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From the headwater to the delta: A synthesis of the basin-scale sediment load regime in the Changjiang River

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ABSTRACT

Many large rivers in the world delivers decreasing sediment loads to coastal oceans owing to reductions in sediment yield and disrupted sediment deliver. Understanding the sediment load regime is a prerequisite of sediment management and fluvial and deltaic ecosystem restoration. This work examines sediment load changes across the Changjiang River basin based on a long time series (1950–2017) of sediment load data stretching from the headwater to the delta. We find that the sediment loads have decreased progressively throughout the basin at multiple time scales. The sediment loads have decreased by ~96% and ~74% at the outlets of the upper basin and entire basin, respectively, in 2006–2017 compared to 1950–1985. The hydropower dams in the mainstem have become a dominant cause of the reduction, although downstream channel erosion causes moderate sediment load recovery. The basin-scale sediment connectivity has declined as the upper river is progressively dammed, the middle-lower river is leveed and river-lake interplay weakens. The middle-lower river has changed from a slight depositional to a severe erosional environment, from a sediment transport conduit to a new sediment source zone, and from a transport-limited to a supply-limited condition. These low-level sediment loads will likely persist in the future considering the cumulative dam trapping and depleted channel erosion. As a result, substantial hydro-morphological changes have occurred that affect the water supply, flood mitigation, and the aquatic ecosystem. The findings and lessons in this work can shed light on other large river systems subject to intensified human interference.

1. Introduction

Larger rivers deliver most of the terrestrial flux of sediment to the coastal oceans and seas. Past estimates suggest that a total sediment discharge of approximately 15–20 billion tons per year comprises 95% of the sediment entering the oceans (Milliman and Ren, 1995; Syvitski et al., 2005). This large-scale flux plays a significant role in land-ocean interactions, particularly with respect to carbon and pollution exchange (Milliman and Meade, 1983; Syvitski et al., 2005).

Under the impacts of climate change and human activities, many of the world's large rivers have experienced a measurable decrease in sediment flux over the past few decades (Walling and Fang, 2003; Vörösmarty et al., 2003; Syvitski et al., 2005). Numerous case studies of these impacts have been well documented (Dynesius and Nilsson, 1994; Walling, 2006; Yang et al., 2015). Consequently, many large delta systems are experiencing increased erosion, loss of salt marshes, and flooding of the immediate hinterland, which poses an increasing threat to human life in these areas (Syvitski and Saito, 2007). This decrease in sediment flux is accompanied by a reduction of particulate nutrient loading from rivers to oceans, thus affecting the land-ocean biogeochemical cycling and coastal ocean ecosystems (Syvitski et al., 2005). It is thereby of vital importance to understand the magnitude, direction, and timescales of sediment load changes in order to provide a quantitative basis for defining management constraints and identifying restoration opportunities (Hoffmann et al., 2010).

As one of the world's largest river systems, the Changjiang River basin (CRB) is of major ecological and socioeconomic significance. The amount of sediment delivered to the delta in 1950–1983 was

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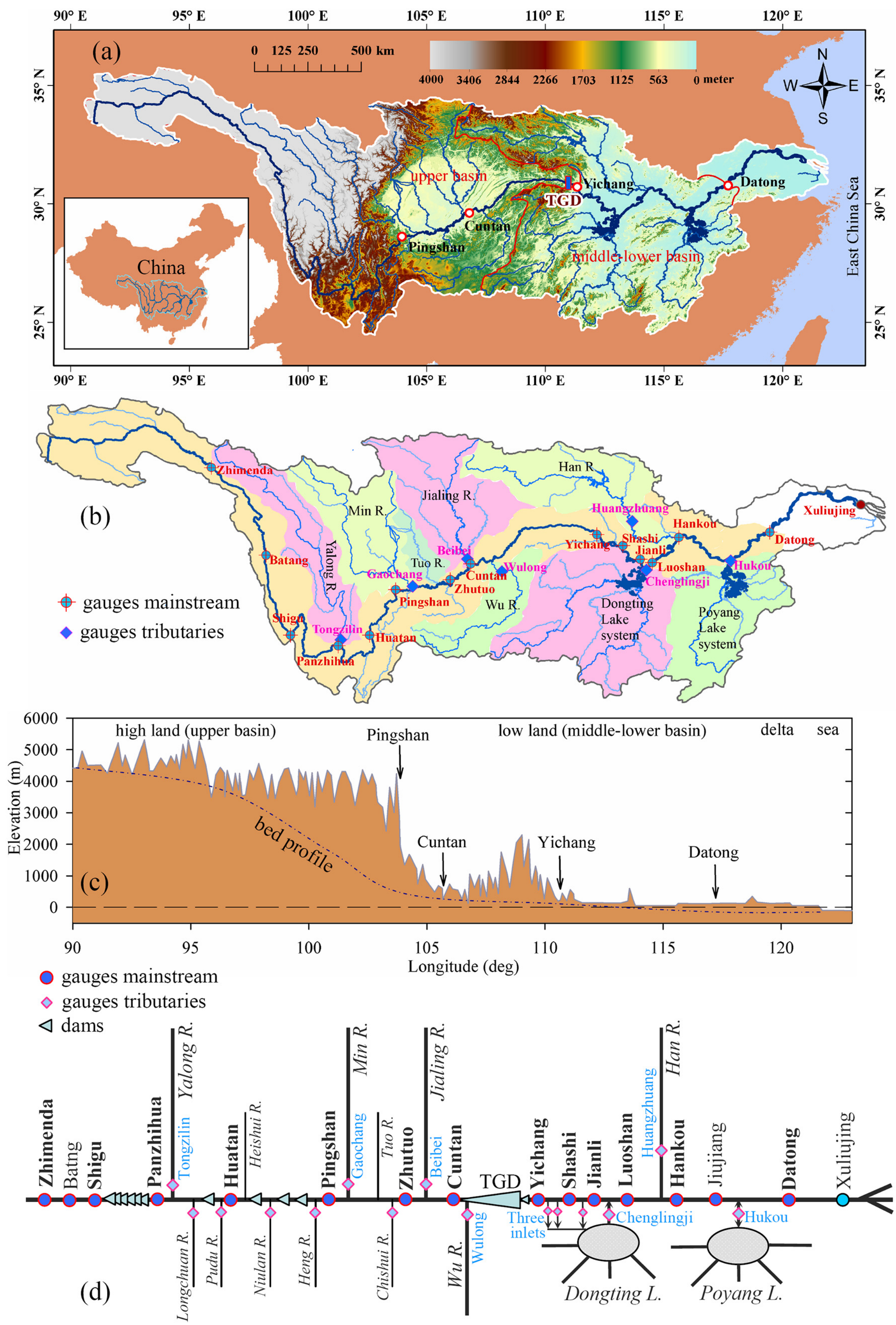

Fig. 1. (a) A DEM and boundaries of the upper and middle-lower sub-basins, (b) the division of tributary basins and the location of gauge stations, (c) Longitudinal elevation changes, and (d) a sketch showing the relative positions of the gauges and large dams in the mainstem. TGD indicates the Three Gorges Dam.

471.4 ± 72.5 Mt. yr^{-1} according to the Datong gauge (Fig. 1), which accounted for ~4.5% of the global terrestrial sediment flux (Milliman and Meade, 1983). Formerly an aggradational system, the CRB had been subjected to sediment-related management challenges including severe surface soil erosion, rapid reservoir sedimentation and loss of storage capacity, channel aggradation and sedimentation in natural lakes (Yang et al., 2006, 2014; Wang et al., 2007). For centuries, flood mitigation has been the focus of river management in the CRB. Although this has remained an important issue, several other activities including land use changes and dam construction during the last century have begun to have a far greater impact. These activities have collectively led to a reduction in sediment loads, and the associated sediment deficit has led to channel degradation, loss of wetland and habitats, and delta erosion (Yang et al., 2011, 2018). Although the overall decrease in sediment load is well known, the spatial and temporal nature of these changes has not been studied in detail at the basin scale. Such an understanding can provide important insight for future management of the river basin, which is the focus of this study.

A huge amount of research has been devoted to studying sediment load changes in the CRB. Shi et al. (1985) and Gu and Ian (1989) examined sediment yield patterns and sediment load changes in the upper basin. Following their research, Yang et al. (2006, 2011, 2018), Wang et al. (2007, 2008), Hu et al. (2009), Xu and Milliman (2009), Hassan et al. (2011), Dai and Lu (2014), and Guo et al. (2018) have documented the sediment load reductions that have been ascribed to reforestation measures and hydropower dams including the Three Gorges Dam (TGD). Liu and Zuo (1987), Li et al. (2013), Dai and Lu (2014), Xu et al. (2013), Zheng (2016), and Yang et al. (2018) have discussed the impacts of the TGD on the river system with respect to river and sediment discharges, ecological and environmental issues, and social and economic aspects. However, several inconsistencies are present regarding the pattern of sediment load changes and the impact of land use changes (Dai and Lu, 2014), which can be ascribed to inconsistent data and/or different analysis methods at different significance levels. Furthermore, past studies have mainly examined the sediment load regime in part of the river system, e.g., the middle-lower river downstream of the TGD (Fig. 1). To the best of our knowledge, basin-wide sediment load changes have not been documented and remain insufficiently understood.

Construction of the TGD was completed in 2003 and this was followed by a pilot operation period from 2003 to 2008. Almost a decade of recent data recorded since the dam became fully operational provides an opportunity for rigorous assessment of the dam's impact on sediment delivery. Following the completion of the TGD, more hydropower dams have been constructed along the mainstem. Therefore, we provide in this work a comprehensive synthesis of the sediment flux regime and its changes based on re-examination of a long time series of sediment load data over the interval 1950–2017 throughout the CRB from the headwater to the delta. This provides an integrated picture of the spatial patterns of sediment flux and its changes over time. In addition, we attempt to clarify the causes and interpret the river-system responses with respect to fluvial hydro-morphological adaptations, and we examine the changes in network connectivity and the disposition of sediment sources and sinks. These insights are expected to clarify river management strategies. The findings also have relevance for global terrestrial sediment flux and land-to-ocean interactions in similarly large river systems.

2. The Changjiang River and data sources

2.1. Introduction to the Changjiang River

Stretching west-eastward in the middle of China, the Changjiang River is one of the world's largest rivers in terms of mainstem length (~6300 km), drainage area (1.9 million km^2), and streamflow. According to data recorded between 1950 and 2005 at Datong, the streamflow was 903.4 ± 124.6 billion m^3 yr^{-1}, and the sediment load was 413.8 ± 103.4 Mt. yr^{-1}. The CRB is home to ~480 million people and contributed to 41.6% of the national gross domestic product (GDP) in 2015, which demonstrates its critical role in national socioeconomic development (Chen et al., 2017).

The CRB has highly significant spatial variations in landscape, rock type, land use, climate pattern, and precipitation. The CRB is geographically divided into upper and middle-lower sub-basins and a delta region with divisions at Yichang (1770 km upward from Xuliujing, head of the delta, the same definition of along-river distance applies throughout this work) and Datong (500 km) based on varying hydrological and geomorphologic features (Fig. 1). The upper basin has a high relief at 3000–5000 m and is basically mountainous with widespread gullies and gorges (Fig. 1a and b). The axial river gradient between Zhimenda and Pingshan is ~0.0013. The headwater zone upstream of Batang, i.e., the Tibetan Plateau, is characterized by a persistently cold climate and low precipitation (Wang et al., 2007). The river reach between Batang and Pingshan, also referred to as the Jinsha River, is composed of gullies and gorges in a hot and dry climate with poor vegetation coverage. The region between Pingshan and Yichang has a relatively low relief compared with the headwater zone (Fig. 1b); its landscape includes high mountains and canyons with a high precipitation. The middle-lower basin between Yichang and Datong consists of a low-lying floodplain with a wet and warm climate pattern. The reach between Zhicheng (~60 km downstream of Yichang) and Luoshan, referred to as the Jing River, is a highly meandering river, with complex river networks that connects to the natural Dongting Lake. The middle-lower river overall has a gentle bed slope with a mean river gradient of ~0.00011. Influenced by the Asian monsoon, the annual precipitation is 270–500 mm in the upper CRB and 1600–1900 mm in the middle-lower basin (Gemmer et al., 2008; Wang et al., 2012). The river downstream of Datong is influenced by oceanic tides, whereas the region seaward of Xuliujing is dominated by bidirectional tidal currents and is defined as a delta zone.

A number of tributaries form part of the CRB, including the Yalong, Min, Jialing, Wu, and Han rivers and two natural lake systems: the Dongting and Poyang lakes (Fig. 1 and Table 1). The Dongting Lake receives flows from four secondary tributaries and connects to the mainstem at Chenglingji. In addition, three inlets are located between Yichang and Jianli where mainstem water and sediment are diverted into the Dongting Lake (Fig. 1d). The Poyang Lake has five secondary tributaries and connects to the mainstem at Hukou. Reverse flows and associated sediments, i.e., flows from the mainstem to the Poyang Lake, occur occasionally at Hukou during the wet season. In addition, a few small tributaries with a smaller drainage area but a high sediment yield are present, including the Longchuang, Pudu, Heishui, Niulan, Heng, Tuo, and Chishui rivers (Fig. 1d). These small rivers were generally excluded in previous studies of the sediment budget due to data scarcity. However, the reduction in sediment loads of the large tributaries means that the sediment sources of these smaller tributaries probably have become significant for the sediment budget.

2.2. Data

Instrumental data of river discharge and sediment loads are readily available as hydrometric stations for monitoring river discharge were established at Hankou and Yichang in the 1860s, whereas sediment-load monitoring was initiated in 1923. More generally consistent sediment load data from sites across the river basin beginning in 1950 are available despite several gaps in the early 1950s (Table 1). The annual streamflow and sediment load data used in the present study were collected from government websites (http://xxfb.hydroinfo.gov.cn), yearbooks and bulletins (CWRM, 2001–2018; http://www.mwr.gov.cn/sj/tjgb/zghlnsgb/), and the literature (Yang et al., 2006; Wang et al., 2008; Guo et al., 2018). The Hydrology Bureau of the Changjiang Water Resources Commission conducts measurements that are

Table 1
Drainage area, streamflow and sediment loads in the sub-basins (bold) and tributaries (italics) of the CRB. The streamflow and sediment loads are the multi-year averaged values of the entire data range with one standard deviation.

River name	Gauge	Drainage area (km^2)	Streamflow (billion m^3)	Sediment load (million tons)	Data range
Upper river	**Zhimenda**	137,700	13.1 ± 3.6	9.5 ± 5.9	1957–2017
Upper river	**Batang**	187,507	29.0 ± 5.8	13.1[a]	1960-2017
Upper river	**Shigu**	214,184	42.6 ± 6.8	25.3 ± 12.5	1958–2017
Upper river	**Panzhihua**	259,177	56.3 ± 8.9	46.5 ± 25.2	1966–2017
Yalong R.	*Tongzilin*[1]	*118,294*	*59.1 ± 9.7*	*24.4 ± 15.1*	*1961–2017*
Longchuang R.	*XiaoHGY*	*9225*	*0.7 ± 0.5*	*4.3 ± 3.5*	*1963–2017*
Pudu R.	*Sanjiangkou*	*11,657*	*3.5*	*5.3*	-[b]
Upper river	**Huatan**	425,949	125.3 ± 20.8	160.2 ± 68.9	1958–2017
Heishui R.	*Ningnan*	*3530*	*2.2 ± 0.4*	*4.7 ± 2.9*	*1959–2016*
Niulan R.	*Xiaohe*	*13,672*	*4.8*	*11.7*	-[b]
Heng R.	*Hengjiang*	*14,800*	*8.6 ± 1.7*	*12.1 ± 6.3*	*1961–2016*
Upper river	**Pingshan**[2]	458,592	142.4 ± 21.8	215.4 ± 107.7	1956–2017
Min R.	*Gaochang*	*135,378*	*84.2 ± 9.4*	*41.9 ± 22.8*	*1956–2017*
Tuo R.	*Fushun*	*27,840*	*12.2 ± 2.8*	*8.2 ± 8.3*	*1957–2017*
Chishui R.	*Chishui*	*20,440*	*9.7*	*7.1*	-[b]
Upper river	**Zhutuo**	694,700	263.6 ± 31.2	267.5 ± 111.4	1956–2017
Jialing R.	*Beibei*	*156,142*	*65.1 ± 16.5*	*93.8 ± 78.2*	*1956–2017*
Upper river	**Cuntan**	866,559	342.9 ± 39.4	366.0 ± 164.4	1950–2017
Wu R.	*Wulong*	*83,035*	*48.5 ± 9.2*	*22.2 ± 14.9*	*1956–2017*
Upper river	**Yichang**	1,005,500	429.4 ± 47.1	391.2 ± 220.3	1950–2017
Middle river	**Shashi**	–	391.0 ± 37.8	347.2 ± 187.1	1956–2017
Dongting L.	*Three inlets*[3]	–	*80.5 ± 34.6*	*95.5 ± 72.2*	*1956–2017*
Middle river	**Jianli**	–	356.6 ± 42.5	294.2 ± 140.2	1951–2017
Dongting L.	*Chenglingji*	*262,340*	*285.2 ± 62.1*	*37.9 ± 18.4*	*1951–2017*
Middle river	**Luoshan**	1,294,910	635.9 ± 74.1	333.5 ± 156.3	1954–2017
Middle river	**Hankou**	1,488,000	708.4 ± 88.7	327.1 ± 144.8	1953–2017
Han R.	*Huangzhuang*	*142,056*	*46.3 ± 16.3*	*42.2 ± 53.2*	*1951–2017*
Poyang L.	*Hukou*	*162,200*	*152.4 ± 43.2*	*10.4 ± 4.7*	*1952–2017*
Lower river	**Datong**	1,705,400	895.8 ± 125.1	361.1 ± 146.8	1951–2017

[1] Data based on Xiaodeshi (plus Wantan) station 6.5 km upstream of Tongzilin before the Ertan Dam was constructed in 1999.
[2] Data at Xiangjiaba since 2011 used due to construction of Xiangjiaba Dam.
[3] Three inlets diverting mainstem flow and sediment into the Dongting Lake.
[a] Time series of sediment load data at Batang were not collected; only the mean value reported in Wang et al. (2007) is included for reference.
[b] Time series of streamflow and sediment load data were not collected; only the mean values in Gu and Ian (1989), Pan (1997), and Wei et al. (2011) are included for reference.

performed following widely accepted standards; thus, all data are quality controlled (Wang et al., 2007).

Annual streamflow and sediment load data were collected throughout the CRB for the period 1950–2017, including 13 gauge stations along the mainstem stretching nearly 5000 km, 12 large tributaries and 4 small tributaries, i.e., a compilation of recordings of ~1680 station years (Fig. 1d and Table 1). The occasional missing data were estimated by correlating the available data with the nearest complete gauge record, e.g., 1987, 1971, and 1970 are missing from Huatan, Zhutuo, and Shashi, respectively. To facilitate consistent comparison of the changes throughout the river, the data of 1956–2017 were analyzed in depth. Note that comparisons of sediment loads are made through time for individual rivers or gauges; the comparison between rivers is limited because of the unique chronology of changes within each sub-catchment, and the variable effect of those changes along the mainstem. In addition, some gauges were relocated because of dam construction or river regulations, e.g., Tongzilin was used to replace Xiaodeshi (plus Wantan) in the Yalong River in 2000, and Xiangjiaba replaced Pingshan in the mainstem in 2011 (Table 1). For our purposes, however, such relocations did not influence the data consistency because the displaced distances are small (e.g., Xiangjiaba is ~10 km downstream of Pingshan).

The annual sediment flux is estimated based on daily-monitored river discharge and suspended sediment concentration which has a measurement error range of 16% (Wang et al., 2007). The suspended sediments are composed mostly of fine material, i.e., silt and clay, with a median diameter of 0.02–0.05 mm. The mean median diameter of the suspended sediment decreased from 0.044 mm at Shigu to 0.031 mm at Pingshan, 0.022 mm at Yichang, and 0.017 mm at Datong in the period prior to 2000 (CWRM, 2003). The suspended sediments have become finer in the recent decade as trapping of coarser sediment by dams has increased. In contrast, the bed material is composed of coarse sands, gravels and pebbles with diameters > 10 mm in the upper CRB and mainly sands downstream of Yichang with grain sizes of 0.1–0.4 mm and a sand fraction > 70% (Wang et al., 2009). The bed load transport flux, including both gravels and coarse sands, was 9.54 Mt. yr^{-1} at Yichang before the closure of the Gezhouba Dam and was reduced to 0.32–1.41 Mt. yr^{-1} thereafter in 1981–1987 (Zhou and Xiang, 1994; Wang et al., 2007). The bed load transport accounts for a small proportion of the total sediment load, at < 5% (Chen et al., 2010), therefore, the bed load was not included in the sediment flux estimates.

2.3. Methods

Sediment budget was used to infer the sediment delivery pattern changes at within-reach scales. It provides a framework to link sediment sources, transport pathways, and sinks based on mass conservation (Kondolf and Matthews, 1991; Parsons, 2011; Hinderer, 2012). For example, the differences between the incoming sediment flux at Cuntan plus Wulong and the outgoing sediment flux of the TGD at Yichang were taken as the reservoir sedimentation. The incoming and outgoing sediment loads of the two lakes were used to interpret the net deposition or erosion within the lakes. Wang et al. (2007) provided a large-scale sediment budget analysis of the CRB. In this work, an in-reach sediment budget was used to indicate sediment deposition or erosion in different reaches along the main river. The sediment balance of a selected river reach considering sediment input, output and in-reach sediment storage or erosion can be written as follows (Hassan et al., 2010):

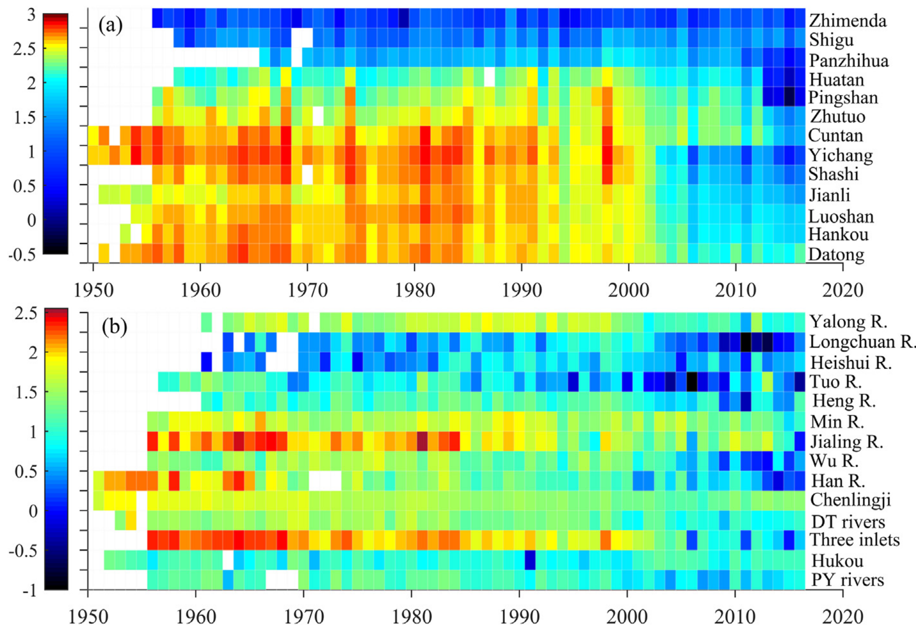

Fig. 2. Time series of annual sediment loads (million tons in log10 scale) (a) along the mainstem and (b) at the mouths of the tributaries.

$$(I_C + I_T + I_E) - (O_C + O_M + O_D) = S + E$$

where I_C, I_T, and I_E are in-reach sediment input from upstream, tributaries, and channel erosion, respectively, and O_C, O_M, and O_D indicate in-reach sediment output at the downstream section, sediment losses from sand mining, and sediment losses from the mainstem to tributaries and floodplains, respectively. S indicates the in-reach sediment storage owing to sedimentation, and E indicates the error or uncertainty term.

The sediment input (I_C) and output (O_C) of the study reach were represented by measurements in the mainstem. Sediment sources from monitored large and small tributaries (I_T) were considered, whereas the other ungauged smaller tributaries remain the main unknown factors in the upper river basin. Channel erosion (I_E) in the upper mainstem was considered to be limited given the significant differences in the composition of the bottom sediments (~cm) and suspended sediments (< 0.1 mm). Estimation of the sediment sources from channel erosion (I_E) was based on river morphological data and was considered only in the river downstream of Yichang in the post-TGD period (see section 4.1). Sediment mining (O_M) predominantly extracts relatively coarse sediments and therefore should not have a significant influence on the suspended transport of fine sediment. However, sand mining may increase channel erosion, causing I_E over and above the natural channel erosion. Information of sand mining and its quantity, location and time, is limited, which creates difficulties in quantifying the mass of the sediment extracted; this is exacerbated by additional undocumented sediment extraction. The amount of overbank sediment lost to adjacent floodplains along the middle-lower river is small under normal flow conditions because of the extensive levees present, although the amount could be considerable during large river floods (Xu et al., 2005). Overbank sediment loss to floodplains has not been quantified due to a lack of measurements during floods. The lack of information on ungauged small tributaries is considered to be the main source of error (E) in the upper basin, and the undocumented sediment mining and overbank sediment losses are the main unknown sources in the middle-lower basin. Also note that the measurement uncertainties in suspended sediment, as well as the spatial variations in sediment bulk density, and unquantifiable uncertainty in the river bathymetric data also contribute to the E term. Despite these uncertainties, the sediment budget analysis is still informative (Kondolf and Matthews, 1991). In general, a sediment output ($O_C + O_D$) to input ($I_C + I_T$) ratio > 1 indicates in-reach channel erosion, and a ratio < 1 indicates in-reach sedimentation; a ratio close to 1 indicates a state with little erosion and sedimentation (close to equilibrium).

We used change-point analysis (Hurst, 1951; Buishand, 1982; Taylor, 2000) to test for non-linear trends in normalized anomalies and to detect change points. The cumulative function T is defined such that its values are calculated as $T_i = T_{i-1} + (\overline{X} - X_i)$; X_i, $i = 1, 2 \ldots N$ is the time series of normalized anomaly; and $\overline{X}$ is the mean value. The mean value for the period 1950–1985 was used as the normalization reference unless otherwise stated. A potential change point is detected when a change in the direction of the T function occurs, where the interval of occurrence is defined by the parameter $T_{diff} = In(T_{max}) - In(T_{min})$, in which In(·) indicates the indices of the maximal (T_{max}) and minimal T (T_{min}). Statistical significance of the identified change points was verified by using a bootstrapping technique at the 5% ($p < .05$) significance level (Castino et al., 2016). This was achieved by conducting the above analysis on the synthetic sequences of annual sediment load based on a random resampling of the original time series data. The level of significance is given by the percentage of bootstrap cycles for which the synthetic T_{diff} parameter is greater than the observed one. Once a primary statistically significant change point was obtained, the same procedure was applied to the sub-time series of the X variable before and after the change point to search for secondary change points. Then Student's *t*-test and Mann-Kendall (MK) test at 5% significance level were used to determine the statistical significance of the linear trend between the change points (Mann, 1945; Kendall, 1948).

3. Results

3.1. Sediment loads in the tributaries

The sediment loads of the large tributaries exhibit a predominant negative trend (Figs. 2 and 3). For example, a 70% sediment load reduction occurred in the Yalong River in 1998–2017 compared with 1980–1997 data, showing a statistically significant change point in 1998, because of the Ertan Dam in 1991–1998-2000, where the three-year convention indicates the years when dam construction started, the water storage commenced, and the construction was finished, respectively; this particular three-year convention was adopted throughout this work. In the Min River, stepwise reductions were detected with significant change points in 1969 ($p < .03$), 1992 ($p < .04$), and 2006

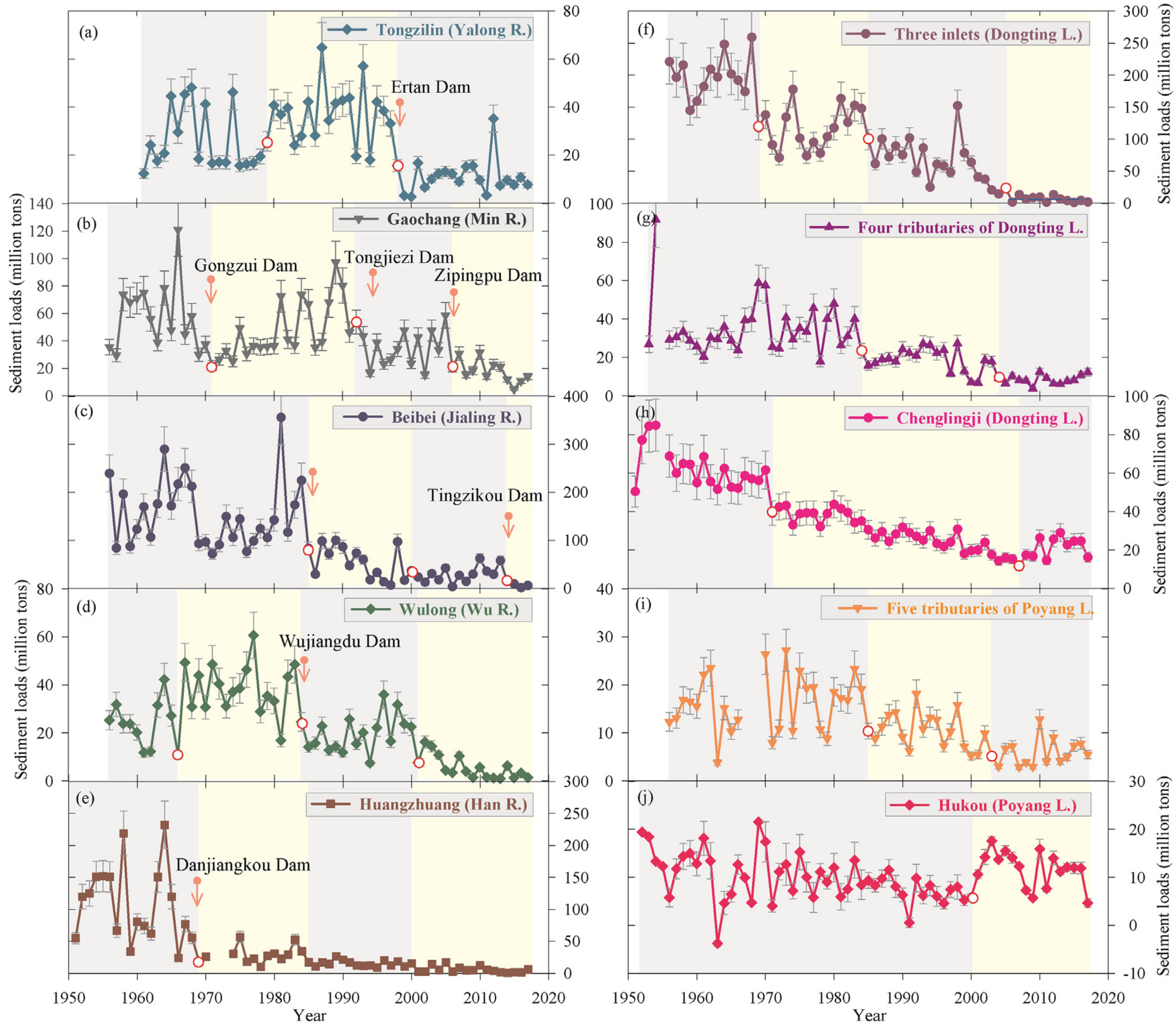

Fig. 3. Sediment load changes at the mouths of large tributaries, inlets and lakes in the CRB in 1950–2017: (a) Tongzilin (Yalong River), (b) Gaochang (Min River), (c) Beibei (Jialing River), (d) Wulong (Wu River), (e) Huangzhuang (Han River), (f) Three inlets (Dongting Lake system), (g) four combined tributaries flowing into the Dongting Lake, (h) Chenglingji (Dongting Lake system), (h) five combined tributaries flowing into the Poyang Lake and (i) Hukou (Poyang Lake system). The red empty circles indicate the change points, and the arrows indicate the year in which the hydropower dams began operation. Shading is used to indicate different time intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Sediment loads (SL) in the tributaries in different intervals; the values are given as means and one standard deviation.

Tributary	Gauge	SL (Mt yr^{-1})	Interval	SL (Mt yr^{-1})	Interval	SL (Mt yr^{-1})	Interval	SL (Mt yr^{-1})	Interval
Yalong River	Tongzilin	25.9 ± 12.5	1961–1979	37.5 ± 11.8	1980–1997	11.2 ± 7.1	1998–2017	–	–
Min River	Gaochang	61.3 ± 24.2	1956–1968	45.8 ± 20.3	1969–1991	36.0 ± 13.7	1992–2005	18.0 ± 7.9	2006–2017
Jialing River	Beibei	155.3 ± 70.3	1956–1984	57.2 ± 32.6	1985–1999	29.1 ± 16.3	2000–2014	5.4 ± 4.2	2015–2017
Wu River	Wulong	23.7 ± 9.7	1956–1966	39.0 ± 10.3	1967–1983	19.9 ± 7.4	1984–2000	5.5 ± 4.8	2001–2017
Four small tributaries[a]		33.4 ± 11.2	1963–2001	16.0 ± 10.7	2002–2016	–	–	–	–
Han River	Huangzhuang	108.2 ± 59.6	1951–1968	25.8 ± 12.6	1969–1989	14.5 ± 4.0	1990–2000	5.6 ± 4.8	2001–2017
Dongting Lake	Four tributaries	35.2 ± 14.3	1953–1984	17.8 ± 6.7	1985–2005	8.6 ± 2.6	2006–2017	–	–
	Three inlets	200.2 ± 32.1	1956–1968	118.2 ± 32.6	1969–1984	64.7 ± 33.6	1985–2005	5.9 ± 4.3	2006–2017
	Chenglingji	62.5 ± 10.4	1951–1970	29.1 ± 9.1	1971–2007	21.7 ± 5.1	2008–2017	–	–
Poyang Lake	Five tributaries	16.2 ± 6.0	1956–1984	10.9 ± 3.6	1985–2000	6.0 ± 2.7	2001–2017	–	–
	Hukou	14.1 ± 3.8	1952–1962	9.4 ± 4.8	1963–1989	6.2 ± 2.4	1990–2000	11.8 ± 3.6	2001–2017

[a] The combined sediment loads of the four small tributaries are summarized by the flux at XiaoHGY, Ningnan, Hengjiang, and Fushun.

($p < .02$; Fig. 3b). The mean sediment load in 2006–2017 was only 29% of that in 1956–1968 (Table 2). For the Jialing River, the sediment loads showed an 81% reduction in 2000–2014 compared with that in 1956–1984 (Fig. 3c). The sediment loads have declined to 5.4 ± 4.2 Mt. yr^{-1} in 2015–2017, showing a reduction of 97% with respect to 1956–1984 data (Table 2). Similar stepwise reduction occurred in the Wu River, with a reduction of 86% in 2001–2017 compared with 1967–1983 data (Fig. 3d and Table 2). Other than the overall reduction at the time scale of 60 years, the sediment loads exhibited significant positive trends in 1970–1990 for the Yalong River ($p < .02$) and the

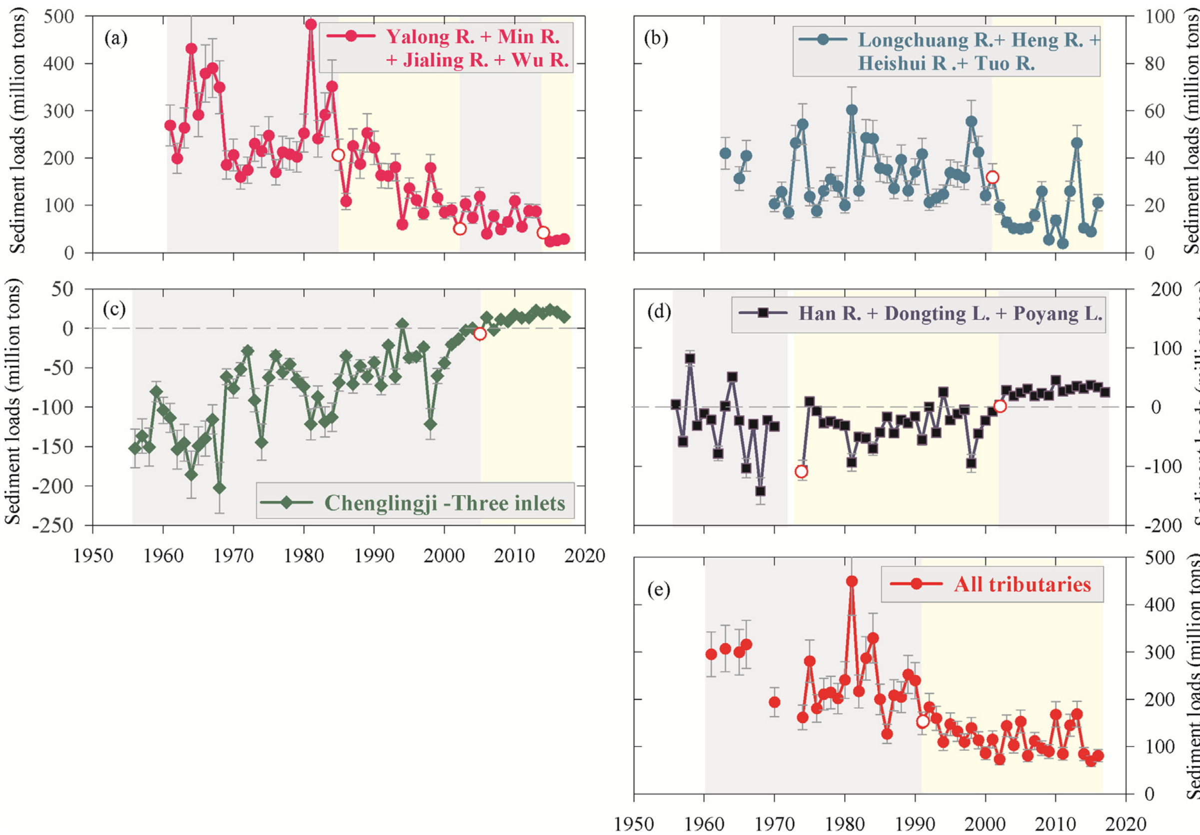

Fig. 4. Total sediment loads of the tributaries, inlets and lakes during 1950–2017: (a) the four large tributaries in the upper basin including the Yalong, Min, Jialing, and Wu rivers, (b) the four small tributaries in the upper basin including the Longchuang, Heng, Heishui, and Tuo rivers, (c) the Chenglingji minus the three inlets, (d) the three large tributaries in the middle-lower basin including the Han River, and Dongting and Poyang lake systems, and (e) all of the large and small tributaries. The red circles indicate the change points. Shading is used to indicate different time intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Min River ($p < .03$), and in 1956–1985 for the Wu River ($p < .02$). These temporal increases in the 1970s and 1980s are ascribed to an increased sediment yield in response to deforestation and land use changes.

The combined sediment loads of the aforementioned four large tributaries, the combined drainage area of which accounts for 66% of that between Panzhihua and Yichang, displayed a gradual decreasing trend from 1985 onward (Fig. 4a). Specifically, the average, 264.2 ± 86.7 Mt. yr^{-1} in 1961–1985, decreased to 64.6 ± 30.3 Mt. yr^{-1} in 2002–2017. The recent years were characterized by an emerging low sediment load that averaged 30.0 ± 8.5 Mt. yr^{-1} in 2014–2017, implying a reduction of 89% compared with that in 1961–1985.

The small tributaries in the upper basin deliver measurable sediment loads to the mainstream. The summarized sediment loads of the Longchuang, Heng, Heishui, and Tuo rivers, at 33.4 ± 11.2 Mt. yr^{-1} in 1963–2001, decreased to 16.0 ± 10.7 Mt. yr^{-1} in 2002–2016 (Fig. 4b and Table 2). These small tributaries presently stand out as important sediment suppliers to the mainstream.

In the middle-lower basin, the sediment loads of the Han River exhibited two significant change points in the late 1960s ($p < .04$) and the late 1980s ($p < .02$) (Fig. 2e). The mean sediment loads were 95% smaller in 2001–2017 compared with 1951–1968 data (Table 2). The sediment loads of the four tributaries emptying into the Dongting Lake exhibited no significant changes between 1950 and the mid-1980s, but declined abruptly in the mid-1980s, followed by a slow decrease until 2017 (Fig. 3g). The loads were approximately 76% smaller in 2006–2017 compared with 1953–1984 data (Table 2). At the three inlets, the sediment loads have reduced progressively since 1950 (Fig. 3f) and were 97% smaller in 2006–2017 compared with 1956–1968 data. This reduction is the consequence of reduced water diversion at the three inlets as a result of main river erosion and lowered river stages as well as aggradation of the inlets (Chen et al., 2001; Yin et al., 2007). Accordingly, the sediment loads at the lake mouth at Chenglingji were reduced by 65% in 2008–2017 compared with 1951–1970 data (Table 2).

Similarly, the total sediment loads of the five tributaries discharging into the Poyang Lake exhibited no directional changes between the mid-1950s and the mid-1980s, although a statistically significant negative trend ($p < .001$) was noted between the late 1970s and the late 2000s (Fig. 3i). A reduction of 63% occurred in 2001–2017 compared with 1956–1984 data. At the lake mouth at Hukou, the sediment loads decreased by 56% in 1990–2000 compared with 1952–1962 data (Table 2). More sediments have been flushed out of the Poyang Lake since 2001 compared with that in the previous two decades owing to sand mining activities (Fig. 3j). When considering the Dongting Lake sediment loads, which is that at Chenglingji minus the loads at the three inlets, as well as the loads in the Han River and Poyang Lake, a net sediment loss of 30.6 ± 28.5 Mt. yr^{-1} from the mainstem was recorded in 1956–2002, which changed, however, to a sediment surplus of 28.7 ± 7.6 Mt. yr^{-1} in 2003–2017 (Fig. 4e). Overall, the sediment loads of most of the tributaries have decreased to low and insignificant quantities during recent years, particularly the Jialing, Wu, and Han rivers (Figs. 3 and 4).

3.2. Sediment loads along the mainstem

The sediment load changes in the mainstem are characterized by

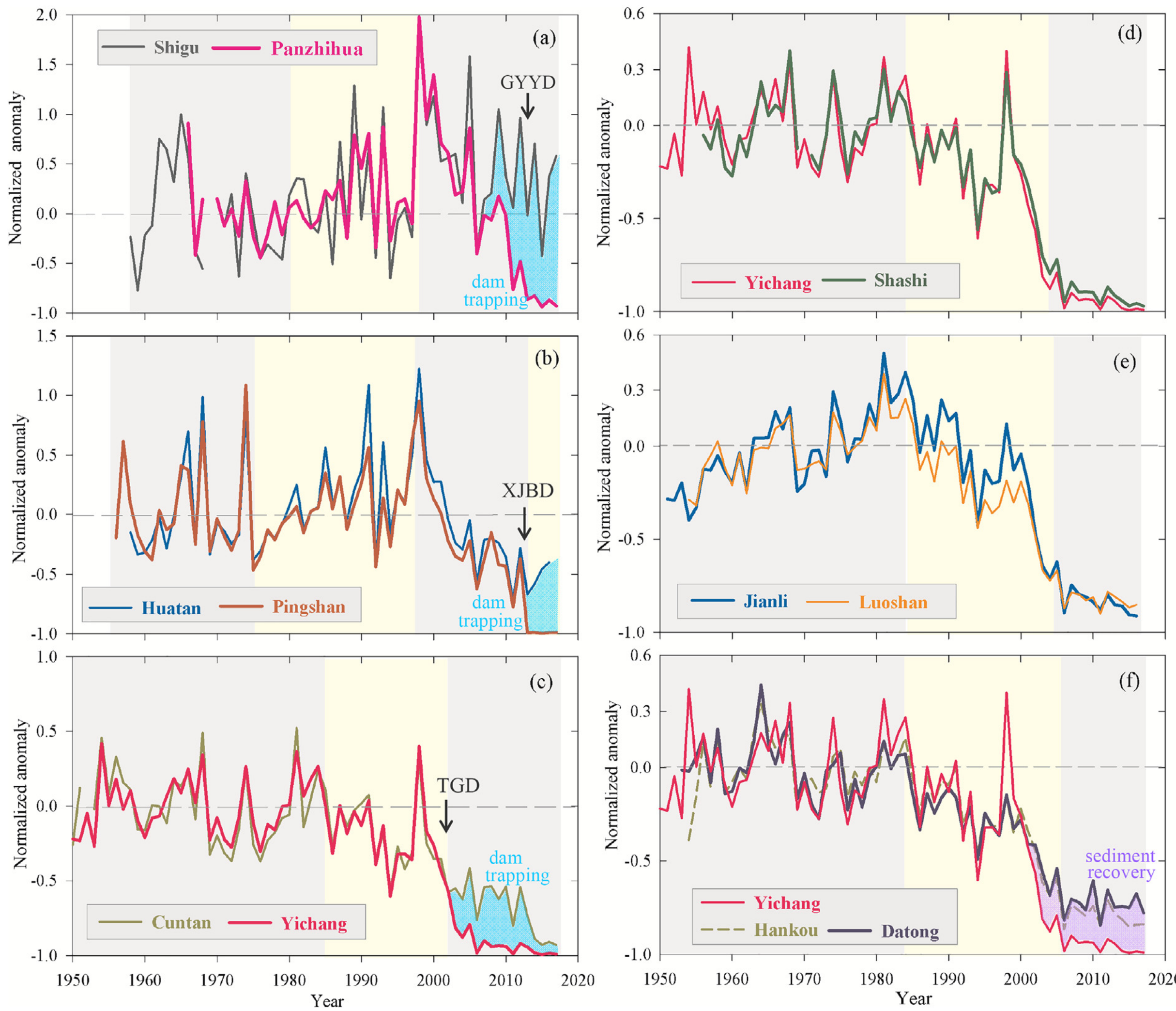

Fig. 5. Normalized anomalies of annual sediment loads at (a) Shigu and Panzhihua, (b) Huatan and Pingshan, (c) Cuntan and Yichang, (d) Yichang and Shashi, (e) Jianli and Luoshan, and (f) Hankou and Datong along the Changjiang mainstem. The reference period is 1950–1985. GYYD in (a) indicates Guanyinyan Dam. XJBD in (b) indicates Xiangjiaba Dam. The differences between the two lines in each plot indicate the impacts of dam trapping or sediment recovery. Shading is used to indicate different time intervals. The light blue shading in panels (a), (b), and (c) indicates the effects of dam trapping, whereas the magenta shading in panel (f) indicates sediment recovery between Yichang and Datong. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Sediment loads (SL) at gauges along the main river; values are given as means and one standard deviation.

Gauge	SL (Mt yr^{-1})	Interval	SL (Mt yr^{-1})	Interval	SL (Mt yr^{-1})	Interval	SL (Mt yr^{-1})	Interval
Zhimenda	8.8 ± 5.3	1956–1980	10.1 ± 5.9	1981–2017	–	–	–	–
Shigu	20.3 ± 10.3	1958–1980	23.7 ± 11.4	1981–1997	32.4 ± 12.8	1998–2017	–	–
Panzhihua	42.4 ± 14.9	1966–1980	56.0 ± 23.1	1981–2010	8.1 ± 6.7	2011–2017	–	–
Huatan	157.2 ± 62.1	1958–1980	205.5 ± 63.8	1981–2002	111.2 ± 31.8	2003–2012	80.5 ± 18.6	2013–2017
Pingshan	245.5 ± 100.6	1956–1975	261.0 ± 78.6	1976–1998	173.8 ± 68.5	1999–2012	1.7 ± 0.7	2013–2017
Zhutuo	316.4 ± 90.1	1956–1975	309.3 ± 72.5	1976–1998	197.2 ± 70.4	1999–2012	37.9 ± 18.2	2013–2017
Cuntan	453.4 ± 111.8	1950–1978	403.2 ± 126.5	1979–2002	180.7 ± 53.9	2003–2013	40.5 ± 8.7	2014–2017
Yichang	523.0 ± 103.7	1950–1985	411.0 ± 129.1	1986–2002	46.6 ± 32.9	2003–2013	6.2 ± 3.2	2014–2017
Jianli	367.3 ± 80.0	1951–1985	341.2 ± 74.7	1986–2002	73.5 ± 33.8	2003–2017	–	–
Luoshan	442.5 ± 70.4	1954–1985	346.6 ± 67.6	1986–2002	86.4 ± 31.6	2003–2017	–	–
Hankou	431.3 ± 65.5	1953–1985	330.4 ± 57.8	1986–2002	101.0 ± 36.5	2003–2017	–	–
Datong	470.4 ± 71.4	1951–1985	317.7 ± 74.3	1986–2005	124.2 ± 31.7	2006–2017	–	–

high spatial and temporal variability. In the main river upstream of Pingshan, the sediment loads showed a positive trend prior to 2000 ($p < .05$), followed by a sharp decline thereafter (Figs. 2 and 5 and Table 3). In the headwater zone, the sediment loads at Zhimenda slightly increased from 8.8 ± 5.6 Mt. yr^{-1} in 1956–1980 to 10.1 ± 5.9 Mt. yr^{-1} in 1981–2017 (Table 3). Approximately 800 km downstream of that area, the sediment loads at Shigu showed a stepwise increase with two significant change points detected in 1980 ($p < .01$) and 1998 ($p < .005$), respectively (Fig. 5a). The sediment loads peaked in 1998 in the reach between Shigu and Pingshan, followed by a rapid reduction thereafter. The increase in the reach between Shigu and Pingshan in the 1970s–1990s is in line with larger sediment loads in the Yalong and Min rivers in the same period (see section 3.1). Subsequently, the mean sediment loads were reduced to 8.1 ± 6.7 Mt. yr^{-1} at Panzhihua in 2011–2017, which was even smaller than that at Shigu, at 27.4 ± 9.9 Mt. yr^{-1} (Fig. 5a and Table 3). The loads further declined to merely 1.7 ± 0.7 Mt. yr^{-1} at Pingshan in 2013–2017 due to the operation of the Xiangjiaba Dam, which is < 1% of the mean value recorded prior to 2000 (Table 3).

The sediment loads increased in the downstream direction between Pingshan and Cuntan owing to the sediment supply from the tributaries (Fig. 5b). Temporally, the sediment loads at Cuntan were reduced by 60% in 2003–2013 compared with 1950–1978 data (Table 3). The temporal changes at Yichang were in line with those at Cuntan prior to 2002, whereas the sharp reduction that occurred around 2003 is attributed to the TGD operation (Fig. 5c). A statistically significant decline was detected in the decades since the mid-1980s at both Cuntan and Yichang. The sediment loads were reduced by 93% in 2003–2017 compared with those recorded in 1950–1985 at Yichang. The reduction to 6.2 ± 3.2 Mt. yr^{-1} in 2014–2017 is < 1% of the mean value recorded in 1950–1985 (Table 3).

The sediment loads have also declined along the middle-lower river following the changes at Yichang, except for a regional increase in the reach between Shashi and Luoshan (Figs. 5d to 5f). The increase in sediment loads at Jianli and Luoshan between 1950 and 1985 was caused by a decrease in sediment lost to the Dongting Lake via the three inlets (Fig. 3f). Specifically, the average sediment loads at Jianli were 155.7 ± 96.6 and 69.8 ± 67.2 Mt. yr^{-1} smaller than those at Yichang in 1951–1985 and 1986–2002, respectively (Table 3). Since 1985, the negative trend in sediment loads has persisted throughout the river downstream of Yichang, although the magnitude and rate of the decrease became smaller in the downstream direction (Table 3).

Further downstream, the decline in sediment loads has been statistically significant at both Hankou ($p < .02$) and Datong ($p < .01$) since 1960 (Fig. 5f). The sediment loads decreased by 75% at Hankou in 2003–2017 compared with 1953–1985 data (Table 3). A temporally stable sediment flux of 124.2 ± 31.7 Mt. yr^{-1} was approached at Datong in 2006–2017, which is 74% smaller than the mean value recorded in 1951–1985. Overall, the sediment loads along the mainstem have decreased progressively over a period of 60 years (Figs. 2 and 5).

3.3. In-reach sediment budget

The in-reach sediment budget analysis reveals apparently different sediment delivery and storage patterns between the upper and middle-lower mainstems (Fig. 6). The sediment output to input ratio was largely > 1 in the upper mainstem prior to 2000, suggesting an in-reach net sediment supply (Figs. 6a-f). This net supply can be ascribed to sediment sources from ungauged small tributaries and debris flows (see section 4.1). In contrast, the meandering river between Yichang and Luoshan had an output-to-input ratio close to 1 prior to 2000, which suggests that it was close to an equilibrium state and acted as a sediment conduit (Fig. 6g). The reach between Luoshan and Datong had an output-to-input ratio averaging < 1 prior to 2000, which suggests in-reach sediment deposition and channel aggradation.

Significant changes in the in-reach sediment budget have occurred since the early 2000s as the human influence has increased. The Shigu-Panzhihua reach has changed from being a net source of sediment to a storage sink since 2011 (Fig. 6b) owing to the sediment trapping effects of the newly built hydropower dams. Similar changes have occurred in the Huatan-Pingshan reach (Fig. 6d) and in the Cuntan-Yichang reach (Fig. 6f) owing to dams such as the Xiangjiaba, Xiluodu, and TGD. A net in-reach sediment supply remained in the reach between Pingshan and Cuntan, but its magnitude has decreased (Fig. 6e). In contrast, the river downstream of Yichang changed from slight aggradation prior to 2000 to net sediment supply and degradation post-2000 (Fig. 6g and h).

3.4. Basin-wide change behavior

The annual streamflow increases gradually in the downriver direction, except for a regional decline noted between Yichang and Jianli (Fig. 7a and c). The downstream increase is ascribed to accumulated inflow from tributaries, whereas water lost into the Dongting Lake caused the regional reduction. A major portion of the streamflow is derived from the regions between Pingshan and Yichang (i.e., the Sichuan Basin), and between Jianli and Datong (i.e., the Two-Lake Basin). This corresponds to the two rain storm zones under the influences of the East Asian monsoon: the Min-Jialing rivers and the Dongting-Poyang lake systems (Gemmer et al., 2008). Over time, the streamflow throughout the river has decreased slightly in the recent decades, but the trend is statistically insignificant ($p < .1$).

To better indicate the temporal sediment load changes, we categorized the time series of data into four intervals: 1956–1985, 1986–2002, 2003–2012, and 2013–2017 (Fig. 7c and d). These periods were chosen because a significant change point of streamflow was detected in 1954 according to the data recorded between 1878 and 2015 at Yichang and between 1865 and 2015 at Hankou (Guo et al., 2018). Similar change points may have occurred for sediment loads, although they were not detected directly from sediment load data due to the shorter record length. In addition, a significant change point occurred in the sediment loads in 1985 at the majority of gauges along the mainstem, as discussed in section 3.2. Moreover, the sediment loads downstream of Yichang have reduced sharply since the TGD began operation in 2003. Further, the sediment load reduction in the upper basin has been reinforced since 2013, when additional hydropower dams were constructed (Fig. 5).

Taking the 1956–1985 as the reference period in which human activities did not induce significant sediment load changes in the mainstem, the yearly sediment loads were shown to increase from the headwater to Yichang in the downstream direction, followed by a decrease until Jianli. From Jianli, the sediment outflow from the Dongting Lake led to a moderate recovery at Luoshan but was followed by a slight decrease in the reach to Hankou. Farther downstream, the sediment sources from the Han River and Poyang Lake resulted in a larger sediment flux at Datong than that at Hankou (Fig. 7d). It is notable that the sediment flux at Datong was smaller than that at Yichang in 1956–1985; the former controls a significantly larger drainage area than the latter. This result is attributed to along-channel sedimentation and sediment lost to the Dongting Lake.

The along-river sediment load variations changed profoundly in the subsequent periods (Fig. 8). Sediment loads in the headwater zone upstream of Shigu changed little; they were slightly larger in 1986–2002 than in 1956–1985 in the reach between Shigu and Zhutuo. Downstream of Zhutuo, a reduction occurred over the entire reach to Datong. Since 2003, the sediment loads downstream of Shigu began to decrease significantly (Fig. 7d). The reduction was most significant between Cuntan and Yichang in 2003–2012 and between Panzhihua and Cuntan in 2013–2017. The nearly linear sediment load increase in the downstream direction starting from Yichang in both 2003–2012 and 2013–2017 suggests sediment recruitment that led to gradual sediment load recovery. The sediment load reduction trend migrated upstream over time (Fig. 7d). Overall, the sediment flux in the CRB has decreased substantially throughout the river downstream of Shigu over the last three decades (Fig. 8). The low sediment loads at Panzhihua, Pingshan, and Yichang in recent years indicate the controlling effects of the dams.

The Changjiang River is becoming overwhelmingly limited in sediment supply as a result of a substantial decline in sediment load. The main river has become increasingly less sediment-laden in the downstream direction (Fig. 9a). The recent years since 2013 are characterized by a particularly low sediment load regime throughout the river downstream of Panzhihua. The tributaries in the northwestern regions of the CRB (i.e., the Yalong, Min, Jialing, and Han rivers) are relatively more sediment-laden than the tributaries in the southeastern regions

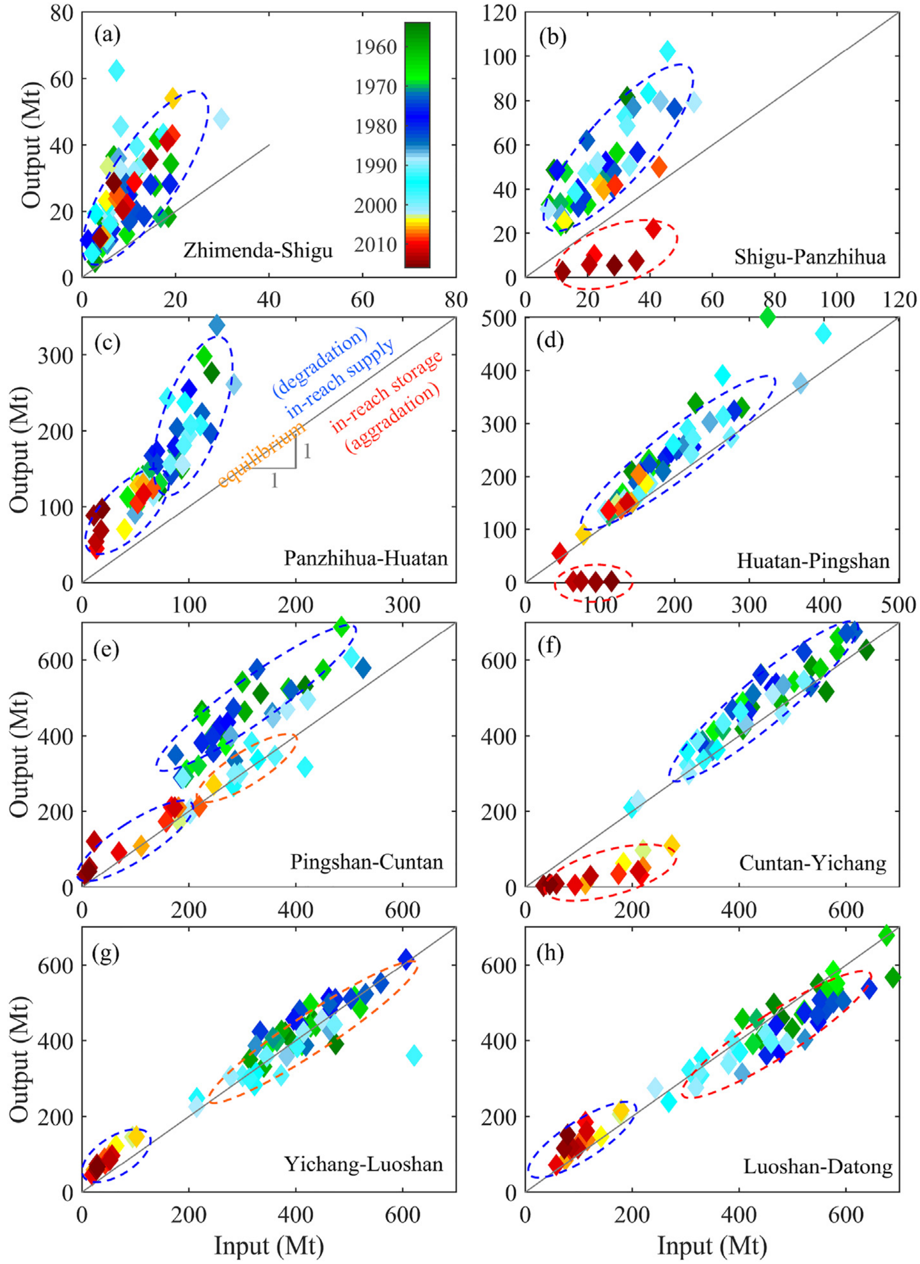

Fig. 6. In-reach sediment input and output correlations along the mainstem in the reaches (a) the reach of Zhimenda to Shigu, (b) Shigu to Panzhihua, (c) Panzhihua to Huatan, (d) Huatan to Pingshan, (e) Pingshan to Cuntan, (f) Cuntan to Yichang, (g) Yichang to Luoshan, and (h) Luoshan to Datong. An output to input ratio equal to 1 indicates equilibrium, whereas ratios < 1 and > 1 indicate in-reach sediment recruitment (degradation) and in-reach sediment storage (aggradation), respectively.

(i.e., the Wu River and the Dongting and Poyang lake systems) (Fig. 9b). The small tributaries along the Jinsha River also carry proportionately higher sediment loads than the large tributaries, i.e., large sediment loads are carried by small streamflows. In contrast, the outflows of the Dongting and Poyang lakes have proportionately smaller sediment loads because of the sedimentation inside the lakes.

4. Discussion

4.1. Causes of sediment load changes

Multiple factors affect the sediment loads in river channels, including climate change, land use, dams, river channel morphological changes and human-induced sand mining and dredging (Table S1). It is generally agreed that climate change is of secondary importance in causing sediment load changes in the CRB at the decadal time scales (Yang et al., 2006, 2015; Dai and Lu, 2014). Changes in land use due to deforestation explain the slight increase in sediment loads prior to the 1980s in the upper basin, whereas reforestation and the hydropower dams in the tributaries initiated the reduction since the mid-1980s (Yang et al., 2006; Wei et al., 2011). Large hydropower dams in the mainstem have become a major factor in accelerating the decline in sediment load since the early 2000s (Yang et al., 2006, 2015, 2018; Dai and Lu, 2014). Nonetheless, isolating and quantifying the impacts of different driving forces remains a challenge because of the buffering and masking effects that cause damping and even removal of signals of increasing or decreasing flux in the downstream direction. This complicates the link between the upstream and downstream responses to human impact (Higgitt and Lu, 1999; Walling, 2006; Wang et al., 2007). Here, we present a more holistic analysis of the sediment

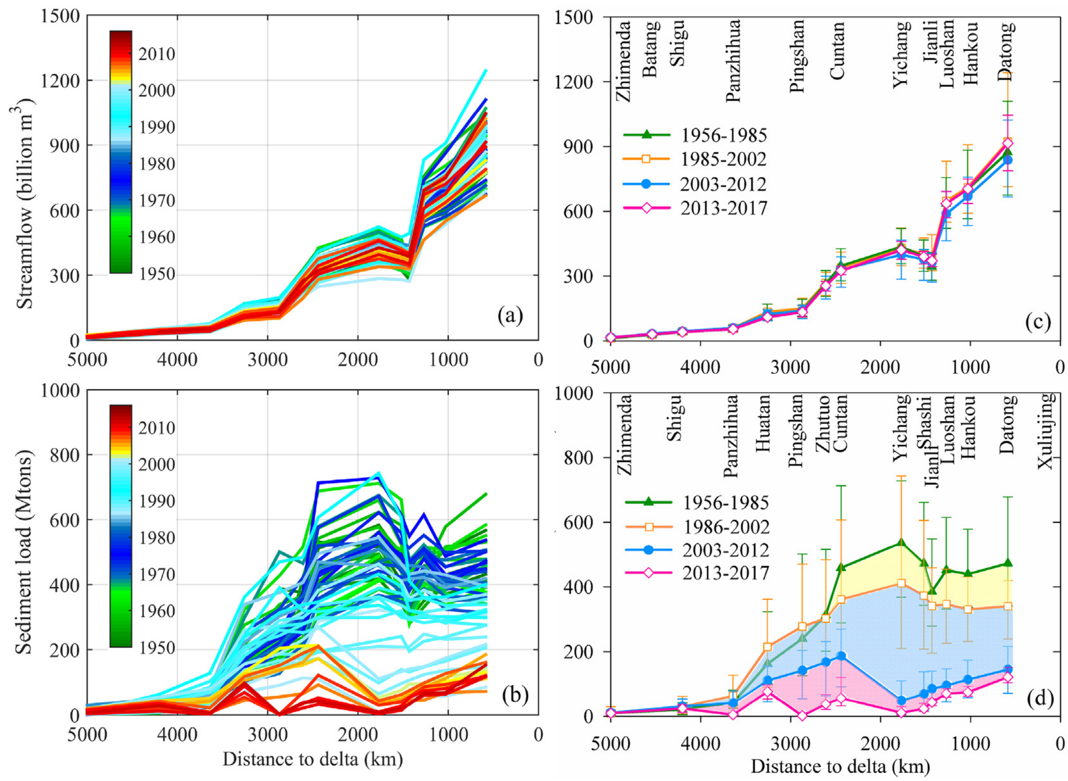

Fig. 7. Along-river changes in annual (a) streamflow and (b) sediment loads between Zhimenda and Datong recorded in 1950–2017, (c) multi-year averaged streamflow, and (d) sediment loads in four intervals. The distance to the delta was measured from Xuliujing, the present-day delta apex shown in Fig. 1. It was notable that the data length at Zhimenda, Batang, Shigu, and Panzhihua is slightly shorter than that at other gauges, as shown in Table 1, which may induce bias on the mean value in the period of 1956–1985.

trapping effects of the large hydropower dams and the factors causing sediment replenishment and sediment load recovery, while an additional review and discussion of the impacts of hydro-meteorological changes, land use changes, and sand mining are included in the Supporting Information.

4.2. Dam impacts

Numerous hydropower dams are operating within the CRB, the majority of which are in the upper basin. The total number of dams in 2016 was > 52,000 and their total storage capacity is ~360 billion m^3, with a flood control capacity of > 77 billion m^3; this ranks the Changjiang River as one of the most heavily dammed rivers in the world (Yang et al., 2011, 2018). In the 1980s, the total sedimentation rate in the man-made reservoirs was 139.9 million m^3 per year in the upper CJR basin (Guo, 2015; Wei et al., 2011). Gao et al. (2015) documented that the sediment trapping rate of the man-made reservoirs crossing the CRB increased from < 30 Mt. yr^{-1} in the 1950s to ~124 Mt. yr^{-1} by 1989 and ~208 Mt. yr^{-1} by 2002. Yang and Lu (2014) reported a total reservoir sedimentation rate of 691.0 ± 93.7 Mt. yr^{-1} across the entire CRB, which may be overestimated because it is even larger than the sediment flux in the main river. These evidences indicate substantial sediment trapping with a consequent reduction in downriver sediment loads.

The statistically significant change points in sediment loads of the tributaries were strongly correlated to the years in which the dams were

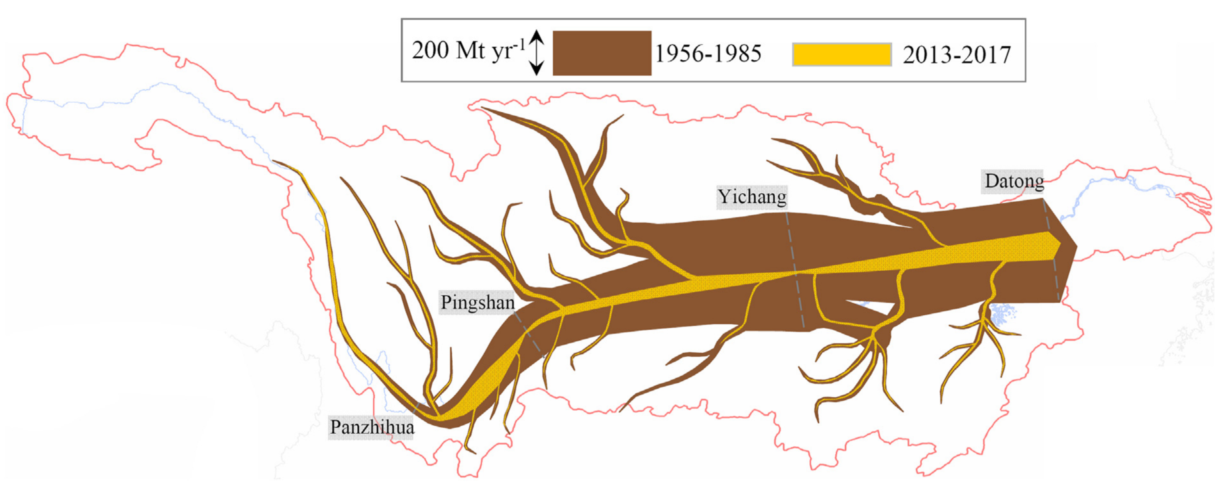

Fig. 8. A sketch of sediment load distribution in 1956–1985 and 2013–2017 throughout the CRB.

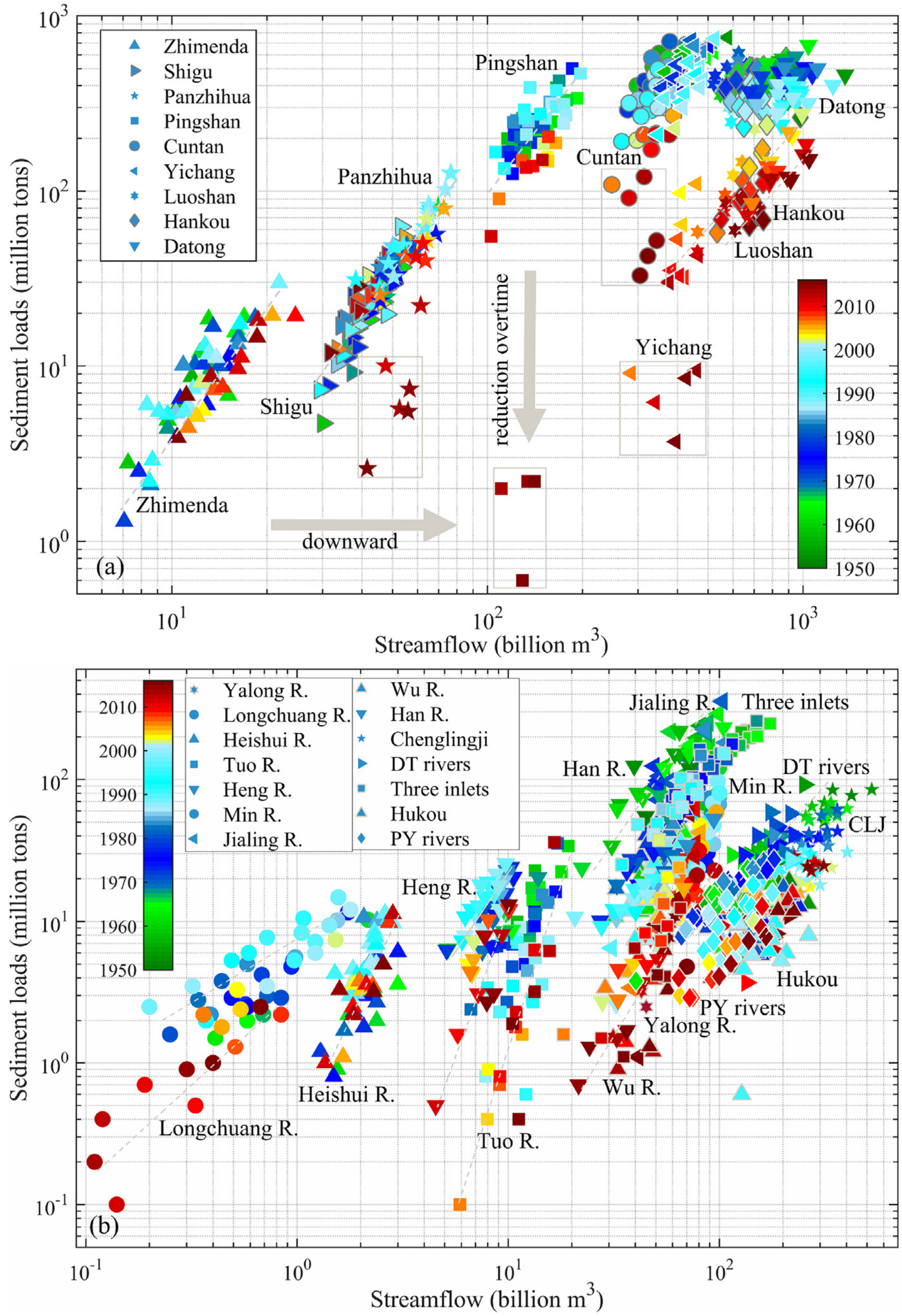

Fig. 9. Rating curves based on the annual streamflow and sediment loads (a) along the Changjiang mainstem between Zhimenda and Datong, and (b) those of the tributaries and lake systems. The boxes in (a) indicate the data points since 2013. The labels 'over-time' and 'downstream' indicate the changes overtime and in the downstream direction. The dashed lines indicate the derived linear relationship between streamflow and suspended loads at double-log scales. CLJ, DT, and PY in panel (b) indicate Chenglingji, Dongting and Poyang, respectively.

put into operation (Fig. 3). Specifically, the Ertan Dam was responsible for the sediment load reduction at the mouth of the Yalong River in 1998 (Figs. 3a and S3). The Gongzui Dam (1966–1970-1979) in the Min River had caused ~58% of sediment load reduction at the dam site (Gu and Ian, 1989), whereas the Tongjiezi Dam (1985–1993-1995) and the Zipingpu Dam (2001–2004-2006) further exacerbated the reduction at the river confluence (Fig. S3). The combined effects of the Bikou Dam (1969–1976-1997), Shengzhong Dam (1977–1984-1998), Baozhusi Dam (1984–1996-1998), Dongxiguang Dam (1992–1995-1996), and Tingzikou Dam (2009–2010-2014) resulted in profound sediment load reduction in the mid-1980s and in the early 2010s in the Jialing River. The Danjiangkou Dam induced a sharp sediment load reduction in the Han River in the late 1960s (Fig. 3e).

The hydropower dams constructed in the mainstem play an even more critical role in disrupting sediment delivery. The first dam constructed in the mainstem was the Gezhouba Dam (1971–1981-1988), at a location ~4 km upstream of Yichang (Fig. 10 and S3). The Gezhouba Dam stored water for the first time in 1981 and its reservoir sedimentation reached a maximum in 1985. The sedimentation rate is ~6.4 Mt. yr^{-1} in 1981–2000 (CWRM, 2002), which is relatively small compared to a sediment flux of 478.8 Mt. yr^{-1} at Yichang in the same period. The TGD (1994–2003-2009) was the second to be built in the mainstem, but is now the biggest, with a dam length of 2335 m and a storage capacity of 39.3 km^3 (Fig. S4). Thus far, the TGD has trapped a

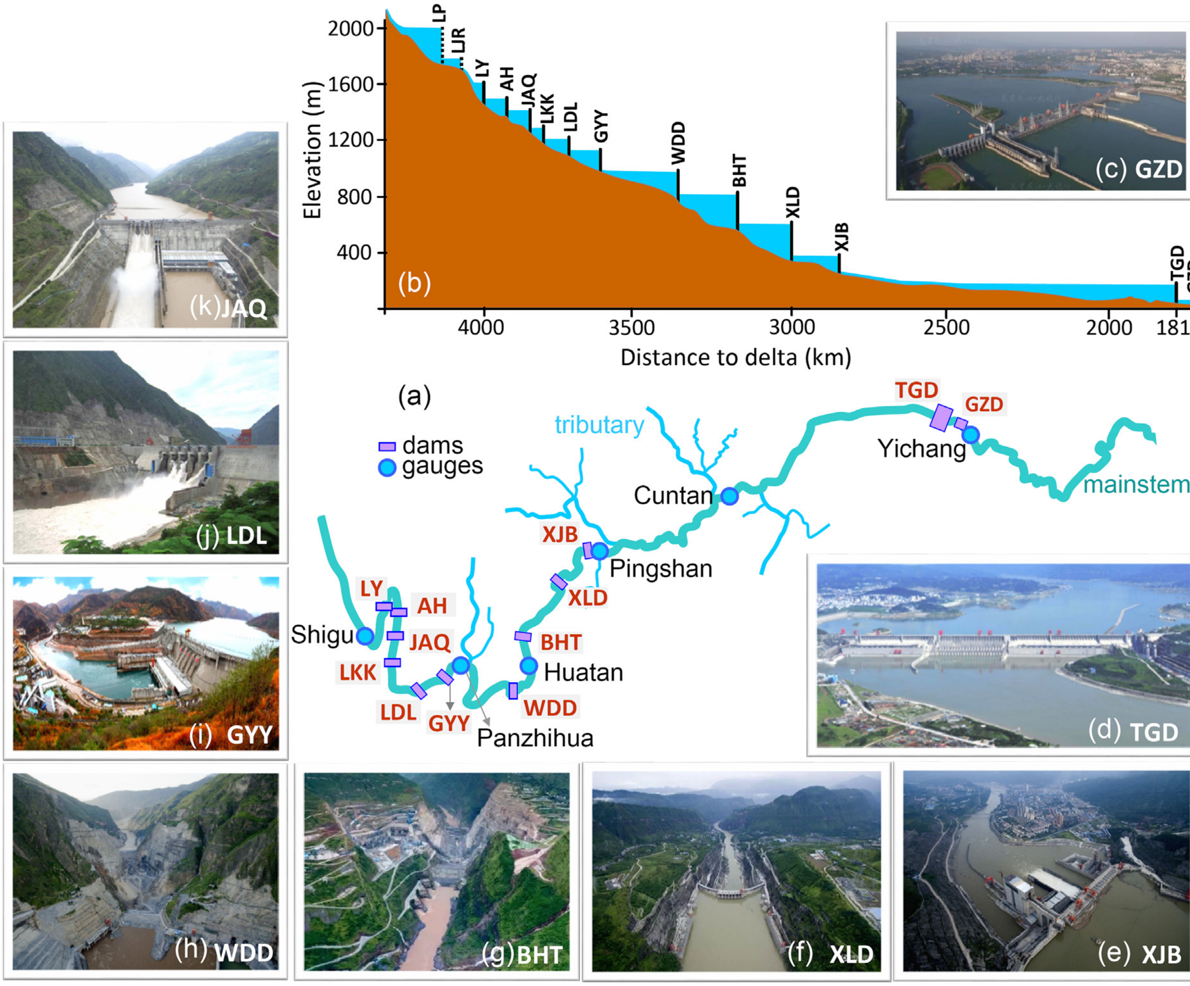

Fig. 10. (a) Location and (b) elevation of the dams in the mainstem of the upper Changjiang River, including (c) Gezhouba Dam (GZD), (d) Three Gorges Dam (TGD), (e) Xiangjiaba Dam (XJB), (f) Xiluodu Dam (XLD), (g) Baihetan Dam (BHT), (h) Wudongde Dam (WDD), (i) Guanyinyan Dam (GYY), (j) Ludila Dam (LDL), Longkaikou Dam (LKK), (k) Jin'anqiao Dam (JAQ), Ahai Dam (AH), and Liyuan Dam (LY).

Table 4
Annual incoming and outgoing sediment fluxes of the TGD and the sediment loads at Datong (unit: Mt. yr^{-1}) in four intervals between 1956 and 2017; values are given as means and one standard deviation).

Interval	TGD in[a]	TGD out[b]	TGD sedimentation	Trapping efficiency	Datong
1956–1985	490.6 ± 105.9	536.3 ± 97.1	−45.7 ± 39.2[c]	–	472.3 ± 75.0
1986–2002	380.0 ± 112.3	411.0 ± 129.1	−31.0 ± 30.8[c]	–	340.2 ± 52.6
2003–2005	226.2 ± 45.6	90.5 ± 23.8	135.7 ± 24.9	60%	189.7 ± 37.3
2006–2013	170.9 ± 53.7	30.1 ± 15.7	140.8 ± 41.4	82%	124.8 ± 37.4
2014–2017	43.6 ± 11.0	6.2 ± 3.2	37.3 ± 8.2	86%	123.0 ± 20.5

[a] Indicates incoming sediment loads based on data at Cuntan plus Wulong.
[b] Indicates the sediment load at Yichang, representing that out of the TGD.
[c] Negative values in the pre-TGD period indicate extra sediment sources in the reaches between Cuntan and Yichang.

total of 1699 million tons of sediment between 2003 and 2017 (i.e., 113.3 ± 58.4 Mt. yr^{-1}). On average, ~60% and ~83% of incoming sediments were deposited in the TGD reservoir in 2003–2005 (pilot operation period) and 2006–2017, respectively (Table 4). This sediment trapping efficiency is in line with the estimate based on the water residence time, as defined by the storage capacity to streamflow ratio (Brune, 1953; Table S2).

Since the completion of the TGD, additional dams have been constructed and more are planned along the upper main river, including the Xiangjiaba, Xiluodu, Baihetan, Wudongde, Guanyinyan, Ludila, Longkaikou, Jin'anqiao, Ahai, and Liyuan dams (Figs. 10 and S3; Table S2). The total storage capacity of the first four of these more recent large dams is ~43.1 km^3, which is even larger than the TGD. The Ludila and Guanyinyan dams have reduced the sediment flux at Panzhihua to a quantity smaller than that at Shigu, the upstream station, since 2011. The Xiangjiaba Dam reduced the sediment flux at Pingshan to 1.7 ± 0.7 Mt. yr^{-1} in 2013–2017. These new dams have reduced the sediment flux to the TGD and have slowed its reservoir sedimentation (Table 4). This change will prolong the time scale of TGD's disruption effects on sediment delivery for 300–400 years compared with the previously expected 80–100 years on the basis of a representative incoming sediment flux in the 1960s (CYJV, 1988; section S1). Presently, the impact of the TGD in addition to the collective effects of all of these large dams has significantly disrupted the sediment delivery throughout

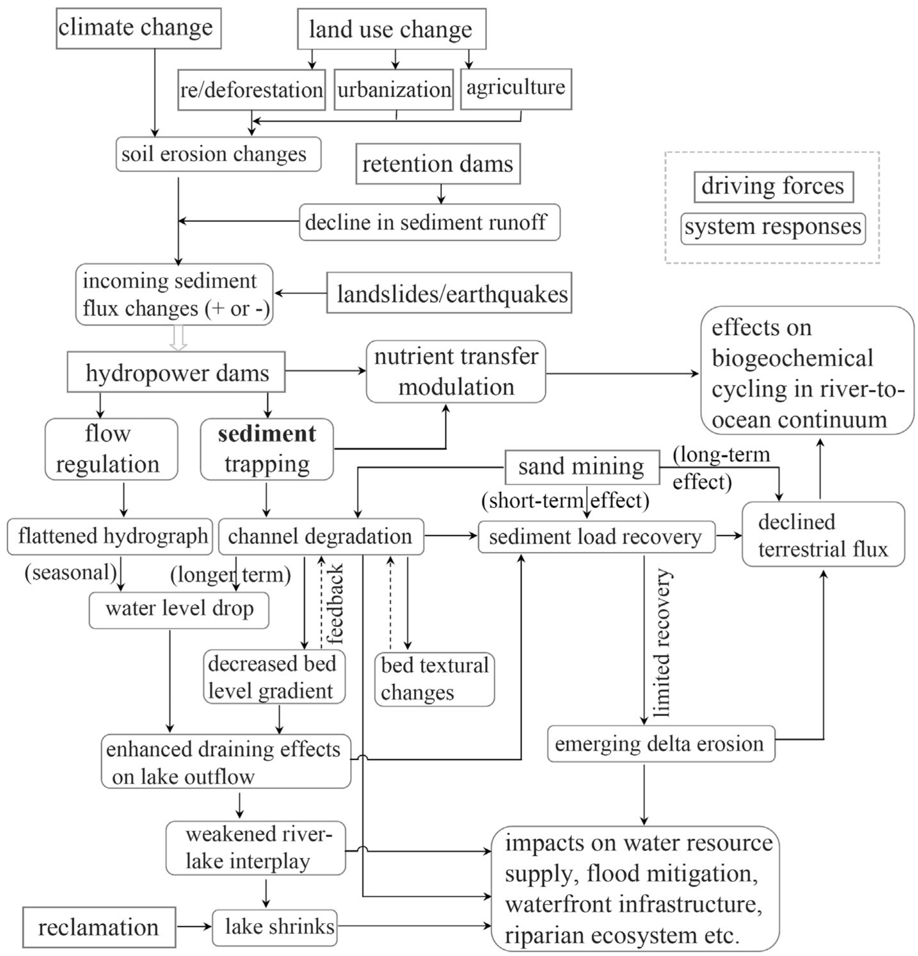

Fig. 11. Cause-consequence flow chart for sediment load changes in the Changjiang River Basin.

the main river; their cumulative sediment trapping effects will remain significant for future centuries to come.

4.3. Sediment recruitment

There are factors that lead to an increase in sediment load, including landslides and channel degradation (Fig. 11). The sediment supplied by landslides and debris flows is becoming an important in-channel source particularly in the upper basin (Liu et al., 2010). Griffiths and Topping (2017) identified the importance of small tributaries in closing sediment budgets, which may also be the case in the upper CRB. Numerous alluvial fans are present along the Jinsha River and they provide ungauged sediment to the mainstem (Figs. S8). For example, two large landslide events that occurred along the mainstem of the Jinsha River in October 2018 deposited a large quantity of sediment, ~2500 million m^3, in the mainstem and blocked the main channel for weeks (Figs. S8). The M_w 7.9 Wenchuan earthquake in the Min-Tuo River basins in 2008 resulted in a huge amount of sediment transported to the river channels that may take more than three decades to disperse (Wang et al., 2015a). The unusually high sediment loads in the Yalong River in 2012 and in the Tuo River in 2013, at 35.2 Mt. and 36.0 Mt., respectively, can be attributed to such events (Figs. 3a and 4b). Such an episodic signal was also detected at Huatan and Zhutuo in the mainstem (Fig. 5a and b). The contribution of landslides and debris flows in supplying sediments merits further quantification.

The two lake systems have supplied more sediment to the mainstem in the recent decades (Fig. 11). From a sediment budget perspective, the Dongting Lake received more sediment from the mainstem via three inlets than the amount exported at Chenglingji prior to 2006 (Fig. 4c). Since 2006, this trend has reversed, thereafter, because of the decline in the sediment loads at the three inlets and the increase in sediment exported from the lake. Specifically, the main river lost 78.2 ± 51.3 Mt. yr^{-1} to the Dongting Lake in 1956–2005, whereas the main river gained a sediment surplus of 14.4 ± 7.0 Mt. yr^{-1} in 2006–2017. The Poyang Lake has also exported more sediment to the mainstem since 2001 (Fig. 3j). The larger sediment flux at the lake mouths (Fig. 3h and j) is attributed to ongoing intensive sand mining, which has disturbed the bed and enhanced the potential for sediment suspension (Lai et al., 2014). However, it should be noted that sand mining results in channel degradation and will cause reduction in suspended sediment loads in the longer term (section S1).

Bed scouring and bank erosion in the mainstem supplies sediment and mitigates the sediment load decline in the lower river. The main river downstream of Yichang was once close to morphodynamic equilibrium (Wang et al., 2007), with some slight degradation along the Jing River (Yichang-Luoshan) and slight aggradation in the reach between Luoshan and Jiujiang prior to the 2000s (Xu, 2013), as evidenced by the in-reach sediment budget analysis (section 3.3). The equilibrium was disrupted as incoming sediment loads have declined significantly since the turn of the century (Yang et al., 2017; Xia et al., 2016). River morphology surveys suggest a total channel erosion volume of 505 million m^3 in the reach between Yichang and Jiujiang in 1981–2002, at a river length of 980 km, for ~24 million m^3 annually (Yang et al., 2017). Channel erosion below the TGD has been enhanced since 2003 (Fig. S5; Li et al., 2009; Yang et al., 2014). In total, the channel volume under a mean river stage was enlarged by approximately 1120 million m^3 in the river between Yichang and Luoshan, over a river length of 408 km, between October 2002 and October 2017 (CWRM, 2014, 2018). Channel volume increased by approximately 337 million m^3 in the reach between Luoshan and Hankou, over a river length of 251 km, between November 2003 and November 2017 (CWRM, 2018). Considering a bulk density of 1.2 ± 0.1 $t\,m^{-3}$ (Yang et al., 2006; Gao et al., 2015), we estimated that the river between Yichang and Hankou lost 1748 ± 146 Mt. of sediment in 2003–2017 (i.e., 125 ± 10.4 Mt. yr^{-1}). It should be noted that the in-reach sediment input and output for the same period were 537 ± 86 Mt. in total at Yichang and 1515 ± 242 Mt. at Hankou, respectively. In addition, an input of approximately 251 ± 40 Mt. into the reach from the Dongting Lake and Han River was recorded. The amount of sediment from channel erosion was more than double the net flux in and out of the reach. This imbalance may be explained by in-reach sediment loss due to sand mining (section S1) and/or by overestimation of channel erosion volume due to an unknown degree of uncertainty in the bathymetric data. Even allowing for some error, this suggests that channel erosion has become a dominant source of sediment supply in the middle-lower river. These extra sediments led to sediment load recovery downstream of Yichang in the post-TGD periods (Fig. 3d). Although the sediment loads at Datong have not been restored to the pre-TGD level, further channel degradation is expected as bed sediment is progressively winnowed, but eventually this degradation will be limited by surface armoring (Lai et al., 2017).

4.4. Changes in sediment connectivity

Sediment connectivity is an important component of river system dynamics and is, as reported by Bracken et al. (2015), 'the connected transfer of sediment from a source to a sink in a system via sediment detachment and sediment transport, controlled by how the sediment moves between all geomorphic zones in a landscape'. The upper and the middle-lower CRB acted as the sediment source zone and a sediment transport conduit, respectively, prior to 1985 (Fig. 12), which is consistent with the conceptual model that is typical of large river systems (Schumm, 1977). However, the sediment connectivity in the CRB was severely interrupted by dams, levees, and sand mining.

The upper and middle-lower basins are disconnected in the sense that only a very small percentage of the sediments produced in the upper basin will reach the middle-lower river and the delta in the post-TGD era (Fig. 12). The upper basin was once the major sediment source zone, particularly the region between Pingshan and Yichang (Fig. 7d). The sediment sources from the Jinsha and Jialing rivers accounted for ~43% and ~30% of the sediment loads at Yichang, respectively. The total sediment production from surface erosion is > 2000 Mt. yr^{-1} within the CRB (Guo, 2015), whereas the mean sediment loads at Yichang were ~523 Mt. yr^{-1} in 1956–1985. This indicates that only approximately one-fourth of the sediments produced from surface soil erosion ends in river channels as suspended sediment loads, i.e., a sediment delivery ratio of ~24% (Wang et al., 2007). In other words, a major portion of sediments from surface soil erosion remain in gullies, canyons, and other terrain (Guo, 2015; Wang et al., 2007). The sediment transport was basically a supply-limited condition in the upper mainstem, given the ample transport capacity in strong and turbulent river flows. Since then, the large hydropower dams and numerous retention dams which are small barrier dams built in river valleys to improve sediment retention, interrupt sediment runoff and in-channel sediment delivery. The dams become a big sediment sink and this sink will persist for centuries until the dams are filled (Fig. 12).

Sediment connectivity between the mainstem and the lakes is also declining. > 1000 of river-connected lakes were once present across the middle-lower basin. However, their number has reduced by a factor of 10 in the past century due to river regulation and reclamation in lakes (Cui et al., 2013). Only large lakes such as the Dongting and Poyang lakes have retained their river-lake connections (Fig. 1). Although, the surface area and volume of the two lakes have decreased historically owing to reclamation and sedimentation (Feng et al., 2013; Zhao et al., 2013; Guo et al., 2018). The connectivity between the main river and the two natural lakes is further weakened owing to declined river-lake interaction. The river stage along the mainstem is falling owing to the regulated river discharge and channel degradation (Han et al., 2017; Guo et al., 2018). This drop relieves the backwater effect exerted on the lake outflow and even induces a draining effect which fosters the outflow from the lakes (Guo et al., 2011, 2018; Mei et al., 2016; Zhang et al., 2016; Fig. S9). This altered river-lake interplay may explain the

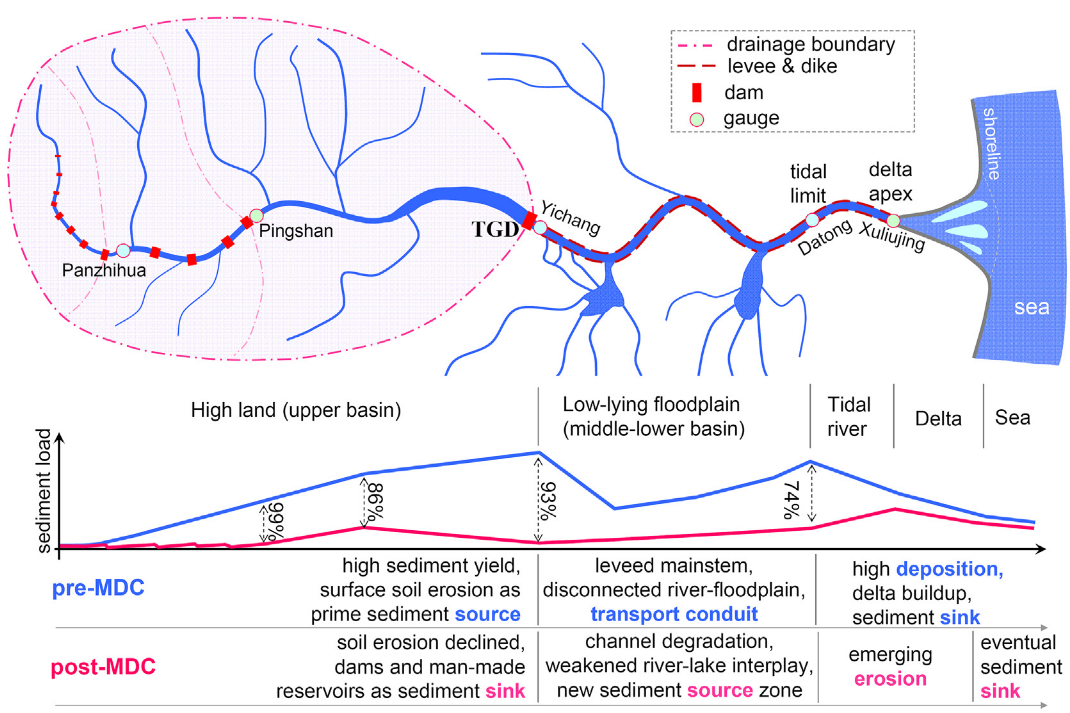

Fig. 12. Sketches of the dammed and leveed CRB system, along-river changes of sediment loads, and sediment source to sink shifts under the pre-dam and post-dam conditions. MDC indicates major dam construction. The vertical and horizontal axes in the lower plot are illustrative and not to scale.

hastened and endured low-water conditions that have occurred more frequently within the lakes since the turn of the century. To conserve the lake ecosystem and counteract the draining effect, plans have been made to construct barriers with sluices at the lake mouths to regulate lake outflows (Wang et al., 2015b). This measure may further reduce the river-lake connectivity, and its environmental and ecological impacts are insufficiently documented and remain in dispute.

The middle-lower river downstream of Yichang once behaved as a sediment transport conduit transferring upstream sediment to the delta and the seas. It was a predominantly sediment-transport-limited condition. The middle-lower river has, however, changed from a mild depositional environment to a severe erosional environment in response to a decline in incoming sediment flux. We infer that the middle-lower main river has experienced a change from being sediment-transport-limited prior to 1985, to being sediment-supply-limited in the post-TGD era from 2003 onward. During the intervening period of 1985–2003, the reach was in transition between these two states.

The middle-lower mainstem was progressively diked and leveed in order to protect the low-lying but densely populated middle-lower CRB from river floods. The dikes and levees constrict water and sediment transport within the main channel, prevent overbank flow, and isolate the floodplains from river connection. Therefore, the dikes and the levees enhance the transfer of sediment within the mainstem and have reduced the river-floodplain connectivity (Fig. 12). Constraining the system reduces the possible system states (e.g., loss of floodplains for flood storage) and thereby limits the ability and resilience of the system in using its many natural degrees of freedom to adapt to changes and extreme events. Overall, the basin-scale sediment connectivity has declined both longitudinally by the hydropower dams and laterally by the levees and weakened river-lake interplay in the CRB.

The sediment load reduction and connectivity decline have fundamental consequences for the fluvial hydro-geomorphology and land-ocean interactions (Fig. 11). For example, severe channel degradation has lowered the river stages by ~1.5 m at Yichang under a river discharge of 10,000 m^3/s between 1960 and 2003 and further by ~1.0 m by 2017 (Yang et al., 2017; Guo et al., 2018). This drop in river stage threatens irrigation and the levees. The shrinkage of natural lakes and the altered river-lake interplay impairs their water supply and flood mitigation function (Li et al., 2009; Fang et al., 2012). Retention of nutrients and organic matter absorbed to sediments may alter the land-to-ocean biogeochemical cycling (Zhang et al., 2015; Fig. 11). Delta erosion is expected as a result of decline in river-borne sediment and sea-level rise (Zhao et al., 2018). In the longer term, removal of the aged hydropower dams would reactivate large quantities of stored sediment, with the potential to induce a very different shift in river system shift. Therefore there is an urgent need to develop integrated basin-scale management strategies that move away from the present operational focus on hydropower dam operation and flood control to take a more holistic view that seeks to restore resilience and the capacity of the system to adapt to future changes.

The sediment budget analyses are influenced by the uncertainties in the data and a lack of information on ungauged small tributaries and sand mining. The sediment loads from the small tributaries and landslides stand out as important and unignorable sources to the mainstem. The lack of information on extensive sand mining and dredging may have also led to an overestimation of the influences of the TGD on sediment load reduction in the downstream river. From this perspective, we identify several key knowledge gaps that merit future study. First, more field data and comprehensive modeling tools are needed to separate and to better quantify the impacts of climate change and human activities on streamflow and sediment load changes, particularly regarding land use changes and their subsequent impact on sediment yield. Second, the basin-scale sediment production, sediment runoff, and sediment delivery and deposition at different time scales, even at geological time scales, need to be better tracked and quantified by using integrated models and geochemical proxies. Third, understanding the hydro-morphological changes and associated time scales downstream of the TGD will help to develop management policies and restoration opportunities. This will require continued monitoring of river bathymetry and sediment loads in the future. Moreover, development of large-scale morphodynamic models that incorporate textural changes and morphodynamic feedback mechanisms could make a valuable contribution.

4.5. The global context

The CRB is not the only large river undergoing intensive human interference and dramatic sediment load reduction. For example, the sediment supply to the sea from the Nile River has nearly vanished because of the sediment trapping effects of the New Aswan Dam and sediment deposition in the deltaic channel networks (Stanley, 1996; Vörösmarty et al., 2003). Hydropower dams and river engineering activities (e.g., bank revetment and meander cutoffs) have caused sediment load reduction from ~400 Mt. yr^{-1} to 145 Mt. yr^{-1} in the Mississippi River (Meade and Moody, 2010), resulting in delta erosion and shoreline retreat which, in turn, have made the restoration of habitats and the provision of flood defense more challenging (Blum and Roberts, 2009). The Yellow River, once the most sediment-laden river in the world, has experienced a sediment flux reduction from 1221 Mt. yr^{-1} in the 1950s to 143 Mt. yr^{-1} in the 2000s as a result of reforestation and dam construction (Wang et al., 2016). In addition, increased water abstraction has reduced the streamflow in the Yellow River, which is partially responsible for the sediment load decline (Miao et al., 2011). Similar sediment load reductions are present in other large rivers such as the Amazon River (Latrubesse et al., 2017), the Mekong River (Kummu et al., 2010; Schmitt et al., 2017), and the Ebro River (Tena and Batalla, 2013). The Mekong and the Amazon rivers are two large systems that are strongly influenced by recent hydropower dam construction, comparable to the Mississippi and Changjiang rivers. Overall, the sediment load reduction is much more significant than the streamflow changes in the majority of rivers, suggesting that human-induced land use changes and dams play a more profound role than climate change. Given the dramatic changes that have occurred in most large rivers around the world, the mapping of continent-scale sediment flux by Milliman and Meade (1983) and Syvitski et al. (2005) now requires updating. The cumulative impact of this sediment load reduction on global land-to-ocean transport and the flux of organic matter, nutrients and contaminants also need to be re-evaluated.

The basin-scale sediment connectivity and source-to-sink patterns under natural conditions, identified in Schumm (1977), are modified by large-scale human development and activities. This can result in fragmented river systems where network connectivity is altered, which often disrupts established sources and sinks, thereby disrupting the functional role of the constituent parts of the system. Such source-sink changes are ubiquitous in many rivers such as the Mississippi (Bentley Sr et al., 2016) and the CRB in this study. To some degree, fluvial systems are resilient to sediment load changes in response to dam construction and land use changes by channel morphodynamic adjustment. For example, Nittrouer and Viparelli (2014) reported that the sand content has not decreased significantly in the lower 1100 km of the Mississippi River after major dam construction in the upstream basin due to sediment recruitment from bed scour. The degree of sediment load recovery, however, depends on the bed sediment composition and the distance between the dam and the delta. The opportunity for sediment recovery is smaller if the dam is located in the lower river close to the delta, such as the Aswan Dam in the Nile. Sediment recovery can also be constrained by a limited availability of fine sediments on the bed, such as the river below the TGD in the Changjiang system, even though the TGD is ~1800 km upstream of the delta (Yang et al., 2017; Lai et al., 2017). Similar sediment-supply-limited conditions were also observed in the Colorado River after the construction of the Glen Canyon Dam (Topping et al., 2000; Topping et al., 2018) and in the Green River (Grams and Schmidt, 2005). The Colorado River in the Glen Canyon, USA, is still adjusting to sediment-supply limitation > 50 years after the Glen Dam was completed and sediment inputs from tributary streams may take decades to fully propagate through the mainstem river system (Topping et al., 2018). Predicting the time at which river erosion and sediment load recovery will stop, however, is still technically challenging owing to the lack of information on bottom sediment composition, uncertainty in sediment transport models, and complexity of large-scale morphodynamic changes in rivers (Castelltort and van den Driessche, 2003; Di Silvio and Nones, 2014; Lai et al., 2017).

5. Conclusions

This work provides a synthesis of the sediment delivery pattern and its spatial and temporal changes throughout the CRB based on a comprehensive examination of a long time series of sediment load data. We briefly discuss the causes, the implications, and impacts of sediment load changes when considering the entire river system. Overall, the Changjiang River has become increasingly sediment deficient and has experienced insignificant streamflow changes alongside progressive sediment load reduction. Sediment loads at most stations began to decline in the mid-1980s, followed by an abrupt drop since 2003 in the river downstream of the TGD. The sediment loads have continued to decrease since 2013 owing to the newly built large dams upstream of the TGD. The sediment loads at the outlets of the upper basin and the entire basin have reduced by 96% and 74% in 2006–2017 compared with 1950–1985 data, from 523.0 ± 103.7 Mt. yr^{-1} to 22.1 ± 17.2 Mt. yr^{-1} and from 470.4 ± 71.4 Mt. yr^{-1} to 137.3 ± 41.5 Mt. yr^{-1}, respectively. The Changjiang River is therefore becoming another heavily dammed large river undergoing substantial sediment load reduction.

The large hydropower dams constructed in the mainstem are the prime cause of the sediment load reduction. Sediment recruitment from channel degradation and the lakes has mitigated the reduction in the downriver, although the sediment flux reaching the delta is still significantly lower than the pre-dam level. The sediment loads are highly likely to persist at low levels in the coming decades to centuries in response to the cumulative dam impacts and the diminishing contribution from channel erosion.

The middle-lower river has changed from a slightly depositional environment and a sediment transport conduit to a severe erosional environment and a prime sediment source zone. Delivery of suspended sediment in the middle-lower river has also changed from transport-limited condition to supply-limited conditions. Sediments from river erosion below the TGD have become the main sediment source to the delta and the sea. Severe channel incision has lowered the bed level and river stage, which has weakened the river-lake interplay and has caused numerous hydro-geomorphological changes. The basin-scale sediment connectivity has declined as the upper river has been progressively dammed and the middle-lower river has been extensively dyked and leveed, and river-lake interplay has weakened. A sediment source shift is ongoing from surface soil erosion in the upper basin, to river channel erosion in the middle-lower basin, which is accompanied by changes in sediment composition and the associated nutrient loading.

We identified several research topics for future study and propose that integrated sediment management is critically needed. The Changjiang River is not the first and will not be the last large river that is heavily dammed and affected by climate change and human activities. The findings derived in the CRB have implications for evaluation of the human impacts in other large river systems, such as the Amazon and Mekong rivers, that are also subject to ongoing dam construction. Furthermore, this study highlights the need for updating the estimates of the global land-to-ocean terrestrial material flux.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.earscirev.2019.102900.

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