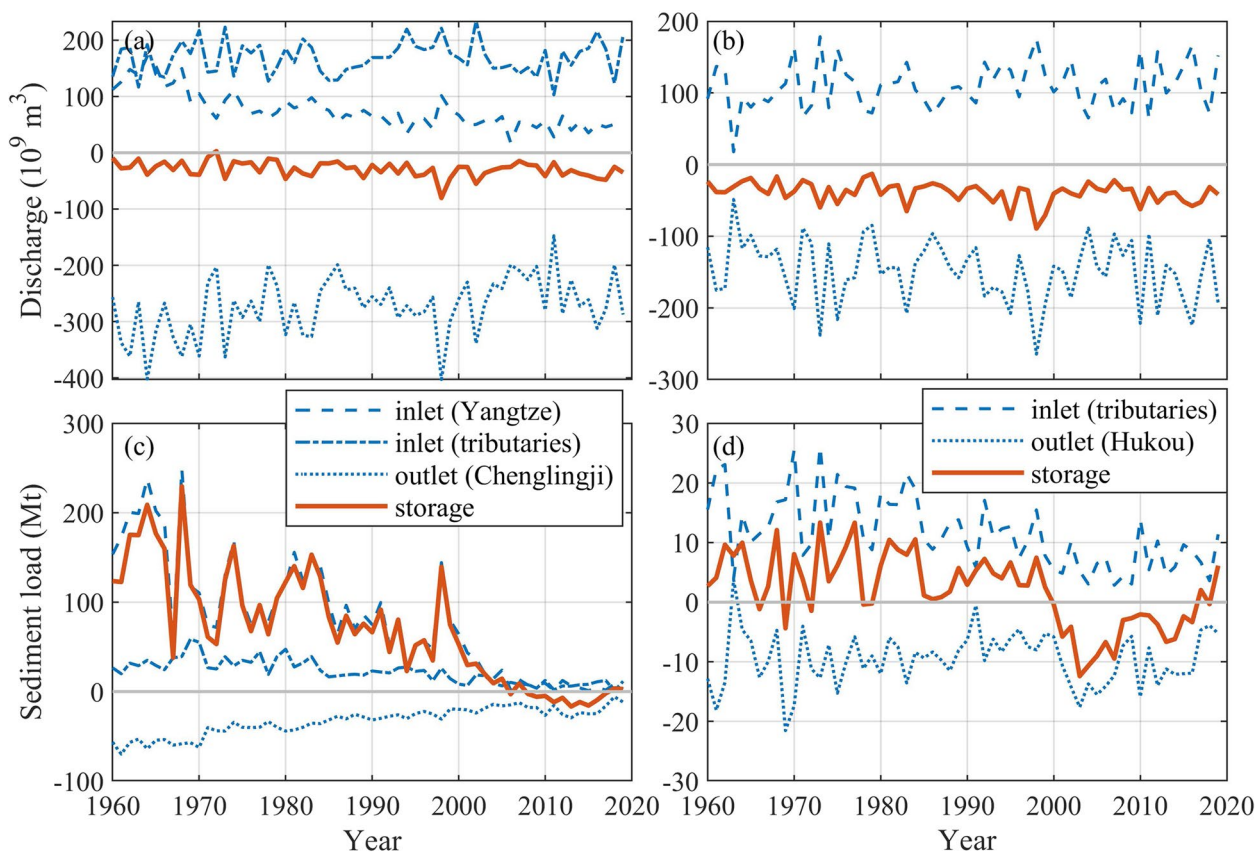


Fig. 4 Annual river discharge **a, b** and suspended sediment load **c, d** at the inlets, outlet and the storage ('inlet-outlet') of the Dongting Lake **a, b** and Poyang Lake **b, d**. The storage is the difference of the river/sediment discharges from the inlets and outlets of the lakes. Positive value means more discharges flow into the lake whereas negative means more discharges flow out of the lake

tributaries (Fig. 4c). However, along with the decreasing sediment supply from the Yangtze and tributaries into Dongting Lake, the sediment discharge from Dongting Lake to the Yangtze is also decreasing. But because the influx decrease more than the outflux, the sediment balance suggests that Dongting Lake shifted from sedimentation to erosion after 2007. This trend reverted to minor sedimentation after 2018.

At Poyang Lake, the river inflow from the tributaries remains stable while the outflow to the Yangtze at Hukou station increases slightly (Fig. 4b). Therefore, the discharge storage at the Poyang Lake decreases. Note that both the Dongting and Poyang Lake keep supplying similar amounts of river flow (30–50 billion m³/yr) to the mainstream channel. The sediment loads into and out of Poyang Lake are also decreasing. However, an abrupt increase in sediment supply at the outlet from the Poyang Lake to the mainstream occurred in 2000, resulting in an apparent shift from sedimentation to erosion after 2000. Since 2018, the Poyang Lake has shifted from erosion to sedimentation. Note that, although both the

Dongting Lake and Poyang Lake supply a similar amount of sediment (~10 Mt/yr) to the mainstream after 2006 and 2000, respectively, much less sediment was annually stored at Poyang Lake than Dongting Lake before erosion started.

3.2 Sediment budget of the river-lake system

A new sediment budget in the middle-lower Yangtze River including the various tributaries and sources sinks is presented before and after 2003 in Fig. 5. The annual mean sediment load at Yichang decreased from 485.4 Mt/yr in 1960–2002 to 34.2 Mt/yr in 2003–2019 (–93%), from 396.3 to 97.1 Mt/yr at Hankou (–75%), from 35.8 to 3.4 Mt/yr at Han River at Huangzhuang (–91%), and from 418.6 to 132.2 Mt/yr at Datong (–68%). At Dongting Lake, the sediment load at the inlets from the Yangtze decreased from 110.4 Mt/yr in 1960–2002 to 8.3 Mt/yr in 2003–2019 (–92%), the sediment load from the tributaries decreased from 27.7 to 8.3 Mt/yr (–70%) whereas the sediment load at the outlet (Chenglingji) decreased from 38.9 to 18.5 Mt/yr (–52%). At Poyang

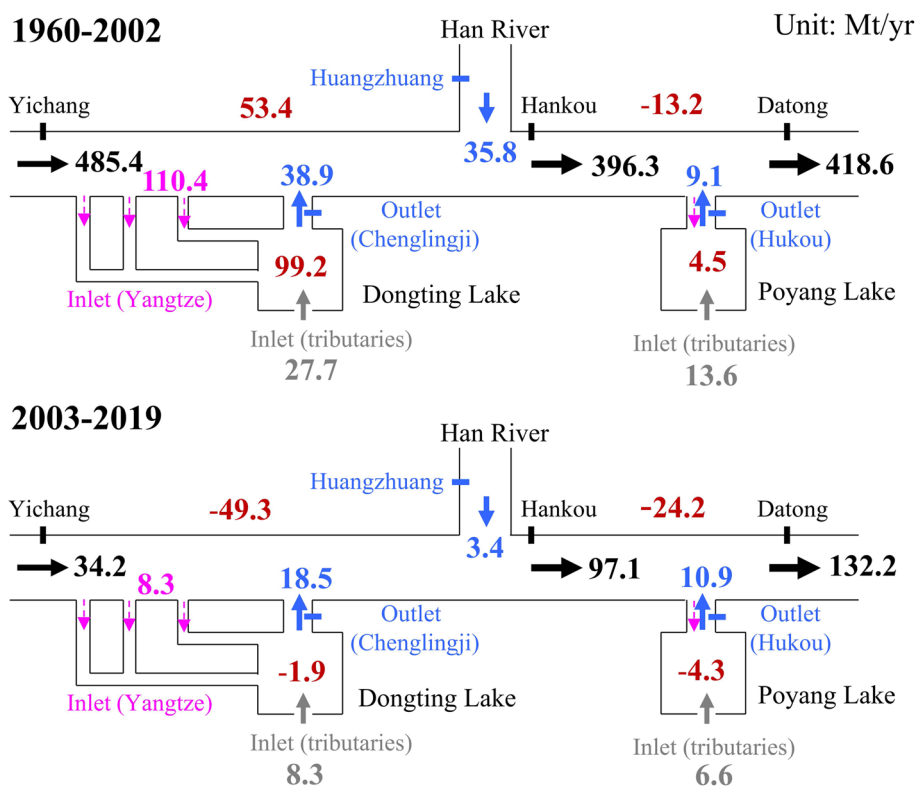


Fig. 5 Sediment budget of the river-lake system from Yichang-Datong in the middle-lower Yangtze River during 1960–2002 and 2003–2019

Lake, even though sediment is temporally transported from the mainstream Yangtze River to the lake (i.e., during a period of rapidly rising water levels resulting from a river flood in the Yangtze), the lake mainly transports sediment towards the Yangtze River. The annual mean total sediment load (‘out-in’) at the outlet (Hukou) increased from 9.1 to 10.9 Mt/yr (+20%). Consequently, according to the sediment mass balance, the reach Yichang-Hankou shifted from 53.4 Mt/yr sedimentation in 1960–2002 to 49.3 Mt/yr erosion in 2003–2019

whereas erosion in the reach Hankou-Datong doubled from 13.2 Mt/yr to 24.2 Mt/yr. The Dongting Lake shifted from strong sedimentation of 99.2 Mt/yr over the period 1960–2002 to slight erosion of 1.9 Mt/yr over the period 2003–2019. Poyang Lake, finally, shifted from 4.5 Mt/yr sedimentation to 4.3 Mt/yr erosion.

The changes in sediment accumulation in the mainstream channel and its two lakes further illustrate sediment accumulation and loss (Fig. 6). Since 1960, the reach Yichang-Hankou, Dongting and Poyang Lake sustained

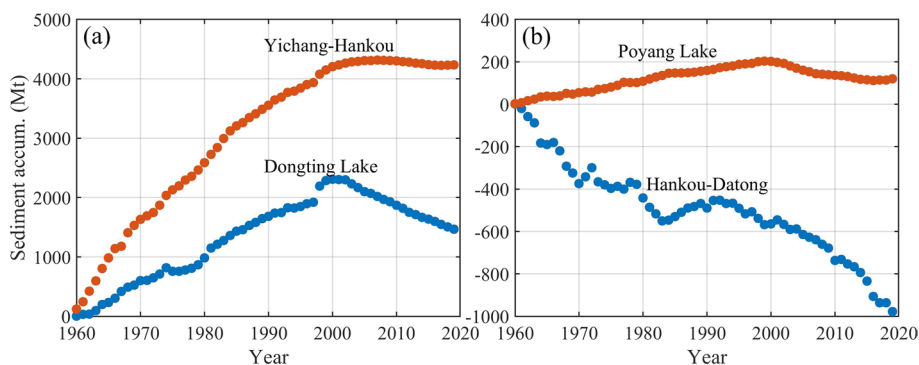


Fig. 6 Changes in sediment accumulation in the **a** reach Yichang-Hankou and Dongting Lake, and **b** reach Hankou-Datong and Poyang Lake from 1960 to 2019

accretion for a long period whereas erosion prevailed along the reach Hankou-Datong. The reach Yichang-Hankou accreted faster (63 Mt/yr) over the period 1981–2000 compared to the period 1960–1980 (49 Mt/yr) followed by a sediment loss after 2000. Meanwhile, the Dongting Lake accreted slower (79 Mt/yr) over the period 1981–2000 compared to the period 1960–1980 (123 Mt/yr). The Dongting Lake shifted from accretion to erosion in 2006, which is later than in the mainstream channel (2000). After 2017, sediment accumulates again in Dongting Lake (2.1 Mt/yr). The reach Hankou-Datong gained sediment over the period 1983–1992 (+6.4 Mt/yr) while it eroded over the period 1960–1982 (−23 Mt/yr) and after 1992 (−26 Mt/yr). Sediment accretion in Poyang Lake decreased from 6.3 and 1.6 Mt/yr over the period 1960–1982 and 1983–1991 and reverted to 3.5 Mt/yr erosion from 1992 to 2016. The shift from accretion to erosion at the Poyang Lake occurred in 2000. Poyang Lakes accumulates sediment again since 2016.

3.3 Contribution of different sediment sources

Although upstream riverine sediment, the river bed, tributaries and the lakes supply sediment to the mainstream Yangtze River, the contributions are quite different between the reaches Yichang-Hankou and Hankou-Datong (Fig. 7). Apparently, the sediment load from the upstream is the main sediment source (>80%) to the reach Yichang-Hankou before 2003, but then then

strongly reduces afterwards. The mean sediment contribution from Han River is 18% during 1960–1968, followed by a strong reduction due to sediment trapping in Danjiangkou reservoir. After 2003, channel erosion contributes to 50% of the sediment supply to the mainstream and increasing over time, reaching its maximum of 75% in 2017. The Dongting Lake started exporting sediment to the mainstream channel since 2006, providing an additional sediment source. The relative importance of sediment from the Dongting Lake was highest in 2015, accounting for 38% of the combined sediment sources. The contribution of Dongting Lake firstly increased and then decreased with the mean contribution of 17% from 2006 to 2019 or 20% concerning no contributions in 2007 and 2018.

In the reach Hankou-Datong, riverbed erosion is the main sediment source although the contribution slightly decreased from 94% in 1960–2000 to 75% in 2001–2019. In contrast, the sediment contribution from the upstream increased from 4% in 1960–2000 to 17% in 2001–2019 with the largest contribution (47.5%) recorded in 2016. The contribution from the Poyang Lake maintained stable (2%) during 1960–2000 whereas the mean contribution reached approximately 8% from 2001 to 2016 and 5% from 2017 to 2019.

The morphodynamic changes of the river-lake system in response to reduced sediment supply can be further analyzed by identifying the relative sediment

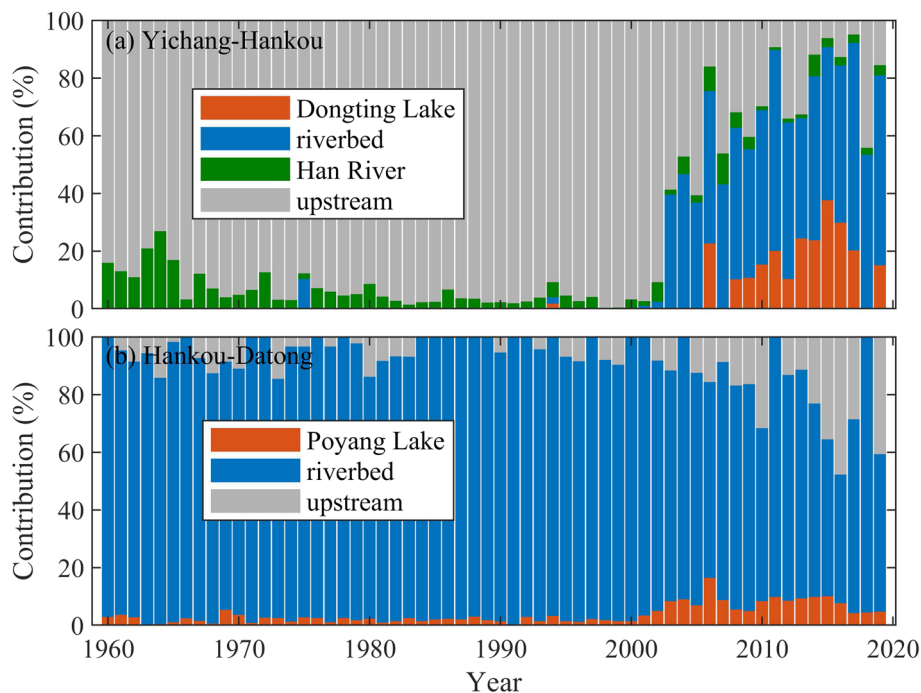


Fig. 7 Relative contribution (%) of sediment sources to the reaches **a** Yichang-Hankou and **b** Hankou-Datong from 1960 to 2019

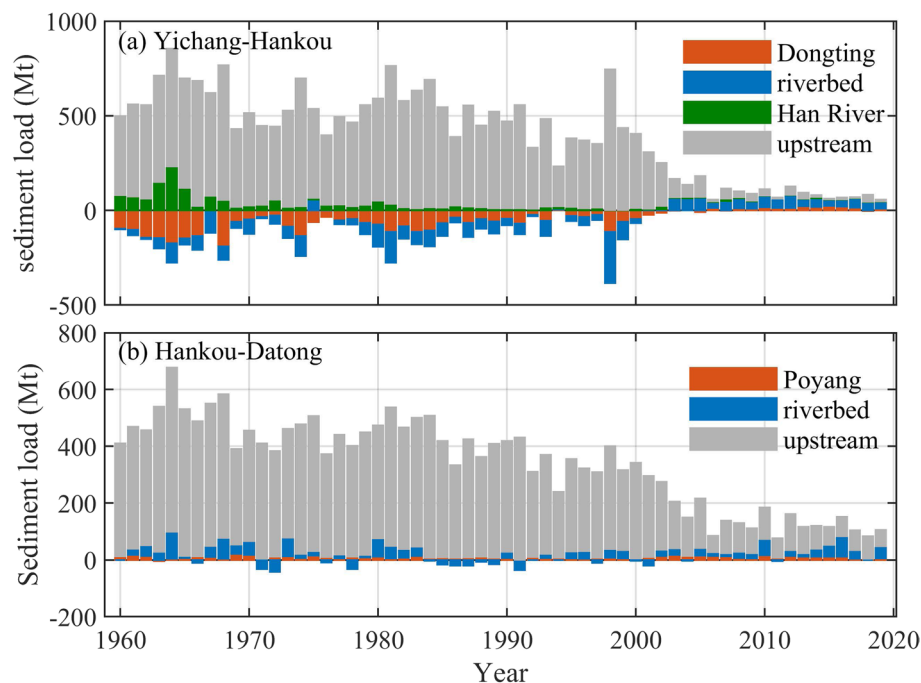


Fig. 8 Changes in exported sediment load from the upstream, riverbed and the lakes to the reach **a** Yichang-Hankou and **b** Hankou-Datong from 1960 to 2019. Positive indicates sediment is exported from the source to the mainstream whereas negative means that sediment is imported from the river to the source

source contribution in absolute numbers (Fig. 8). In the reach Yichang-Hankou, before 2000s, the riverbed and Dongting Lake are the sediment sink with the temporal changes in phase with the upstream sediment supply. After 2000s, the channel degradation and lake erosion supplied sediment with the magnitude of ~ 50 Mt/yr and 10 Mt/yr, respectively. In the reach Hankou-Datong. The channel erosion alternatively occurred in the history and becomes continuous after reduced upstream sediment supply. Sediment from the Poyang Lake supplied similar amount of sediment (~ 10 Mt/yr) no matter before or after reduced sediment supply and this amount is much smaller than that from the upstream and channel degradation.

4 Discussion

4.1 Sand mining

The sediment budget and relative contribution of sediment sources based on gauging data provides a strong indication of the main sediment sources and sinks. Concerning the accuracy, our results suggest that the sediment loads at Yichang and Datong during 2003–2007 are the same as those shown by Le Leeuw et al. (2010), and the sediment loads at Yichang and Hankou during 1998–2019 are the same as those shown by Deng et al. (2022). A relatively larger inconsistency with Le Leeuw et al.

(2010) occurs at the amount of sediment supplied from the tributaries to Poyang Lake, as Le Leeuw et al. (2010) estimated the sediment demand from sand production, not from the measurements. Even though, both studies concluded that there was minor sedimentation at Poyang Lake between 1980 and 2000. Therefore, the calculated sediment budget is reliable to understand the lakes' responses.

However, such a sediment approach has its shortcomings resulting in a number of remaining uncertainties. Firstly, the sediment balance is only based on major tributaries and ignores the non-gauged smaller tributaries. However, the non-gauged tributaries account for less than 5% of the river basin and consequently also the sediment yield is relatively low – this source of uncertainty is therefore limited (Yang et al., 2007, 2014; Xu and Milliman, 2009). Secondly, bank erosion occurs in the middle-lower Yangtze River, particularly in the reach upstream of the outlet of the Dongting Lake (347-km Jingjiang reach). Bank collapse is frequently documented but unfortunately the amount of sediment eroded was not recorded over time (Xia et al., 2016). Recently, Deng et al. (2022) has quantified the relative contribution of bank erosion to the total channel erosion as 18% after the Three Gorges Project.

A third source of uncertainty is sand mining. Sand mining led to a large reduction in available sediment until 2001 after which illegal sand mining in the Yangtze River was brought under control. Afterwards, sand mining was intensive in Poyang (after 2000) and Dongting (after 2006) Lake, leading to severe bed degradation and the reduction of water levels. Sand extraction in Poyang Lake was estimated at approximately 236 million m³/yr (equal to 389 Mt/yr) over the period 2005–2006 (de Leeuw et al., 2010; Lai et al., 2014). Extrapolating this volume of sand over the 3000 km² surface of the Poyang Lake can result in 0.1 m lowering of the entire lakebed on average, which accounts for 4.4% of the lake level decline (Mei et al., 2015). Min et al. (2011) found that sand mining decreased the main watercourse elevation by 2.4 m and increased its width by 96 m from September 1999 to May 2008, enhancing the river and sediment discharge to the Yangtze at the outlet of the lake. Therefore, sand mining dominates the morphological changes and the response of the lake to reduced sediment supply. In the Dongting Lake, previous studies have reported 180–200 ships with a sand mining capacity of 2500 m³/h per ship, with the minimum sand mining as much as 930 Mt/yr in peaks years, which is approximately twice the sediment supply in the mainstream Yangtze River before 2003.

Overall, non-gauged tributaries and bank collapse limitedly influence the sediment balance in the river-lake system whereas sand mining plays an important role and should be carefully considered when interpreting the changes in sediment balance. Future regulation and protection measures may reduce riverbank collapse and sand mining, decreasing these uncertainties.

4.2 Response to reduced sediment supply: Dongting vs. Poyang

The Dongting Lake and Poyang Lake show different changes in sediment import, export and net deposition/ erosion during the period 1960–2019 (Table 1). The Dongting Lake connects to the Yangtze River with 3 inlets and 1 outlet, therefore strongly exchanging water and sediment. From 1960 to 2002 to 2003–2019, with the river discharge at Yichang remaining relatively stable, the river flow from the Yangtze into the lake decreased by 44% whereas the exported river discharge decreased by 15%. As a result of the decreasing net river discharge into Dongting Lake, the size and water volume of the lake decreased from 1960 to 2019 (Fig. 4). Moreover, with the sediment load at Yichang decreasing by 93%, the imported sediment from the Yangtze River into the lake decreased by 92.5% whereas the exported sediment decreased by only 52.4% (Fig. 5). Because of the very large initial sediment surplus, Dongting Lake sustains accretion for a long term but at a certain point starts eroding. Although the sediment from the tributaries is also decreasing (by 27%), the decline in Yangtze sediment influx implies that their contribution to the total lake sediment budget increased from 20% to 50%. Therefore, the tributaries of the Dongting Lake become increasingly important over time in delivering river flow and sediment.

In contrast, the Poyang Lake connects to the Yangtze River with only one outlet. The main sediment source in the Poyang Lake is from the tributaries and Yangtze backflow at the outlet (Hukou station) provides only a minor contribution (Li et al., 2017; Huang et al., 2018). The river and sediment discharges from the Yangtze River are only

Table 1 Comparisons between the Dongting and Poyang Lake

		Dongting Lake	Poyang Lake
Basic info	water surface (km ²)	2600	3700
	volume (10 ⁸ m ³)	165	300
	connect with Yangtze	3 inlets, 1 outlet	1 inlet/outlet
	number of tributaries	4	5
Mean river discharge (10 ⁹ m ³ /yr)	inlet (tributaries)	168.8	109.74
	inlet (Yangtze)	75.31	2.03
	outlet (Yangtze)	273.22	150.6
Mean sediment load (Mt/yr)	inlet (tributaries)	22.2	11.61
	inlet (Yangtze)	81.51	1.3
	outlet (Yangtze)	33.16	11.14
Net accretion/ erosion rate (Mt/yr)	accretion rate	93.65(1960–2005)	5.07(1960–1999)
	erosion rate	6.78(2006–2019)	5.34(2000–2019)
	accretion rate	3.15(2018–2019)	2.61(2017–2019)
Relative contribution	maximum	38%	8%
	average	20%	4%

2% and 10% (respectively) compared to that from the tributaries whereas the river and sediment discharges from Poyang Lake to the Yangtze River are 135% and 86% of the total imported discharges, respectively. Thus, the changes in the river and sediment discharges from the tributaries of the Poyang Lake control the exported discharges. For instance, the river discharges from both the tributaries and the outlet remain stable whereas the sediment discharges from both the tributaries and the outlet are decreasing. Therefore, the Poyang Lake maintains quasi-equilibrium for a long term, e.g., at an accretion rate of 5 Mt/yr before 2000.

Both the Dongting Lake and Poyang Lake shifted from accretion to erosion; however, the transition times are in 2006 and 2000, respectively. The transition from accretion to erosion occurred at the time when the exported sediment from Dongting and Poyang Lake to the Yangtze increased (Fig. 4). The transition from erosion to accretion in recent years is consistent with the increasing trend of the imported sediment from the tributaries of the Dongting and Poyang Lake.

The increased sediment export from the lake to the river is caused by morphological changes in the Yangtze River. Due to the upstream dam construction, especially the operation of the TGD, severe erosion took place downstream of the TGD. Specifically, the same river discharges (10,000–30,000 m³/s) lead to approximately 1–2 m lower water levels in the main channel from 2008 to 2020 at both Yichang and Hankou station (Fig. 9a, b). In contrast, the water level in Dongting Lake under relatively high river discharge conditions (10,000–30,000 m³/s) rises after 2017 (Fig. 9c). This corresponds to the decrease in erosion of Dongting Lake following a period of more intense erosion between 2006 and 2017 (Fig. 4c and Fig. 6c). Note that the same river discharge results in a larger spread of water levels in the lakes than along the main channel, which may be caused by the phasing of the water level relative to the river discharge. Based on the bathymetry maps in 1995, 2003 and 2011, Zhu et al. (2014) found that the mean bed level in Dongting Lake accreted 3.7 cm over the period 1995–2003 to erosion of 10.9 cm over the period 2003–2011,

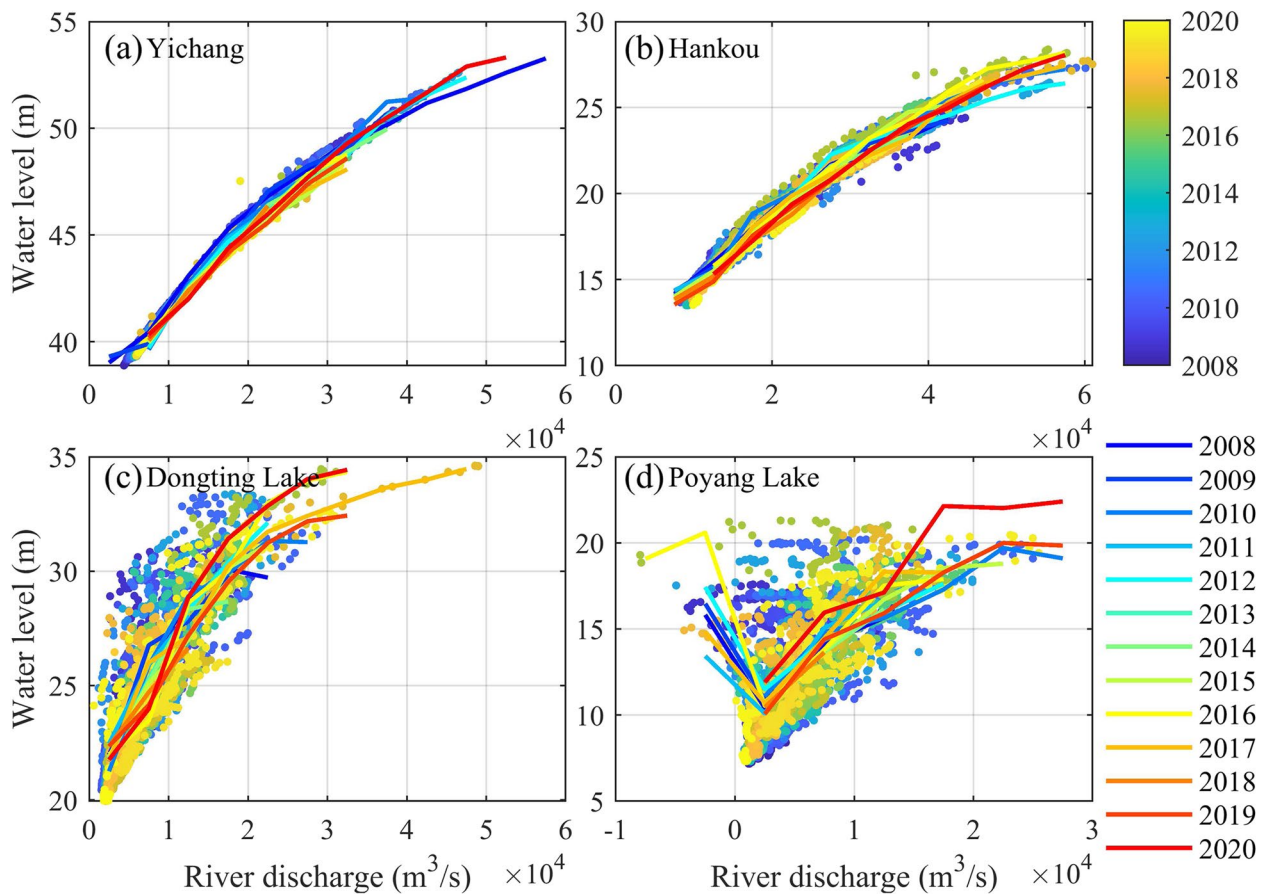


Fig. 9 Relationship between the water level and river discharge at **a** Yichang, **b** Hankou, **c** Chenglingji at Dongting Lake and **d** Hukou at Poyang Lake during 2008–2020. The lines are binned from – 10,000 to 60,000 m³/s in an increment of 5000 m³/s

particularly at the East Dongting Lake. Consequently, the mean water level decreased 0.19–0.4 m at different areas of the Dongting Lake after 2003 (Yang et al., 2016). Nevertheless, the depth of the erosion in the lake is smaller than the water level decline at Yichang, which favors flow from the lake to the channel and therefore sediment export from the lake to the river. In the Poyang Lake, sand mining dominates the response of Poyang Lake after 2000 as discussed in Section 4.1. However, sand mining activities has decreased since 2008 and the erosion is less compared before, resulting in increased water levels especially in recent years (Fig. 9d). This is also consistent with the weakened erosion after 2017–2018 (Fig. 4d and Fig. 6d). Note that the increase in water levels in the lakes due to morphological changes play an important role in reducing channel capacity and therefore increasing flood risks (Nakayama and Shankman, 2013).

4.3 The buffer effect of lakes

The buffer effect of the lakes can be identified from the relative sediment source contribution which indicates the changes in the sediment regime. Before the 1970s, the relative sediment source contribution to the reach Yichang-Hankou from the upstream Yangtze River and the Han River accounts for 85% and 15% (respectively) whereas these two account for 95% and 5% (respectively) in the period 1970–1980. Similarly, the relative sediment source contribution to the reach Hankou-Datong from the upstream, riverbed, and Poyang Lake are 10%, 87%, and 3%, respectively before 1980s. The relative sediment source contribution in these periods was relatively stable, suggesting a quasi-equilibrium state. After 1980, the relative sediment source contribution significantly changed due to the reduced sediment supply. Sediment sources other than the upstream sediment supply dominate the sediment balance in the main channel of the Yangtze River and bed sediments become an important sediment source. Specifically, the riverbed erosion increases since 2000 and becomes the main sediment source accounting for >50% of the total sediment load. Meanwhile, the relative sediment source contributions from the Dongting and Poyang Lake increase from 2000s onwards, peaking at 38% and 17% (respectively) and then decrease until 2019 (Fig. 7). This suggests that the buffer effects of the lakes last for ~20 years and a new quasi-equilibrium state of the lakes is expected in the near future. This morphological response time is shorter than that in the mouth zone of the Yangtze Estuary (~30 years) (Zhu et al., 2019).

However, the buffer effect of the lakes may be overestimated in magnitude of the contribution if only interpreting from the relative sediment source contribution. From 1960 to 2002 to 2003–2019, in the Dongting

Lake, the sediment imported from the mainstream decreased from 110.4 Mt/yr to 8.3 Mt/yr whereas the exported sediment decreased from 38.9 Mt/yr to 18.5 Mt/yr (Fig. 5). Therefore, although the Dongting Lake shifted from sedimentation to erosion, the sediment export to the Yangtze River at the outlet (Chenglingji) decreased. In contrast, in the Poyang Lake, although the incoming sediment from the tributaries decreased from 13.6 Mt/yr to 6.6 Mt/yr, the exported sediment at the outlet (Hukou) to the Yangtze River increased from 9.1 Mt/yr to 10.9 Mt/yr. Therefore, it seems that Poyang Lake now exports more sediment than Dongting Lake in response to reduced sediment supply. However, the increase in export from Poyang Lake probably results from sand mining rather than morphodynamic adaptations, as suggested by the speed at which export changes. At Dongting lake, the export reduces gradually (Fig. 4c, reflecting morphodynamic adaptations and gradual reduction in sediment supply) whereas the sediment export at Poyang Lake rises abruptly (see Fig. 4d and Section 4.2).

5 Conclusions

Two large lakes connecting with the Yangtze River, Dongting and Poyang Lake, have changed sediment regime in response to a reduced fluvial sediment load in the mainstream river. We quantified the contribution of the lakes to the sediment budget of the Yangtze River based on field data from 1960 to 2019. Our results suggest that both lakes first shifted from sedimentation to erosion, but reverted back to accretion (or very little erosion) around 20 years later. The Dongting Lake changed from net sedimentation to erosion in 2006, and back to sedimentation in 2018. The Poyang Lake changed from net sedimentation to erosion in 2000, and then to sedimentation again in 2017. The morphological responses in the Dongting Lake are influenced by both the morphological adaptation due to the changes in water level gradient as well as sand mining. The shift from source to sink in 2000 in the Poyang Lake is strongly controlled by sand mining which enhances the sediment exported from the lake to the mainstream.

We quantified the buffer effects of Dongting and Poyang Lake to sediment load recovery in the Yangtze River accounting for 38% and 17%, respectively. The relative contribution of these two lakes to the total sediment budget of the Yangtze River increased since 2000s, but decrease again in recent years. This suggests that the response time of both lakes to the large sediment reduction of the Yangtze River because of TGD is approximately 20 years, and appears to be approaching a new morphological equilibrium.

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Authors' contributions

Study conception and design were conducted by Qing He. Material preparation and data collection were performed by Chunyan Zhu, Yuning Zhang, Weiming Xie, Leicheng Guo and Xianye Wang. The first draft of the manuscript was written by Chunyan Zhu, Yuning Zhang and Dirk Sebastiaan van Maren. All authors commented on previous versions of the manuscript. The authors read and approved the final manuscript.

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Availability of data and materials

The data used in this work are publicly available on Bulletin of China River Sediment (<http://www.cjh.com.cn>).

Declarations

Competing interests

The authors declare no competing interests.

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