Global and Planetary Change 162 (2018) 8–17

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Human impacts on sediment in the Yangtze River: A review and new perspectives

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ARTICLE INFO

Editor: Dr. T.M. Cronin

Keywords:
Sediment
Grain size
Yangtze River (Changjiang)
Three Gorges Dam
Human impacts

ABSTRACT

Changes in riverine suspended and riverbed sediments have environmental, ecological and social implications. Here, we provide a holistic review of water and sediment transport and examine the human impacts on the flux, concentration and size of sediment in the Yangtze River in recent decades. We find that most of the fluvial sediment has been trapped in reservoirs, except for the finest portion. Furthermore, soil-conservation since the 1990s has reduced sediment yield. From 1956-1968 (pre-dam period) to 2013–2015 (post-dams and soil-conservation), the sediment discharge from the sub-basins decreased by 91%; in the main river, the sediment flux decreased by 99% at Xiangjiaba (upper reach), 97% at Yichang (transition between upper and middle reaches), 83% at Hankou (middle reach), and 77% at Datong (tidal limit). Because the water discharge was minimally impacted, the suspended sediment concentration decreased to the same extent as the sediment flux. Active erosion of the riverbed and coarsening of surficial sediments were observed in the middle and lower reaches. Fining of suspended sediments was identified along the river, which was counteracted by downstream erosion. Along the 700-km-long Three Gorges Reservoir, which retained 80% of the sediment from upstream, the riverbed gravel or rock was buried by mud because of sedimentation after impoundment. Along with these temporal variations, the striking spatial patterns of riverine suspended and riverbed sediments that were previously exhibited in this large basin were destroyed or reversed. Therefore, we conclude that the human impacts on sediment in the Yangtze River are strong and systematic.

1. Introduction

Sediment is an important element in rivers and their connecting waters. The sediment flux determines the deposition rate in a delta, thereby affecting its fate in the face of sea level rise (Giosan et al., 2014). The suspended sediment concentration (SSC) plays a key role in determining sunlight penetration and water quality (Stefan et al., 1983; Bilotta and Brazier, 2008). The grain size of sediments in hydro-environments also has major implications for ecology, geomorphology and engineering (Etter and Grassle, 1992; Xu et al., 2012).

Rivers are increasingly affected by human activities such as dam construction, soil conservation, water diversion and sand mining (Syvitski et al., 2005; Tessler et al., 2015). In many rivers, including the Mississippi, Yellow, Indus, Orange, Yenisei, Chao Phraya, Volta, Song Hong and Krishna Rivers, sediment fluxes have declined by 60–90% over recent decades (Walling, 2006; Milliman and Farnsworth, 2011). In extreme examples, such as the Nile, Ebro, Colorado and Yisil Irmak Rivers, sediment fluxes have decreased to almost nothing (Vörömarty et al., 2003; Milliman and Farnsworth, 2011). In response to this sediment starvation, the effect of subsidence becomes increasingly evident and many deltas have experienced increased erosion (e.g., Wiegel, 1996; Chu et al., 2006; Blum and Roberts, 2009; Giosan et al., 2014). Despite the many studies of anthropogenic changes in the flux of fluvial sediments, less is known about the human impacts on the SSC and the grain size of suspended and riverbed sediments. There is a need to understand human-induced systematic changes in riverine sediment properties (e.g., flux, concentration, grain size and deposition/erosion).

The Yangtze River (Fig. 1) is an ideal site for studying human impacts on fluvial sediment because of the river's rapid socio-economic development over the past four decades and the availability of

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https://doi.org/10.1016/j.gloplacha.2018.01.001
Received 17 October 2017; Received in revised form 27 December 2017; Accepted 2 January 2018
Available online 05 January 2018

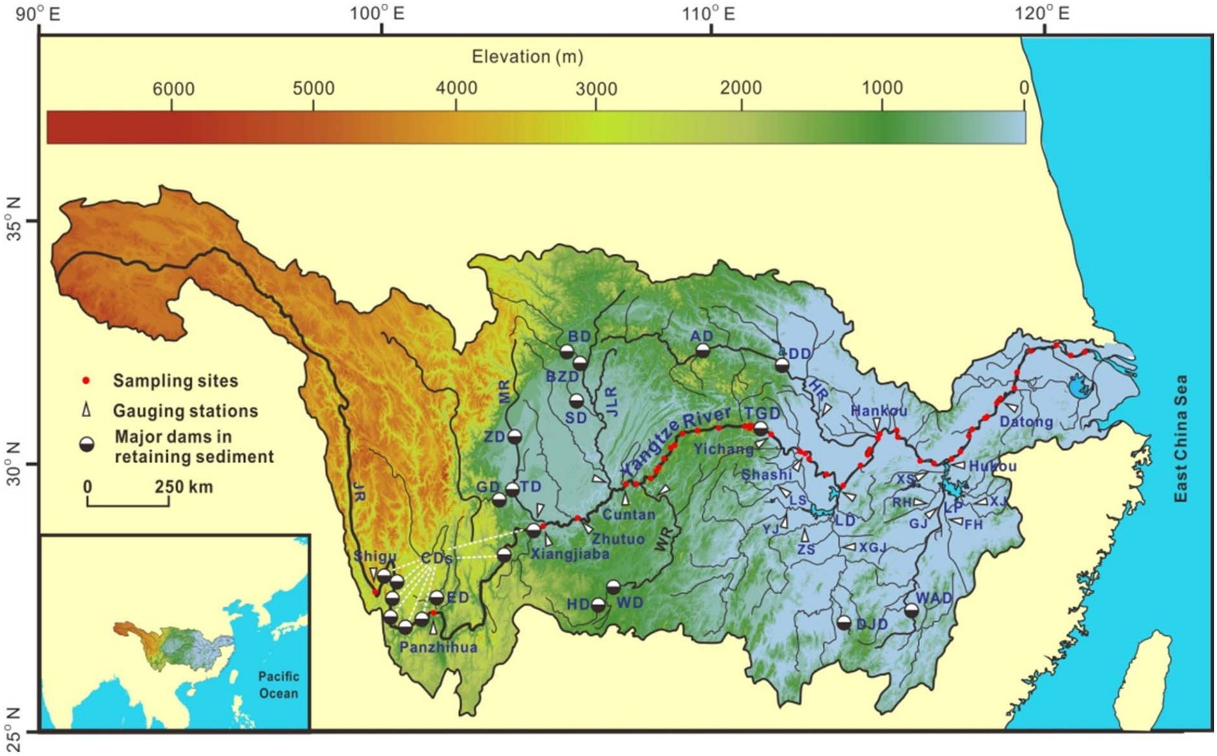


Fig. 1. Sketch map of the study area showing the sediment sampling sites (red dots), gauging stations (white triangles) and super reservoirs (circles). JR: Jinshajiang River; MR: Minjiang River; JLR: Jialingjiang River; HR: Hanjiang River; WR: Wujiang River; LD: Lake Dongting; LP: Lake Poyang; DD: Danjiangkou Dam; TGD: Three Gorges Dam; AD: Ankang Dam; GD: Gongzui Dam; TD: Tongjiezi Dam; ZD: Zipingpu Dam; BD: Bikou Dam; SD: Shengzhong Dam; BZD: Baozhusi Dam; WD: Wujiangdu Dam; HD: Hongjiadu Dam; ED: Ertan Dam; DJD: Dongjiang Dam; WAD: Wanan Dam; CDs: Cascade Dams; LS: Lishui; YJ: Yuanjiang; ZS: Zishui; XGJ: Xiangjiang; XS: Xiushui; RH: Raohe; GJ: Ganjiang; FH: Fuhe; XJ: Xinjiang. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

extensive data. Over the past 15 years, many studies have investigated the anthropogenic changes in Yangtze sediment discharge (e.g., Yang et al., 2002; Yang et al., 2006; Zhang et al., 2006; Chen et al., 2008; Dai and Liu, 2013; Dai and Lu, 2014). However, previous research has not incorporated the changes after 2012, when cascade reservoirs began to operate in the Jinshajiang River, the main sediment source of the Yangtze. As in other rivers, little is known of the human impacts on the SSC and grain size in the Yangtze River. Although the temporal changes in the SSC at Datong (tidal limit of the Yangtze) between 1956 and 2013 have recently been reported (Dai et al., 2016), the changes in the SSC remain unknown both for most of the main river and for the tributaries of the Yangtze. The human impacts on the sediment grain size are also undetermined for most of the Yangtze River, despite the sediment coarsening that has been identified immediately downstream of the Three Gorges Dam (TGD) (Luo et al., 2012). In this study, we provide a holistic review of water and sediment transport in the Yangtze basin and examine the systematic human impacts on sediment (flux, concentration, grain size, channel deposition/erosion) of the Yangtze River at the basin scale between 1956 and 2015 with newly updated data. In addition, the last sediment source, the Jinshajiang River which contributes an average of ~234 Mt/yr sediments to the main river between 1956 and 2012, now has been retained by large dams and the sediment flux has decreased by > 99% since 2013 (MWRC, 2013). Therefore, our results can represent the maximum impact on sediment resulting from human activities in the Yangtze River in some respects.

2. Study area

The Yangtze River originates on the Qinghai-Tibet Plateau 5100 m above sea level, and flows eastward to the East China Sea (Fig. 1). Among global large rivers, the Yangtze ranks first in population (450 million people), 12th in basin size (1800,000 km^2), 3rd in length (6300 km), 5th in water discharge (900 km^3/yr), and 4th in sediment flux (470 Mt/yr before dams) (Milliman and Farnsworth, 2011; Yang et al., 2015). The Yangtze basin is characterized by a subtropical, warm and wet climate. The basin-wide precipitation average is ca. 1050 mm/yr. Approximately half of the precipitation is lost to evaporation (Jiang et al., 2007). The Yangtze Basin consists of seven major sub-basins with variable climatic and hydrological conditions (Table S1): the Jinshajiang, Minjiang, Jialingjiang, Hanjiang and Wujiang Rivers and Lakes Dongting and Poyang (Fig. 1). Precipitation is lower in the northern and western regions compared to the southern and eastern regions, ranging from 730 mm/yr in the Jinshajiang basin to 1560 mm/yr in the Lake Poyang basin (Table S1). The upper reaches of the Yangtze are generally considered to extend to Yichang, i.e., the outlet of the Three Gorges Dam; the middle reaches extend from Yichang to Hukou, where Lake Poyang flows into the main river, and the lower reaches extend from Hukou to the river mouth (Zhao et al., 2000). The upper reaches drain mountainous areas, whereas the middle and lower reaches flow through low-lying plains with wider channels (Fig. 1) (Chen et al., 2007).

3. Materials and methods

Riverbed sediments were sampled with a grab sampler along the main Yangtze River (Fig. 1) from 2000 to 2015 (Table S2) to investigate the downstream trends of grain size and to compare pre- and post-TGD riverbed grain sizes. The water discharge, suspended sediment flux and median size (D_{50}) data were obtained from the Yangtze Water Resources Committee (YWRC) of the Ministry of Water Resource of China (MWRC) (http://www.mwr.gov.cn/sj/#tjgb). The multi-year average of D_{50} ($\overline{D}_{50}$) was calculated using the following equation:

$$\overline{D}_{50} = \frac{\Sigma Q_{si} * D_{50\,i}}{\Sigma Q_{si}} \tag{1}$$

where Q_{si} is the sediment flux and D_{50i} is the D_{50} for the year i. The average D_{50} of sediment deposited in the Three Gorges Reservoir (TGR) was calculated using the following equation:

$$\overline{D}_{50} = \frac{Q_{s\text{-}in} * D_{50\text{-}in} - Q_{S\text{-}out} * D_{50\text{-}out}}{Q_{s\text{-}in} - Q_{s\text{-}out}} \tag{2}$$

where $Q_{s\text{-}in}$ represents the sediment inflow into the TGR, $Q_{s\text{-}out}$ is the sediment outflow from the TGR, $D_{50\text{-}in}$ is the mean D_{50} of $Q_{s\text{-}in}$, and $D_{50\text{-}out}$ is the mean D_{50} of $Q_{s\text{-}out}$.

4. Results and discussion

4.1. Human activities

In the Yangtze Basin, land use reduced the forest cover from ca. 80% in 3000 years BP, to 28% in the 1950s, and to 17% in the 1980s (Shi, 1999; Xu, 2011), which has led to the long-term but slow increase in sediment yield and fluvial sediment flux (Wang et al., 2011; Yang et al., 2015). Since the 1990s, however, soil-conservation programs have been implemented. By 2015, the soil-conservation area reached ca. 400 × 10^3 km^2 (Fig. 2a). Prior to the 1960s, the Yangtze Basin dams were rare and small. At the end of 1968, the Danjiangkou Dam (DD), the largest reservoir in Asia at the time, was put into operation in the Hanjiang River, which is one of the major sediment sources of the Yangtze. During the subsequent half-century, numerous new and large dams have been constructed in the Yangtze Basin. The most important development has been the closure of the TGD in 2003. The TGD is the world's largest dam (Nilsson et al., 2005). It was constructed at the outlet of water and sediment from the upper Yangtze basin (60% in area and 80% in sediment supply of the entire basin). In 2012–2013, cascade reservoirs began to operate on the Jinshajiang River, which is the largest sediment source of the Yangtze River, especially the Xiluodu, the third largest reservoir in the Yangtze basin (Fig. 1). Since then, all of the sub-basins have been intensely disturbed by dams. By 2015, the number of large dams in the Yangtze basin was nearly 200, and the corresponding cumulative reservoir capacity increased to 300 km^3, or 50 times larger than that in the 1950s (Fig. 2a).

4.2. Decrease in sediment flux

The Yangtze sediment discharge began to decrease in 1968 when the DD in the Hanjiang River began operation. This dam decreased the annual sediment discharge from Hanjiang to the main Yangtze by ca. 80 Mt (Fig. 3a). Immediately after the DD, the Gongzui Dam (GD) in the Minjiang River and the Bikou Dam (BD) in the Jialingjiang River were constructed, which together decreased the sediment discharge by > 30 Mt/yr (Fig. 3b–c; Lin, 1992; Han and Yang, 2003). In the earlier 1980s, the sediment discharge from the Wujiang River began to decrease due to the construction of the Wujiangdu Dam (WD) (Fig. 3d). Later, at the end of the 1990s, the sediment discharge from the Jinshajiang River began to decrease as a result of the construction of the Ertan Dam (ED) in the major tributary of the Jinshajiang. Since the end of 2012, cascade dams were put into operation in the mainstem of the Jinshajiang, which further reduced the Jinshajiang sediment discharge to almost nil. Over these two periods, the annual sediment discharge decreased by ca. 80 and 170 Mt, respectively (Figs. 1, 3e). Since 1968, numerous other dams were constructed in the above sub-basins and the sub-basins of Lakes Dongting and Poyang, which also contributed to reducing the sediment into the Yangtze River (Yang et al., 2011). The impact of soil-conservation on sediment discharge has gradually increased with the area of soil-conservation. This hypothesis is supported by the progressive flattening of the trends in cumulative sediment discharge from the above rivers (upward convex dotted lines) since the

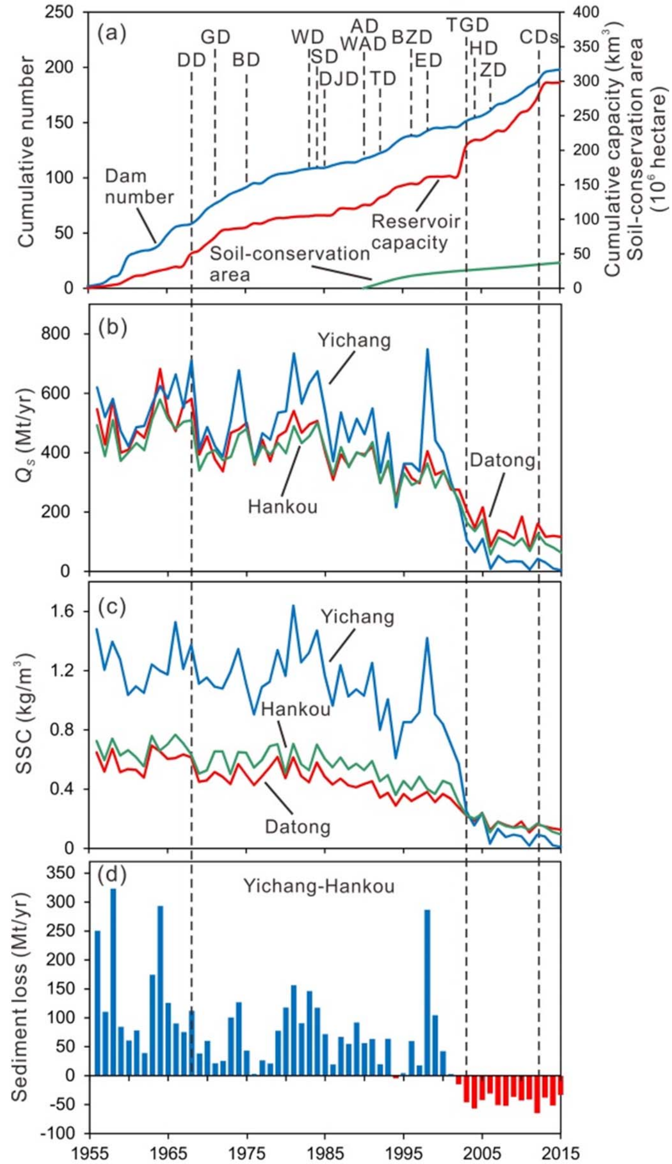
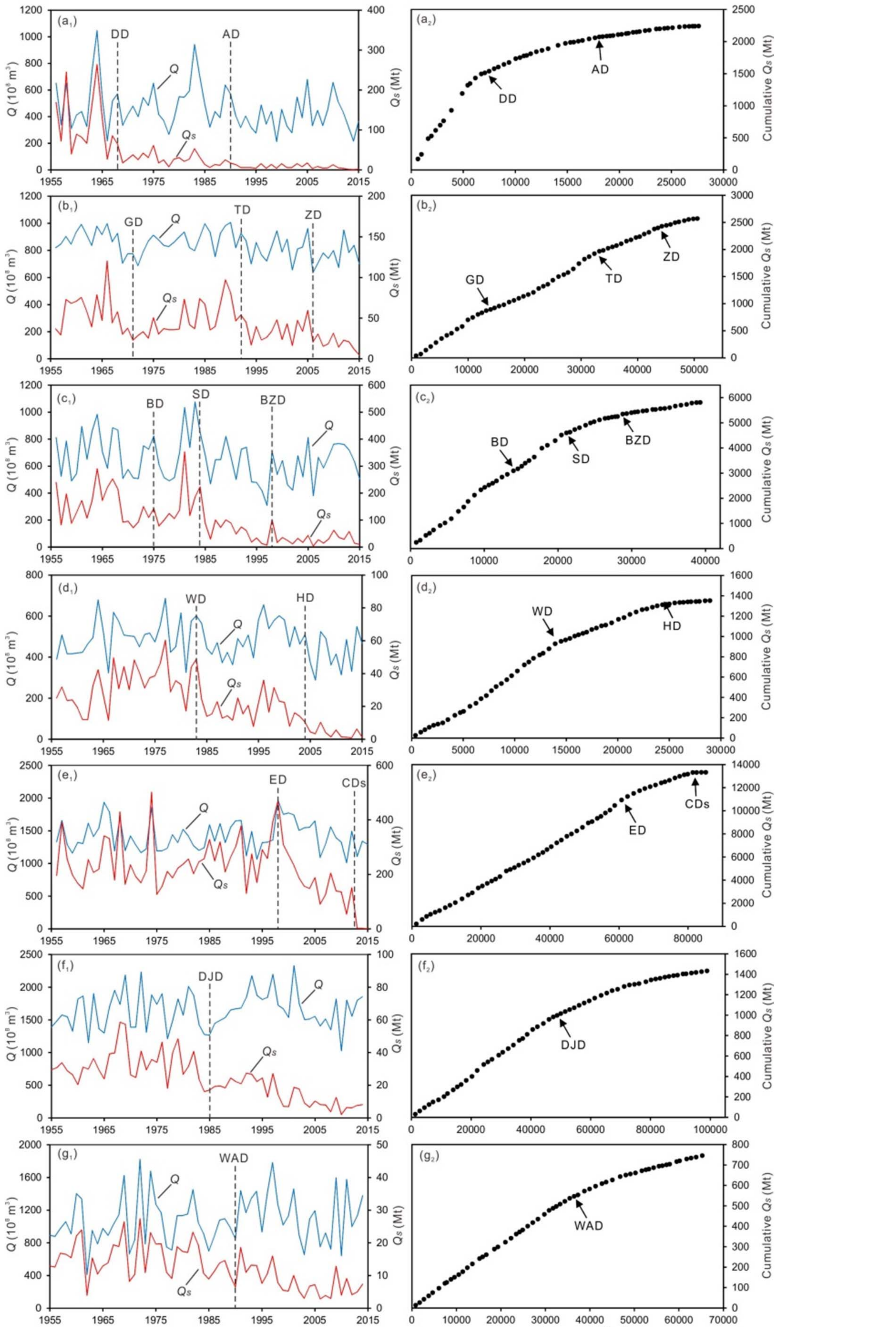


Fig. 2. Temporal changes in the number of dams, reservoir storage capacity, area of soil conservation, sediment flux, SSC and riverbed accretion/erosion in the Yangtze River. (a) Cumulative number and capacity of large dams/reservoirs (each with a storage capacity > 0.1 km^3) and area of soil conservation in the Yangtze basin, (b) annual suspended sediment flux (Q_s) at gauging stations, (c) annually averaged suspended sediment concentration (SSC) at gauging stations, (d) annual suspended sediment loss between Yichang and Hankou (positive/negative values reflect the net riverbed accretion/erosion). Annual riverbed accretion/erosion between the Yichang and Hankou Stations was calculated following the method of Yang et al. (2014), based on the sediment inflow/outflow measured at these gauging stations.

1990s (Fig. 3). From the pre-dam period (1956–1968) to the post-dams and soil-conservation period (2013–2015), the sediment discharge decreased by 99% in both Jinshajiang and Hanjiang, 89% in Wujiang, 85% in Jialingjiang, 80% in Minjiang, and by 76% and 62% in the tributaries of Lakes Dongting and Poyang, respectively; furthermore, the total sediment discharge from the sub-basins decreased by 91%. In the mainstem Yangtze River, the sediment flux decreased by 99% at the Xiangjiaba gauging station (upper reach), 97% at the Yichang station (upper-middle reaches), 83% at the Hankou station (middle reach), and 77% at the Datong station (tidal limit) (Table 1). These sediment decreases are more serious than those reported in previous studies (Dai and Lu, 2014; Yang et al., 2015; Mei et al., 2016) because new data in recent years have been included in the present study.



(caption on next page)

Fig. 3. Time series of water (Q) and sediment discharges (Q_S) and cumulative Q_S vs. cumulative Q in the Hanjiang (a), Minjiang (b), Jialingjiang (c), Wujiang (d) and Jinshajiang Rivers (e).

4.3. Decline and spatial pattern change of the SSC

Because the water discharge has changed little, the SSCs within the Yangtze basin have shown similar decreases to those of the sediment flux (Table 1; Fig. 2b–c). This differs greatly from many other rivers, such as the Nile, Colorado, Yellow and Indus Rivers, where both water discharge and sediment flux have synchronously declined (Vörömarty et al., 2003; Milliman and Farnsworth, 2011; Wang et al., 2011) and the SSC changes are less significant. Within the above watersheds, considerable water withdrawal was a major cause of sediment decrease (Wiegel, 1996; Rodriguez et al., 2001; Wang et al., 2007). In comparison, there are lots of water resources in the humid Yangtze basin, where decreased water is a minor cause of sediment decline, whereas dam construction and soil-conservation are the dominant causes of decreases in sediment flux and the SSC (Yang et al., 2015; Table 1). A similar situation to that in the Yangtze was found in the Pearl River basin (Zhang et al., 2008; Meade and Moody, 2010).

Similar to the decreases in sediment flux, the declines in SSC in the sub-basins began in different years. This led to the phase characters of SSC declining at Datong. Prior to 1968, no large dam had been constructed in the main sediment yield sub-basins, and the human impacts on the Yangtze's SSC were negligible. At the end of 1968, the DD operation in the Hanjiang River led to the first decline of SSC at Datong. In the mid-1980s, the construction of SD in the Jialingjiang and WD in the Wujiang led to the second decline of SSC. In 2003, the TGD operation on the main Yangtze caused the third decline in SSC. Since 2013, the cascade dams in Jinshajiang have resulted in the most recent decline in SSC at Datong. Although SSC continued to be closely related to water discharge, the SSC in the later four phases decreased step by step, and the exponent of the regression relationship between SSC and water discharge decreased from > 1 to < 1 (Fig. 4a). Within the 77% total decline in SSC at Datong (Table 1), 16% of the decline occurred from 1969 to 1985, 21% occurred from 1986 to 2002, 34% occurred from 2003 to 2012, and 6% was seen from 2013 to 2015. Other dams and soil-conservation efforts have also contributed to reducing the SSC in different phases, although the above dams were probably the most impactful.

The SSC decrease in the flooding season was more drastic than the decrease in the dry season. For example, the SSC in July and August at Datong decreased by > 80% from the 1956–1968 phase to 2013–2015 phase, whereas only a 40% decline in SSC was found in January and February (Fig. 4b). Presumably, flow velocity in natural rivers is high during the flood season, and coarse bed materials are resuspended. As a river flows into a reservoir, the current velocity suddenly decreases, and much of the coarse bed-material load settles out. In contrast, the suspended sediments during the dry season mainly include the fine wash load, which barely settles out in reservoirs.

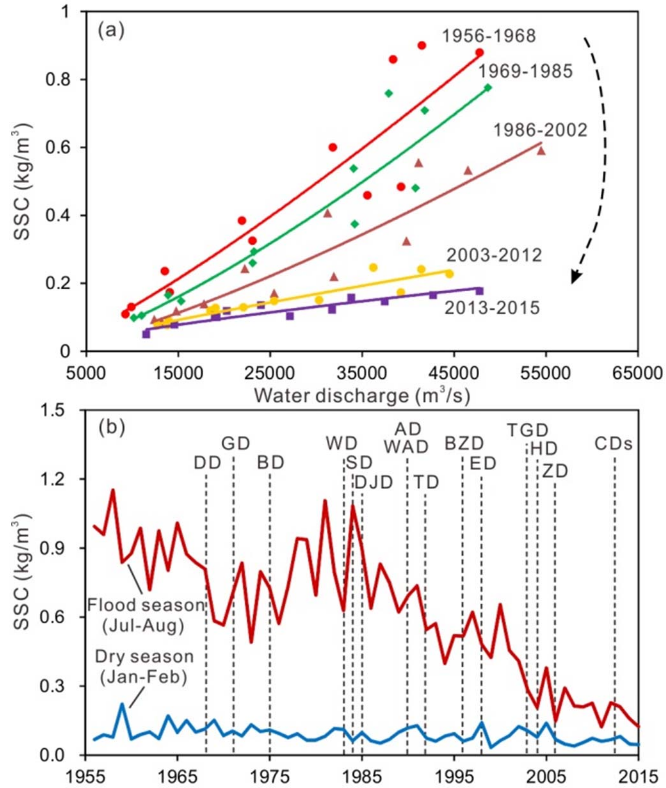


Fig. 4. Decline of the SSC at Datong Station. (a) Correlations between the SSC and water discharge in different periods, based on mean monthly data. From 1956 to 1968: prior to SSC decline ($C = 1.81 \times 10^{-6} Q^{1.21}$, $r^2 = 0.93$). From 1969 to 1985: after construction of the DD on the Hanjiang River ($C = 4.15 \times 10^{-7} Q^{1.34}$, $r^2 = 0.95$). From 1986 to 2002: dams were constructed in the Jialingjiang, Minjiang and Wujiang rivers, and basin-wide soil conservation was carried out ($C = 3.80 \times 10^{-7} Q^{1.31}$, $r^2 = 0.91$). From 2003 to 2012: after the TGD was constructed on the main Yangtze River ($C = 2.17 \times 10^{-5} Q^{0.87}$, $r^2 = 0.92$). From 2013 to 2015: after cascade dams, in particular Xiluodu Dam, were constructed in the Jinshajiang River ($C = 4.11 \times 10^{-5} Q^{0.79}$, $r^2 = 0.86$). In the above correlations, C represents the SSC, Q represents the water discharge, and R is the correlation coefficient. Significance levels of all the correlations are $p < 0.001$. (b) Time series of the SSC in the flood and dry seasons.

The spatial pattern of SSC within the Yangtze watershed has been destroyed, because the SSC declines were spatially uneven. Prior to dam

Table 1
Temporal changes in water discharge (Q), sediment flux (Q_S) and SSC in the sub-basins and the mainstem of the Yangtze River.

	Pre-dam period (1956–1968)			Post-dams and soil-conservation (2013–2015)			Change (%)[a]		
	Q (km^3/yr)	Q_S (Mt/yr)	SSC (kg/m^3)	Q (km^3/yr)	Q_S (Mt/yr)	SSC (kg/m^3)			
Jinshajiang R. (Xiangjiaba, upper Yangtze)	148	255	1.72	125	1.6	0.013	−16	−99	−99
Minjiang R.	90.6	61.5	0.68	77.4	12.6	0.163	−15	−80	−76
Jialingjiang R.	73.7	180	2.44	61.9	27.2	0.439	−16	−85	−82
Hanjiang R.	51.9	115	2.21	30.2	1.3	0.043	−42	−99	−98
Wujiang R	48.1	26.3	0.55	44.9	2.8	0.063	−6.8	−89	−89
Lake Dongting (four rivers)	157	30.7	0.20	173	7.3	0.042	11	−76	−79
Lake Poyang (five rivers)	96.1	15.1	0.16	117	5.5	0.047	22	−62	−71
All sub-basins	665	684	1.03	629	58.3	0.093	−5.4	−91	−91
Yichang (upper-middle reach of Yangtze)	449	560	1.45	410	14.4	0.037	−8.7	−97	−97
Hankou (middle reach of Yangtze)	699	469	0.67	677	78.8	0.116	−3.1	−83	−83
Datong (tidal limit of Yangtze)	862	511	0.59	865	118	0.136	0.3	−77	−77

[a] Negative value represents a decrease.

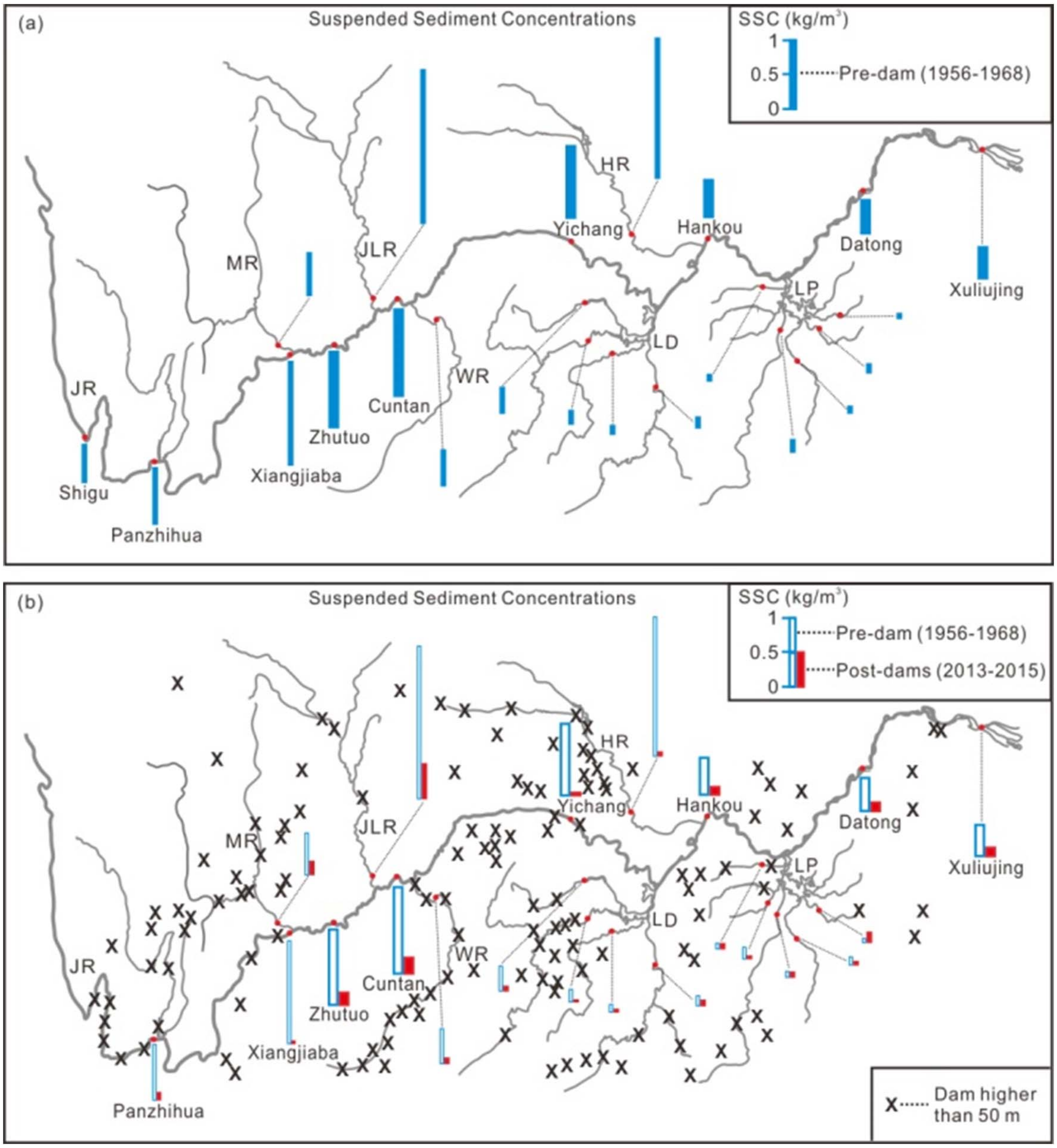


Fig. 5. Histogram of the period-averaged SSC at gauging stations within the Yangtze watershed. (a) The SSC over the pre-dam period. (b) Comparison of SSC between the pre-dam and post-dams periods.

construction, the SSC in the northern and western regions overall (mainly the Jialingjiang, Hanjiang and Jinshajiang sub-basins) was one order of magnitude higher than that in the southeastern regions (i.e., the Lake Dongting and Lake Poyang sub-basins) (Fig. 5a; Table 1). However, after the human impacts over the past half-century, this spatial pattern of SSC has disappeared (Fig. 5b). In fact, the SSC of the Jinshajiang decreased to even less than in the two lake sub-basins (Table 1). More importantly, the original decreasing trend in the SSC downstream along the main Yangtze River has been reversed. Prior to 1968, the SSC decreased down river from 1.7 kg/m^3 at Xiangjiaba (upper stream) to 0.6 kg/m^3 at Datong (tidal limit). Since 2013, however, the SSC increased downstream from 0.013 kg/m^3 at Xiangjiaba to 0.14 kg/m^3 at Datong (Table 1).

4.4. Emergence of erosion in the river channel and delta

Prior to the operation of the TGD, the sediment flux and SSC at Yichang were both significantly higher than those at the downstream stations at Hankou and Datong (Fig. 2b to c), which reflects deposition under rapid decreases in the river slope and flow velocity. However, both the sediment flux and SSC at the downstream stations have become significantly higher than those at Yichang since the construction of the TGD (Fig. 2b to c). Based on our calculations of the sediment budget, we found that severe downstream erosion (ca. -60 Mt/yr) occurred between Yichang and Datong and that > 80% of the erosion occurred between Yichang and Hankou (Fig. 2d). These findings agree with previous studies (Yang et al., 2011; Dai and Liu, 2013) and also indicate that severe erosion continued from 2013 to 2015 (Fig. 2d). Riverbed erosion has become the dominant source of Yangtze sediment transport to the sea. By comparing the SSC at Cuntan station with the combined SSC of the Jinshajiang, Minjiang and Jilingjiang Rivers (Fig. 6), we also found that the main river channel between Xiangjiaba and Cuntan changed from accumulation to erosion after the construction of cascade dams in the Jinshajiang. The gauged area in Jinshajiang is 459×10^3 km^2, 135×10^3 km^2 in Minjiang, 157×10^3 km^2 in Jilingjiang, and 867×10^3 km^2 at Cuntan station. The three sub-basins

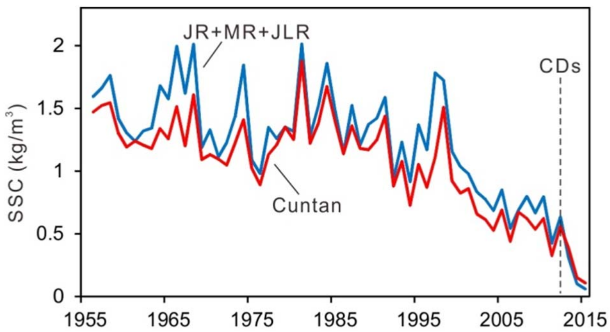


Fig. 6. Time series of combined SSC of the Jinshajiang, Minjiang and Jialingjiang Rivers (JR + MR + JLR) in comparison with the SSC at Cuntan station. CDs: Cascade dams.

amount to 87% of the catchment area gauged at Cuntan. Together, they probably contributed > 95% of the sediment into the main river between Xiangjiaba and Cuntan, considering that the 13% ungauged areas along the main river are low in topographic relief (Fig. 1). Prior to the cascade dams in the Jinshajiang, the SSC from the three sub-basins together were significantly higher than the SSC at Cuntan. After the cascade dams, however, the SSC at Cuntan became higher than the SSC from the three sub-basins (Fig. 6). This shift suggests erosion in the main river between Xiangjiaba and Cuntan. Based on the water and sediment budget and on an analysis of factors influencing sediment yield in the ungauged areas, we found that the main river channel between Xiangjiaba and Cuntan changed from an accumulation rate of ca. 10 Mt/yr before 2012 to a new erosion rate of ca. − 20 Mt/yr in 2013–2015. Based on an analysis of bathymetric data surveyed before 2012, previous studies have reported the emergence of erosion in the Yangtze delta after closure of the TGD (Yang et al., 2011; Li et al., 2015; Luo et al., 2017). Because the Yangtze sediment discharge and SSC further decreased by ca. 20% in the post-CDs period (118 Mt./yr and 0.136 kg/m^3 in 2013–2015) relative to the first ten years of operation of the TGD (145 Mt/yr and 0.173 kg/m^3 in 2003–2012), we expect that the erosion in this delta has most probably continued and has intensified.

4.5. Variations in sediment grain size

Prior to dam construction, the suspended sediments in the Yangtze mainstem exhibited a notable fining trend downstream. The median size (D_{50}) of suspended sediments decreased from 0.029 mm at Xiangjiaba to 0.019 mm at Zhutuo, 0.017 mm at Yichang, 0.007 mm at Hankou, and 0.009 mm at Datong. Presumably, this fining trend in grain size downstream reflects the influence of flow velocity (Paola and Seal, 1995) which generally slows downriver due to decreasing river slope and a widening of the river channel (Chen et al., 2007). Notably, the significant decrease in D_{50} between Yichang and Hankou reflects the sorting and selective deposition of suspended sediments because of abrupt decreases in flow velocity. However, after the construction of numerous dams, the D_{50} values (2013–2015) decreased to 0.006 mm at Xiangjiaba, 0.012 mm at Zhutuo, and 0.009 mm at Yichang, whereas the D_{50} values increased to 0.015 mm at Hankou and 0.011 mm at Datong. Although the annual D_{50} value fluctuated over time, an overall temporal fining trend was found at all of the upstream stations above Yichang (Fig. 7a). This temporal fining trend has been coinstantaneous with the decreasing SSC trend, and both trends reflect the selective deposition of suspended sediments in the reservoirs. This argument is well supported by the example in the TGR, where the D_{50} of sediment inflow was 0.010 mm, the D_{50} of reservoir sedimentation was 0.011 mm, and the D_{50} of sediment outflow was 0.005 mm (Yang et al., 2014). In contrast, the coarsening of suspended sediments observed at Hankou and Datong was ascribed to riverbed erosion. Riverbed sediments are generally coarser than suspended sediments (Fig. 7). As shown above, riverbed erosion has become the dominant source of suspended sediment in the middle (Hankou) and lower (Datong) reaches since the beginning of the TGD.

Prior to human impacts, the Yangtze riverbed sediments exhibited a stepwise downstream fining trend (Fig. 8). Upstream (above Yichang), the riverbed sediment was dominated by gravel and the D_{50} value was generally > 30 mm. In the Three Gorges, the riverbed can even be rock. Downstream from the Three Gorges, the D_{50} value abruptly decreased to < 0.3 mm and further downriver gradually decreased to 0.12 mm near the river mouth (Table 2). These downstream changes in riverbed sediment grain size reflected the control of the river slope and flow velocity. After the closure of the TGD, however, the riverbed sediments in the 700-km-long TGR became mud dominated (the mean D_{50} was 0.011 mm) (Table 2), although a downstream fining trend was also observed in the TGR itself (Fig. 8). This transition is attributed to the deposition of suspended particles within the reservoir. We found that in 2003–2015, the D_{50} of the suspended sediment inflow into the TGR was 0.010 mm, 80% of the sediment inflow was deposited in the TGR, and the mean D_{50} of the sedimentation was 0.011 mm. Conversely, coarsening of riverbed sediment was found in the 1800-km downstream reaches (Fig. 7b; Table 2; Williams and Wolman, 1984). The maximum coarsening was found in the 200-km reaches immediately downstream of the TGD, where D_{50} has increased from 0.29 mm in the pre-TGD period to > 10 mm (gravel) in the post-TGD period (Table 2). This coarsening is presumably a result of riverbed erosion, which tends to resuspend the finer grains and leave the coarser particles on the riverbed. Because maximum riverbed erosion has been identified close to the TGD (Dai and Liu, 2013), the maximum coarsening of surficial sediments was also observed immediately downstream of the TGD (Luo et al., 2012; Table 2). We expect that the maximum coarsening of surficial sediments will extend downstream with the maximum riverbed erosion in future decades, whereas armouring of the maximum coarsening reaches will prevent further erosion.

4.6. Role of the TGD and CDs in changing the Yangtze sediment

The quantitative research on dam impact is important for environmental evaluation. The TGD has undoubtedly played a dominant role between 2003 and 2012 in decreasing the sediment flux and the SSC, although other factors may have also been responsible. In this period, sediment deposition in the TGR reached 180 Mt/yr. Despite the downstream riverbed erosion, the TGD decreased the annual sediment discharge at Datong by > 110 Mt. (Table S3), which is ca. 30% of the cumulative decline in sediment discharge at Datong since 1968. The inter-annual changes in the TGD's impact on sediment flux and SSC were significant. The maximum impact can be more than twice the minimum (Fig. 9). This inter-annual variability is mainly from climatic changes. For example, severe droughts in the Yangtze Basin in 2006 and 2011 resulted in very low water discharge at the gauging stations. Consequently, sediment supply from upstream, sedimentation in the TGR, and the TGR-generated decrease in sediment flux at the downstream stations were all extremely low in 2006 and 2011 (Fig. 9). Because the TGD's impact on annual water discharge was very small (Yang et al., 2015), the role of the TGD in decreasing the downstream SSC was the same as that in decreasing sediment flux. Since 2013, however, most of the sediment in the Jishajiang was retained by the cascade dams, which decreased nearly half of the sediment inflow into the TGR. Over the post-CDs period, the dominant cause of sediment change between Xiangjiaba and the TGD was the CDs, and the TGD's contribution to sediment decrease in the middle and lower Yangtze was halved (Fig. 9).

5. Conclusions

The human impacts on Yangtze River sediment are basin-wide, very strong and systematic. By 2013, all of the tributaries and the mainstem

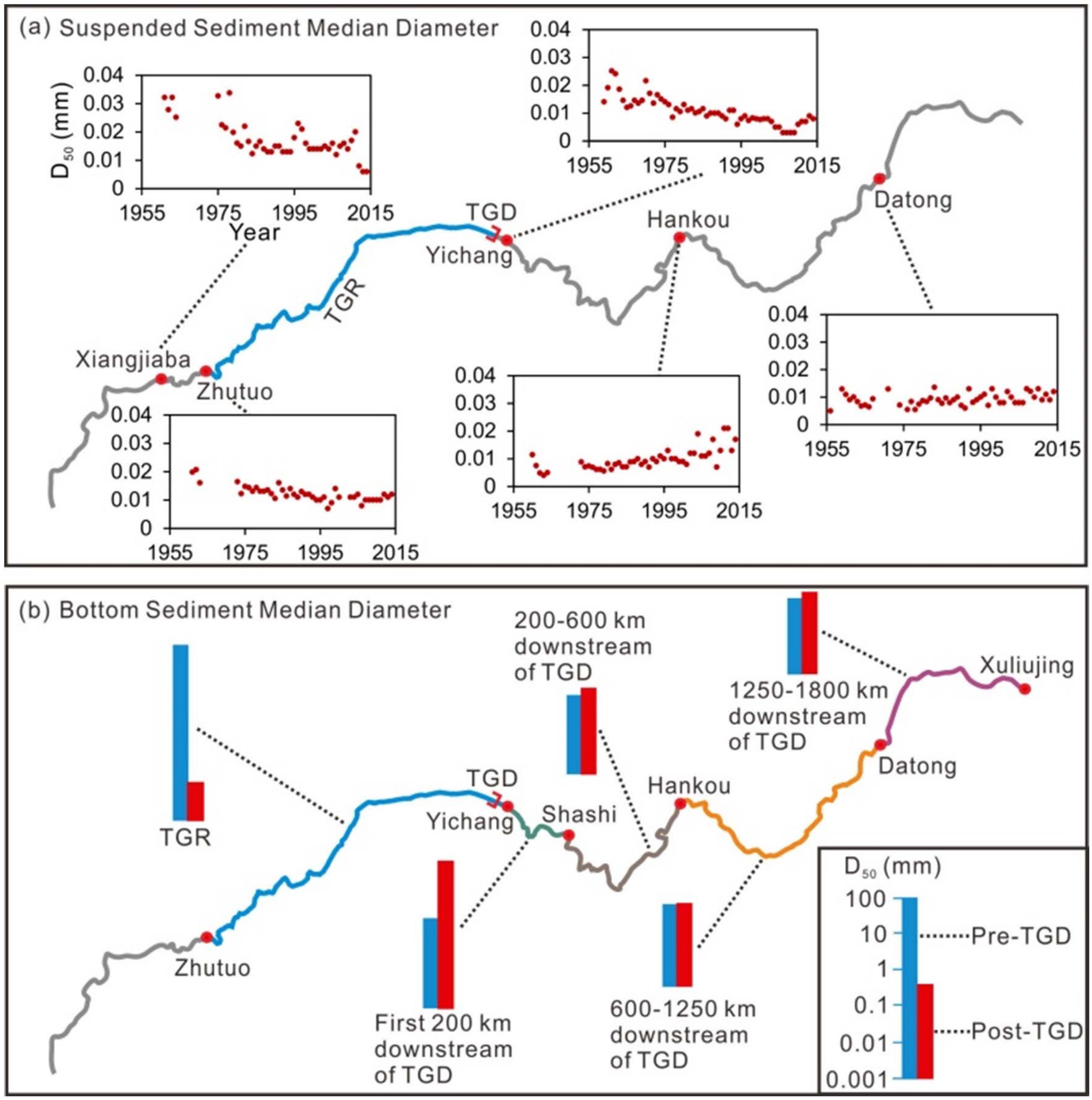


Fig. 7. Temporal changes in the grain size of sediments in the Yangtze River. (a) Annually averaged median size (D_{50}) of suspended sediments at the gauging stations. (b) Comparison of the reach-averaged D_{50} of riverbed sediments between the pre-TGD and post-TGD periods.

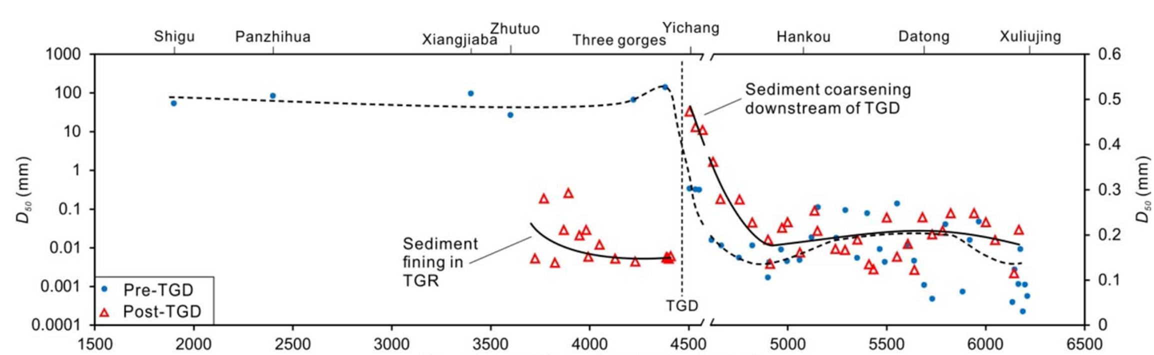


Fig. 8. Median sizes of riverbed sediments along the Yangtze River. After the impoundment of the TGR, fining of surficial sediments was found in the reservoir, whereas coarsening of surficial sediments was observed downstream of the TGD.

have been regulated by dams. Now, > 90% of the sediment from the sub-basins has been trapped in reservoirs. On the main river, the sediment flux has decreased by 99% at Xiangjiaba (upper reach), 97% at Yichang (transition between upper and middle reaches), 83% at Hankou (middle reach), and 77% at Datong (tidal limit). Because the water discharge changes have been smaller, similar declines in the SSC were found. The drastic decline in the SSC has triggered slight riverbed erosion in the upper reaches between Xiangjiaba and the TGR and strong erosion in the middle and lower reaches. That is the riverbed erosion counteracted the decline of sediment flux and the SSC to some

Table 2
Average median size of riverbed sediments of different reaches of the Yangtze River (mm).

Periods	TGR (660 km)	Yichang-Shashi (150 km)	Shashi-Hankou (400 km)	Hankou-Datong (650 km)	Datong-Xuliujing (550 km)
Pre-TGD	> 30	0.290	0.151	0.187	0.116
Post-TGD	0.011	11.5	0.236	0.195	0.171

extent in the downstream reaches. Selective deposition of suspended sediments in reservoirs decreased the D_{50} of the sediment outflow. However, downstream erosion resuspended sediments coarser than the suspended sediment outflow from the reservoirs, which resulted in an increase in the D_{50} of suspended sediments further downstream. Reservoir sedimentation has covered the riverbed gravel or rock with mud; however, feedback erosion coarsened riverbed sediments in downstream channels. Although the changes shown in this study are mainly attributed to the filter effect of the reservoirs, they are also partially attributable to soil conservation. Our findings suggest that human activities can alter river sediment characteristics and processes intensely, which has widespread implications for fluvial environments.

Acknowledgments

This study was funded by the Ministry of Science and Technology of China for the National Key R & D Program of China (2016YFA0600901), the Natural Science Foundation of China (NSFC)-Shandong Joint Fund for Marine Science Research Centers (U1606401) and NSFC (41130856).

Declaration of interest

Conflicts of interest: none.

Contributors

H.F. Yang wrote the draft of the manuscript and prepared the figures. S.L. Yang conceived the study and contributed to the improvement of the manuscript together with K.H. Xu, J.D. Milliman, H. Wang and Z. Yang. Z.Y. Chen performed sampling and analysis of riverbed sediment. C.Y. Zhang performed calculation. All authors have approved the final article.

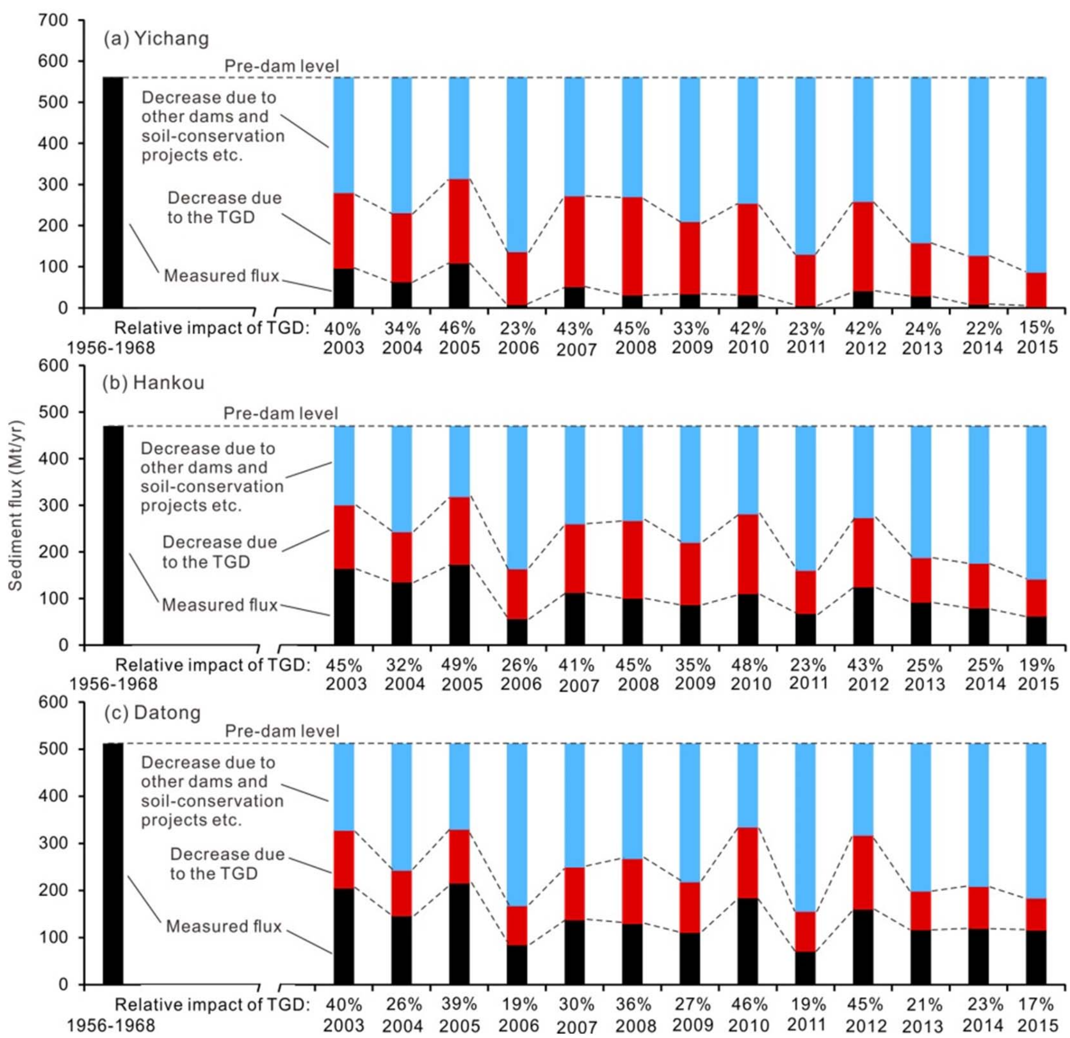


Fig. 9. TGD's impact on the decline of the sediment flux at Datong. The decrease in measured flux from the pre-dam period (1956–1968) to the post-TGD years reflects the cumulative impact of various factors since 1968. The decrease due to the TGD represents the impact from the TGD alone. The decrease due to other dams and soil-conservation projects etc. reflects the combined impact of various influencing factors other than TGD (e.g., other dams, soil-conservation projects, sand mining, water diversion and climatic changes) occurred either before or after the closure of the TGD. The relative impact of the TGD is the ratio of the TGD-generated decrease to the cumulative decrease in percent.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gloplacha.2018.01.001.

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