Journal of Hydrology 566 (2018) 719–734

Contents lists available at ScienceDirect

Journal of Hydrology

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

Review papers

Fluvial sediment transfer in the Changjiang (Yangtze) river-estuary depositional system

Zhijun Dai[a,b,*], Xuefei Mei[a,c], Stephen E. Darby[d], Yaying Lou[a], Weihua Li[a]

[a] State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai 200062, China
[b] Laboratory for Marine Geology, Qingdao National Laboratory for Marine Science and Technology, Qingdao 266100, China
[c] Key Laboratory of Coastal Science and Engineering, Qinzhou University, Qinzhou, Guangxi 535099, China
[d] Geography and Environment, University of Southampton, Southampton SO17 1BJ, UK

ARTICLE INFO

This manuscript was handled by G. Syme, Editor-in-Chief, with the assistance of Jesús Mateo-Lázaro, Associate Editor

Keywords:
Sediment discharge
River-estuary depositional system
Sediment transfer
Changjiang River

ABSTRACT

Knowledge of the transfer of sediment through river systems is essential for understanding the physical, chemical and biological processes on the Earth's surface. A holistic analysis of long-term records of water discharge, sediment transport, riverbed morphology and estuarine hydrology is here used to quantify spatial and temporal variations in fluvial sediment fluxes along the Changjiang River. We show that the establishment of the Three Gorges Dam (TGD) has directly changed the fluvial sediment-transport process by annually trapping 1.23×10^8 t of sediment. The upper Changjiang reach has switched from being the main sediment source before 2003 to a depositional sink of fluvial sediment subsequently. The major lakes, such as Dongting Lake and Poyang Lake, have shifted from being local sediment sinks before 2003 to sediment sources thereafter, such that they now provide sediment to the Changjiang River. Since the 2003 closure of the TGD the riverbed of the middle-lower Changjiang has become the major source of sediment being transmitted downstream, now providing almost 50% of the material entering the estuary. Shoals in the estuarine channels and landward sediment transport from the sea have become major sediment sources for the river estuary. We conclude that dams currently in preparation along the upper Changjiang reach and adjacent lakes may cause the cessation of sediment supply to downstream reaches. Rising sea levels and frequent storms may terminate landward sediment transport, increasing estuarine erosion and inducing seaward sediment transport. It can therefore be expected that substantial erosion could occur in the near future in the Changjiang estuary system.

1. Introduction

Sediment transfer across the Earth's surface is associated with key physical, chemical and biological processes that can strongly shape the global landscape (Allen, 2008). A number of factors, including tectonic uplift, climate, base level and anthropogenic factors, can affect the movement of fluvial sediment (Florsheim et al., 1991; Liu et al., 2016; Romans et al., 2016; Wang and Xu, 2018; Mei et al., 2018). Among these factors, human activities have significantly altered global river sediment transport regimes across the planet (Milliman and Farnsworth, 2011; Syvitski and Green, 2005), with the potential to seriously disturb sedimentation and associated biogeochemical cycles at the global scale. Therefore, there is a pressing need to quantify the extent to which sediment transport processes have been impacted by human interference in the world's fluvial sediment transfer systems (Kuehl et al., 2016; Walsh et al., 2016).

The world's rivers are estimated to contribute over 20 billion tonnes of particulate sediment to the ocean annually (Milliman et al., 1985). The regions of river systems which mark the transition zone between the land and the coastal ocean are a particularly critical interface for human resources and serve as key repositories of geological information (Walsh et al., 2016; Liu et al., 2016). Indeed, it is believed that the majority of fluvial sediment is sequestered in estuaries or around the edges of the continental shelf, with only 5–10% entering the deep sea (Meade, 1996; Liu et al., 2007). Sediment transfer pathways are more complex in estuarine areas compared to those in the ocean due to the combined influence of river discharge, tidal flow, wave action, associated gravitational circulation (Bianchi and Allison, 2009; Uncles and Stephens, 1997), tidal pumping (Mitchell et al., 2003) and flocculation associated with the mixing of freshwater and saltwater (Liu et al., 2016; Walling and Fang, 2003; Syvitski and Green, 2005).

In recent decades there has been growing interest in quantifying the

* Corresponding author at: State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai 200062, China.
E-mail address: zjdai@sklec.ecnu.edu.cn (Z. Dai).

https://doi.org/10.1016/j.jhydrol.2018.09.019
Received 23 June 2018; Received in revised form 15 August 2018; Accepted 8 September 2018
Available online 10 September 2018

transfer of fluvial sediment from source to sink (Walsh et al., 2016; Liu et al., 2016; Blum and Roberts, 2009; Allen, 2008). For example, Bentley et al. (2015) assessed the effects of tectonic, climatic, and anthropogenic influences on the fluvial-marine sediment-dispersal system of the Mississippi River and demonstrated that upstream controls on the sediment supply dominated the downstream morphology. Darby et al. (2016) showed that tropical cyclones play a key role in controlling sediment transfer in the Lower Mekong River. However, equivalent work on the Changjiang River, which is the longest river in Eurasia, has instead mainly focused on studying the provenance of Holocene sediments (Bi et al., 2017) and identifying historical declines in the fluvial suspended sediment discharge (SSD) and suspended sediment concentration (SSC) (Xu and Milliman, 2009; Hu et al., 2009; Wang et al., 2011; Dai and Lu, 2014; Dai et al., 2016a). Previous work on the Changjiang investigated the influence of upstream reservoirs on downstream geomorphology and sedimentation (Luo et al., 2012; Dai et al., 2013a; Yang et al., 2014; Mei et al., 2018), as well as the effects of upstream hydrological processes on sediment transmission to coastal and continental-shelf regions (Milliman et al., 1985; Yang et al., 2007; Dai et al., 2014). However, a holistic synthesis of the fluvial sediment dispersal system of the Changjiang River has not yet been undertaken in response to the effects of intensive human activities. Such a synthesis is necessary to fully assess the fluvial sediment transfer from the Changjiang River to the East China Sea. The main goals of this paper are, therefore, to:

(1) Assess sediment transmission along the Changjiang River from its headwaters to the downstream estuary during the period from the 1950s to the 2010s;
(2) Identify the drivers of sediment-transport variations in this reach, and;
(3) Discern the inter-connections between sediment transfer processes in the Changjiang River and estuarine morphodynamic processes.

2. Background

The Changjiang River stretches 6300 km from the Qinghai-Tibet Plateau to the East China Sea, making it the longest river in Eurasia, with a catchment area of 1.8×10^6 km^2 (Chen et al., 2010). The river bed slope decreases along the river course, with the highest value occurring in the upstream areas between Cuntan and Yichang (0.18‰), declining to 0.026‰ in the reach from Yichang to the estuary, reaching a slope of 0.005‰ within the estuary itself (Fig. 1A). The upper reach of the Changjiang River is considered to end at Yichang, covering an area of 1×10^6 km^2. The middle reach extends from Yichang to Hankou, encompassing the Hanjiang River as well as Dongting and Poyang Lakes. The lower reach stretches from Hankou to the river mouth (Fig. 1B–D). The hydrometric stations at Yichang, Hankou and Datong were selected to reflect the hydrological characteristics of the upper, middle and lower reaches of the Changjiang River, respectively (Fig. 1A). The landward limit of the tidal current is located around Datong (Dai et al., 2016a).

The Changjiang River basin is dominated by the Asian monsoon circulation with abundant rainfall being recorded during the northern hemisphere summer. The annual mean precipitation over the catchment is 1100 mm, which generally diminishes from the southeast to the northwest (Wei et al., 2014). When averaged over the period 1953–2002 the river discharged 1042×10^9 m^3 of water and 0.427×10^9 t of sediment to the estuary each year (BCRS, 2010, 2011, 2012, 2013, 2014). However, 50,000 dams and reservoirs have been built in the river basin over the past 50 years (Yang et al., 2011) and these have greatly changed the river's hydrological and sediment transmission processes (Dai et al., 2013a).

Since the world's largest river-engineering project, the Three Gorges Dam (TGD), was completed in 2003, the SSD has reduced to less than 1.0×10^9 t/yr compared with 4.2×10^9 t/yr during the period 1953–2002 (Yang et al., 2011), a decrease of approximately 70% (Dai et al., 2014). The SSD values recorded in 2006 and 2011 were as low as 0.84×10^8 t and 0.72×10^8 t, respectively (BCRS, 2010, 2011). The Changjiang has gradually changed from being a quasi-natural river to one which is effectively manually controlled because of the extensive effects of reservoir regulation, in addition to water withdrawal and consumption for industrial and agricultural purposes (Mei et al., 2015).

3. Data collection and methods

A series of data sets were used to aid in the characterization of the fluvial sediment transfer system along the Changjiang River. We collated monthly river runoff and Suspended Sediment Discharge (SSD) data for the period between 1950 and 2014, as well as estimates of erosion and deposition of the Yichang-Nanjing reach between 1957 and 1980, 1980–2002, and 2002–2010 compiled by the Changjiang Water Resources Commission (CWRC). The datasets employed are based on records from the hydrometric stations located at Pingshan, Gaochang, Beibei, Wulong, Cuntan, Yichang, Luoshan, Chenglingji, Hankou, Huangzhuang, Hukou and Datong (Fig. 1A) (Supplementary information, Table S1). Pingshan is the control station of Jinshajiang, whereas the stations at Cuntan and Yichang reflect the hydrological conditions with and without the TGD's influence in the upper Changjiang reach, respectively. The stations at Gaochang, Beibei and Wulong are the control stations of Minjiang, Jianglingjia and Wujiang, respectively (Fig. 1A). Chenglingji and Hukou indicate the contributions from Dongting Lake and Poyang Lake to the Changjiang River (Fig. 1B and C), while Hankou is the control station of the middle Changjiang River. Finally, Datong station provides insight into the fluxes of water and sediment being delivered to the estuary. Additionally, flow velocity and water level measurements between 2000 and 2012 at Luoshan, Hankou and Datong were also obtained from the CWRC.

Monthly water discharge and SSD in the main tributaries (Three Inlets and Four Waters) of Dongting Lake and Poyang Lake from the 1950s to the 2010s were also collated from the Bulletin of China River Sediment (BCRS) (BCRS, 2010, 2011, 2012, 2013, 2014) (Supplementary information, Table S1). Estuarine bathymetric maps between 1958 and the 2010s were also obtained (Supplementary information, Table S2). Additional records, including suspended sediment concentration (SSC) and tidal-flow records, were collected from related publications (Dai et al., 2013a,b, 2016b). Occasional missing data were reconstructed through linear regression, which is more straightforward and applicable compared to the exponential regression method. Specifically, linear relationship between monthly water discharge and monthly SSD were established based on observed records, with correlation coefficient exceeding 0.99. Thus, the missing SSD data can be estimated reliably from the derived linear functions and contemporaneous water discharge measurements.

The sediment deposition/erosion volumes along the Changjiang River course and Changjiang estuary were calculated from analyses of bathymetric maps (ranging in scale from 1:50,000 to 1:10,000) through ArcGIS. Additionally, the volume change of the riverbed sediment was converted to weight assuming a bulk density of 1200 kg/m^3 (Dai et al., 2013a). Thereafter, SSD variation along the reaches between Pingshan-Cuntan, Cuntan-Yichang, Yichang-Luoshan, Luoshan-Hankou and Hankou-Datong were calculated through sediment budgeting. Specifically, the sediment budget between two adjacent stations was set as the difference between the sediment output through the downstream station and the sediment input from the upstream station, while also accounting for any, tributary imports and exports. Trends in the long-term water discharge and SSD series were detected through first-order linear regression. The sediment budget was also used to calculate the net SSD contribution of Dongting Lake and Poyang Lake into the Changjiang River. The ratio between the peak tidal discharge during ebbs and the sum of the peak tidal discharge during ebbs and floods, namely, the coefficient of flow dominance, was used to indicate the relative strength

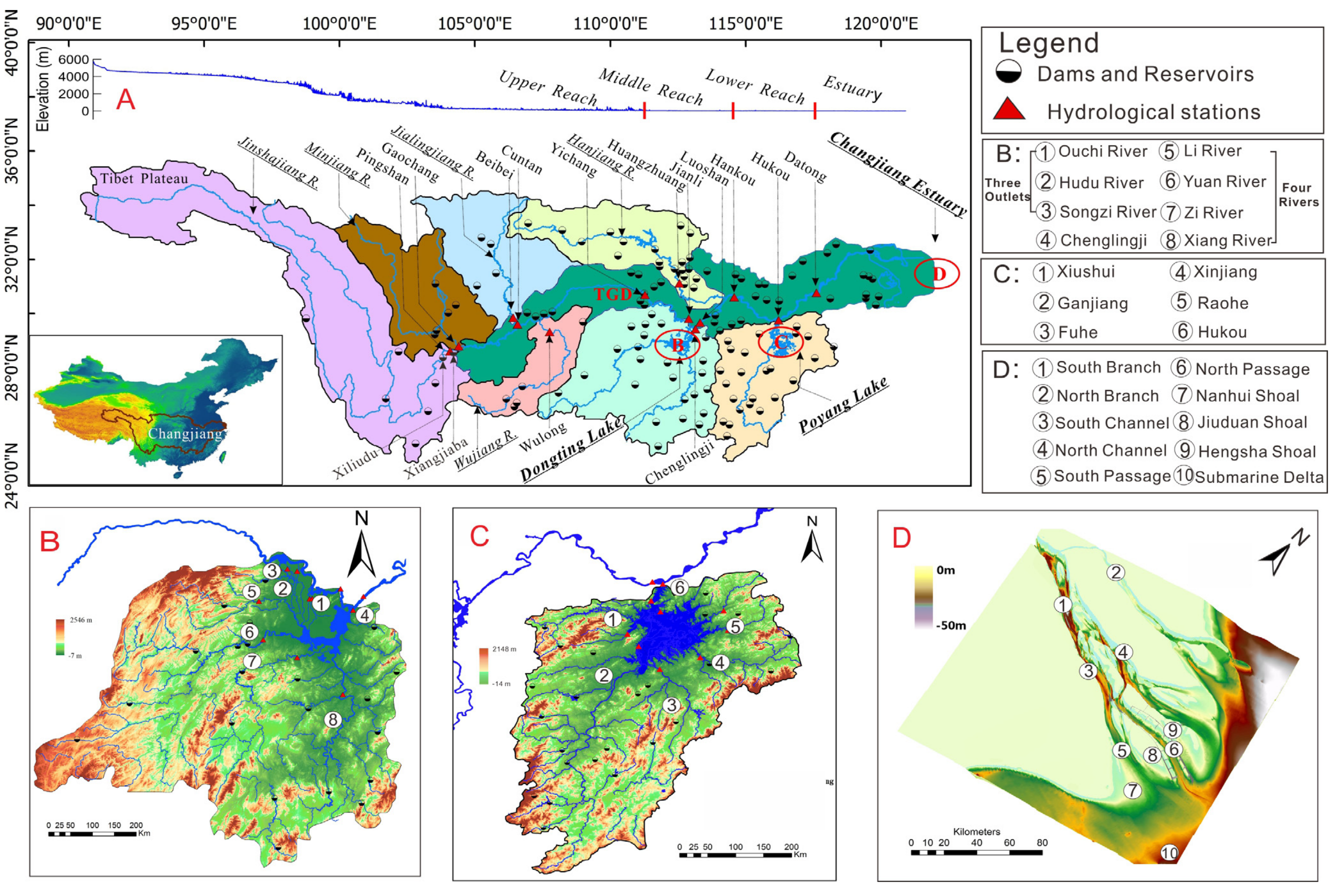

Fig. 1. Overview of the Changjiang River basin showing the main hydrometric stations and zones that are the focus of this study: A. Changjiang area, B. Dongting area, C. Poyang area, D. Changjiang Estuary area.

of the ebb tidal currents (Simmons, 1955). When this coefficient is over 50%, the flow is ebb-dominated.

Regarding the quality of the underpinning data, the monthly flow discharge and SSD at each hydrometric station are processed following a strict set of protocols as set out in 'Specifications for the Observation of River Discharge' (GB-50179-1993JRX, 1993), 'Specifications for the Monitoring Riverine Suspended Matter' (GB 50159-92, 1992), and 'Specifications for the Waterway Survey' (SL257-2000, 2000) before been published to satisfy the 95% confidence limit, including uncertainty estimates, random errors, system errors and pseudo system errors. The river bed bathymetric data were acquired by GPS-RTK (real time kinematic) and echo sounders with a horizontal error of 1 m and a vertical error of 0.1 m. For the estuary, bathymetric data were obtained in 1958, 1978, 1989 and 1997 using Line echo sounders while surveys in 2002, 2004, 2007, 2009 and 2013 employed a DESO-17 echo sounder. The vertical and positioning error of these topographic maps are respectively 0.1 m and 1 m, with approximately 5–20 survey points/km^2. The Changjiang River is a typical alluvial plain with flat estuarine terrain. Therefore, the positioning error of 1 m has only a limited effect on the variation of the erosion/deposition volume. The vertical error of 0.1 m can be ignored since the water depth difference among different years are obviously much larger than 0.1 m. In this study, when the estuarine riverbed variation is smaller than 0.1 m, it is set as fluvial equilibrium, while that over 0.2 m is considered to be a detectable variation in volume.

4. Sediment transfer fluxes and their implications for the Changjiang river-estuary depositional system

4.1. Suspended Sediment Discharge changes in the Upper Changjiang

4.1.1. Annual variations in the water discharge and SSD in the upper Changjiang River

Our data analysis shows that the mean annual water discharge during the 1950s to 2000 at Pingshan, Cuntan and Yichang was 4731 m^3/s, 10982 m^3/s and 13870 m^3/s, respectively (Fig. 2A, C, and E), while the corresponding SSD was 2.53 × 10^8 t/yr, 4.37 × 10^8 t/yr, and 5.01 × 10^8 t/yr, respectively (Fig. 2B, D, and F). In terms of annual time series, there is no apparent trend in the water discharge during this period (Fig. 2A, C, E, and G), but the mean discharge at Pingshan decreased from over 6000 m^3/s before the year 2000 to around 3000 m^3/s after 2010 (Fig. 2A). Meanwhile, large variations were detected in the annual SSD, with an abrupt decline after 2003 (Fig. 2B, D, and F). The average annual SSD at Pingshan, Cuntan and Yichang was 1.39 × 10^8 t, 1.71 × 10^8 t and 0.43 × 10^8 t, respectively, during the period 2003–2014, a reduction of 45%, 60% and 85% compared to the SSD values observed during the period 1951–2000 (Fig. 2H).

4.1.2. Contribution from the sediment budget in the upper reach to the downstream area

The SSD passing through Yichang is contributed by the upper stream from the river source to Pingshan, three major tributaries (Minjiang, Jialingjiang and Wujiang) and riverbed sediment erosion along the Pingshan-Yichang reach (Fig. 1A). The riverbed between Pingshan and Cuntan, which is 447 km in length, was in an erosional state before 2003 with an annual erosion rate of 0.17 × 10^8 t/yr, but it has since transitioned to become a depositional reach, retaining some

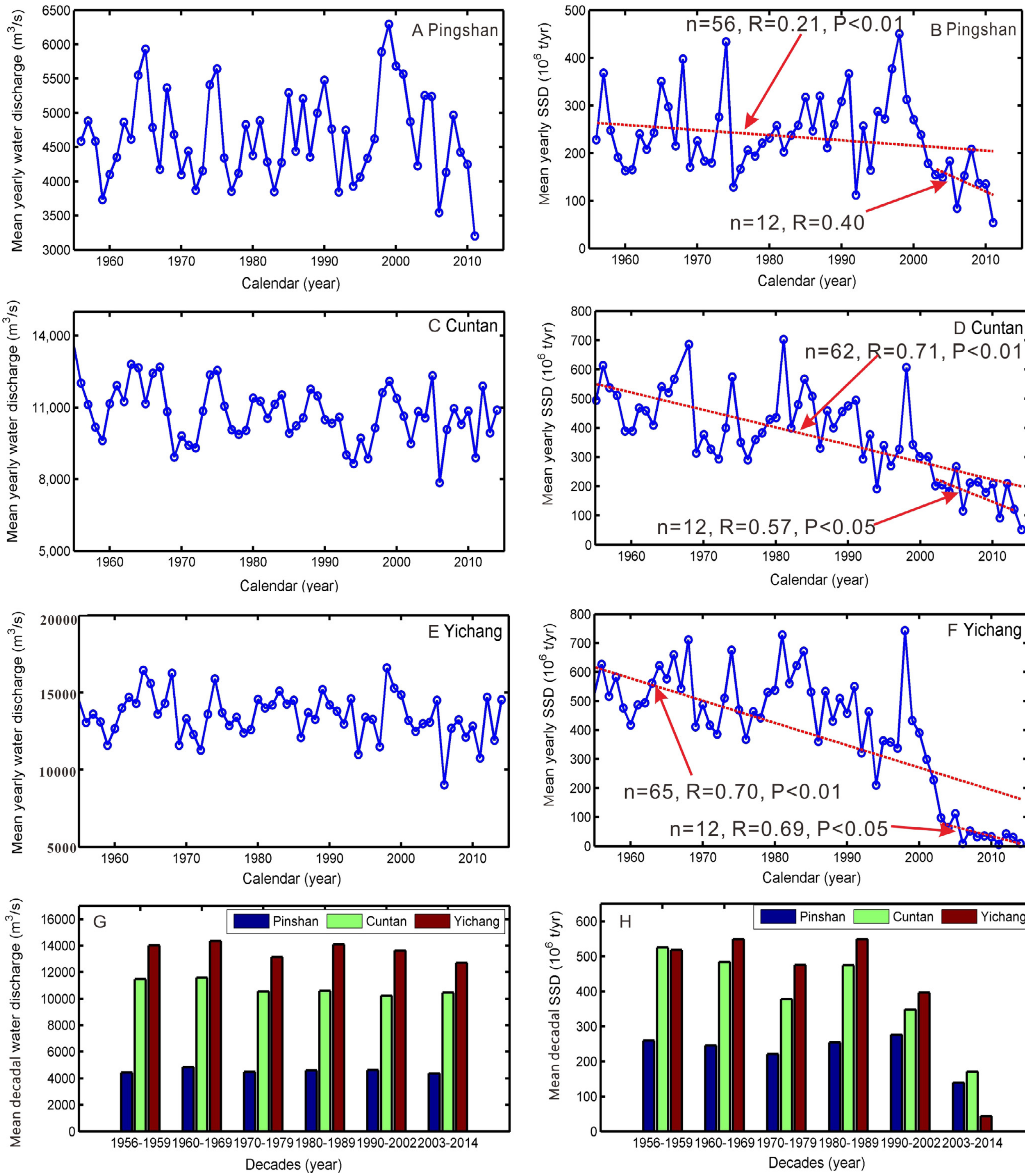

Fig. 2. Variations in the water discharge and Suspended Sediment Discharge (SSD) of the mainstream area in the upper Changjiang reach.

0.17×10^6 t/km yearly since 2003 (Figs. 1A, 3A). The riverbed from Cuntan to Yichang, which covers a length of 638 km, also experienced a similar transition, switching from a yearly erosion rate of 0.06×10^6 t/km before 2003 to a yearly deposition rate of 0.18×10^6 t/km thereafter (Fig. 3B). The upper Changjiang River has changed from being a sediment source that provided approximately 1.2×10^8 t of sediment to downstream reaches each year before 2003, to a sediment sink that has received 2.3×10^8 t of SSD annually thereafter (Fig. 3A and B).

Furthermore, the yearly SSD through Yichang comprised around 83%-160% of that through Datong during 1951–2000, with a mean value of 116% (Fig. 3C); thus, the SSD from the upper reach dominated the SSD that entered the sea. Since 2003, however, the annual SSD contribution from Yichang has dramatically decreased to a value less than 50% (except for a value of 51% in 2005), with an annual mean contribution of 28% during the period 2003–2014 (Fig. 3C). The SSD supplied from the upper reach comprised less than 9% of that passing through Datong in 2011 and 2014. As such, since 2003 the upper reach can no longer be regarded as being the main sediment source for the

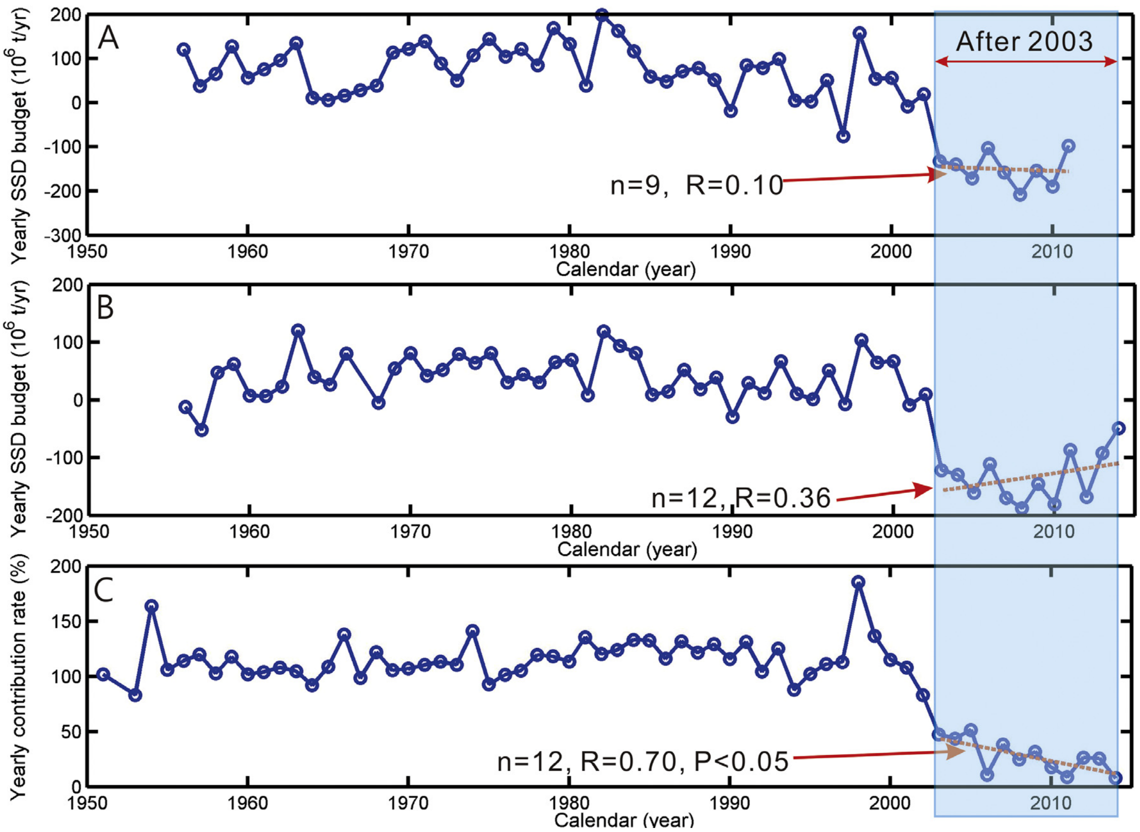

Fig. 3. Yearly Suspended Sediment Discharge (SSD) budget in the upper Changjiang reach: A. net sediment budget of the Pingshan-Cuntan reach (SSD at Cuntan minus that from the upper reach at Pingshan and the tributaries at Beibei and Gaochang); B. net sediment budget of the Cuntan-Yichang reach (SSD at Yichang minus that from the upper reach at Cuntan and the tributary at Wulong); C. SSD ratio between Yichang and Datong.

downstream areas.

4.2. Sediment exchanges with Dongting and Poyang Lakes and their contribution to downstream sediment flux

4.2.1. Dongting Lake

Dongting Lake is a key component of the Changjiang River system, exporting significant volumes of water and SSD to the river (Zhu et al., 2014). However, the lake's water and sediment sources have undergone major changes since the 1950s. Previously, water and SSD was discharged into Dongting Lake by the Three Inlets and Four Rivers (Fig. 1B). The proportion derived from the Four Rivers has gradually increased in recent decades, with the contribution for the water discharge increasing from 53% during 1951–1959, to its present value of 76%. The contribution for the SSD from the Four Rivers has increased from 15% to 48% (Fig. S1). Accordingly, the main SSD source for Dongting Lake has transitioned from being dominated by the Three Outlets to a more even split between the Three Outlets and the Four Rivers.

The sediment budget of Dongting Lake also indicates that there was a long-term phase of deposition within the lake during the period 1951–2002 (Fig. 4A). The mean sediment deposition has been declining from 1.9×10^8 t/yr to 1.7×10^8 t/yr and then 0.6×10^8 t/yr for the periods 1951–1959, 1960–1969 and 1990–2002, respectively (Fig. 4A and B). Subsequently, this prior depositional state ceased after 2003, when the lake shifted to an erosional status, exporting 0.4×10^6 t of sediment each year (Fig. 4A). As Fig. 4C indicates, the lake generally stored sediments during the flood season and provided sediment through erosion during the dry season. Since 2003, however, the deposition rate during the flood season has decreased to only 0.067×10^8 t/yr, while lake bed scouring rate during the dry season has increased to 0.072×10^8 t/yr. The proportional contribution of suspended sediment passing from Dongting Lake to downstream reaches has exhibited a downward trend since the 1950s, decreasing from 14% to 7% in 2002, but significantly increasing thereafter to 19% in 2014 (Fig. 4D).

4.2.2. Poyang Lake

Compared to the pre-TGD period of 1960–2002, Poyang Lake demonstrated only slight variations in the annual water discharge during the post-TGD period, with the output flow indicating a small decrease of around 5% (Fig. S2A, C, and E). However, Poyang Lake has undergone a dramatic change in its sediment budget following the regulation of the TGD (Fig. S2B, D, and F). Specifically, in the period 1960–2002, Poyang Lake received 12.9×10^6 t/yr of SSD from its five tributaries and discharged 9.22×10^6 t/yr to the Changjiang River, so that the output flux comprised around 70% of the input flux (Fig. S2B and D). Subsequently (2003–2012), however, the lake received 5.77×10^6 t/yr of sediment but released more than 12.52×10^6 t/yr. In other words, there was almost 4×10^6 t/yr of sediment deposited in Poyang Lake during 1960–2002 (Fig. 5A), and around 6.75×10^6 t/yr eroded to transport into the downstream reaches after 2003 (Fig. 5A–C).

In terms of the relative proportion of sediment being contributed from Poyang Lake to the Changjiang's downstream reaches, the lake previously contributed approximately the equivalent of 2% of the sediment load passing through Datong, but this proportion increased to 9% during the period 2003–2012 (Fig. 5D). Since the overall magnitude of the sediment output from Poyang Lake has exhibited no observable variations during 1960–2012, the increase in the proportional contribution of sediment from Poyang Lake to the downstream reaches can be attributed to the decrease in fluvial sediment from the upper Changjiang River (Fig. 3). Thus, while the Changjiang's overall SSD

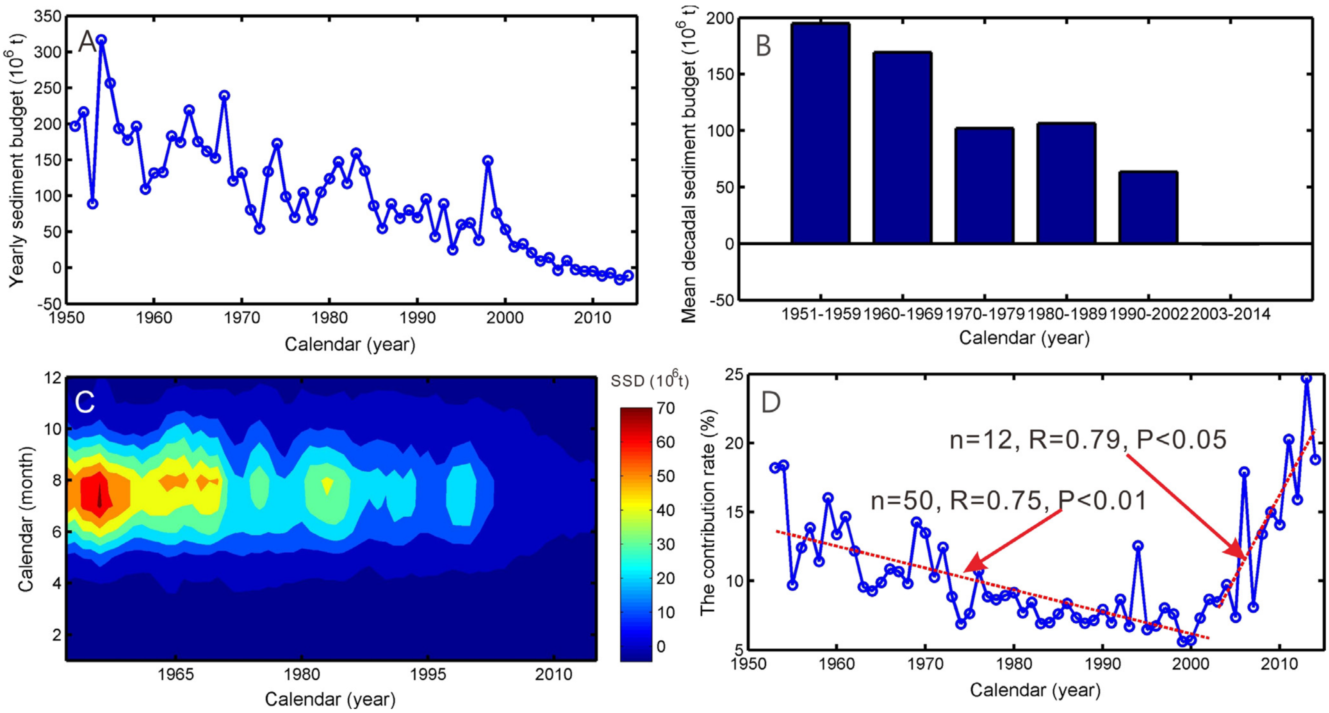

Fig. 4. Sediment budget of Dongting Lake and its contribution to the Suspended Sediment Discharge (SSD) that enters the sea. A–C indicate the yearly, decadal and monthly SSD budgets, respectively; D denotes the ratio of the sediment contributions between Dongting Lake at Chenglingji and Datong.

declines, the relative importance of different sources of sediment to downstream reaches is growing – in this case the Dongting and Poyang Lakes are now much more significant as a source of sediment for the estuary than in previous decades.

4.2.3. Sediment contribution from the Hanjiang River

As the longest tributary of the Changjiang River, the Hanjiang is a key potential source of water and sediment discharge into the East China Sea (Dai et al., 2013a). During the period 1951–2014 the Hanjiang delivered 1480 m^3/s of water each year to the Changjiang (with a range from 550 to 2500 m^3/s) (Fig. S4), with no statistically significant changes over time. The annual sediment flux exported from the Hanjiang into the Changjiang has experienced a significant declining trend with an overall reduction of 95% ($P < 0.01$) during this time (Fig. S3). The mean annual sediment load of the Hanjiang River was 1.31×10^8 t/yr during 1951–1959 but decreased to 0.96×10^8 t/yr

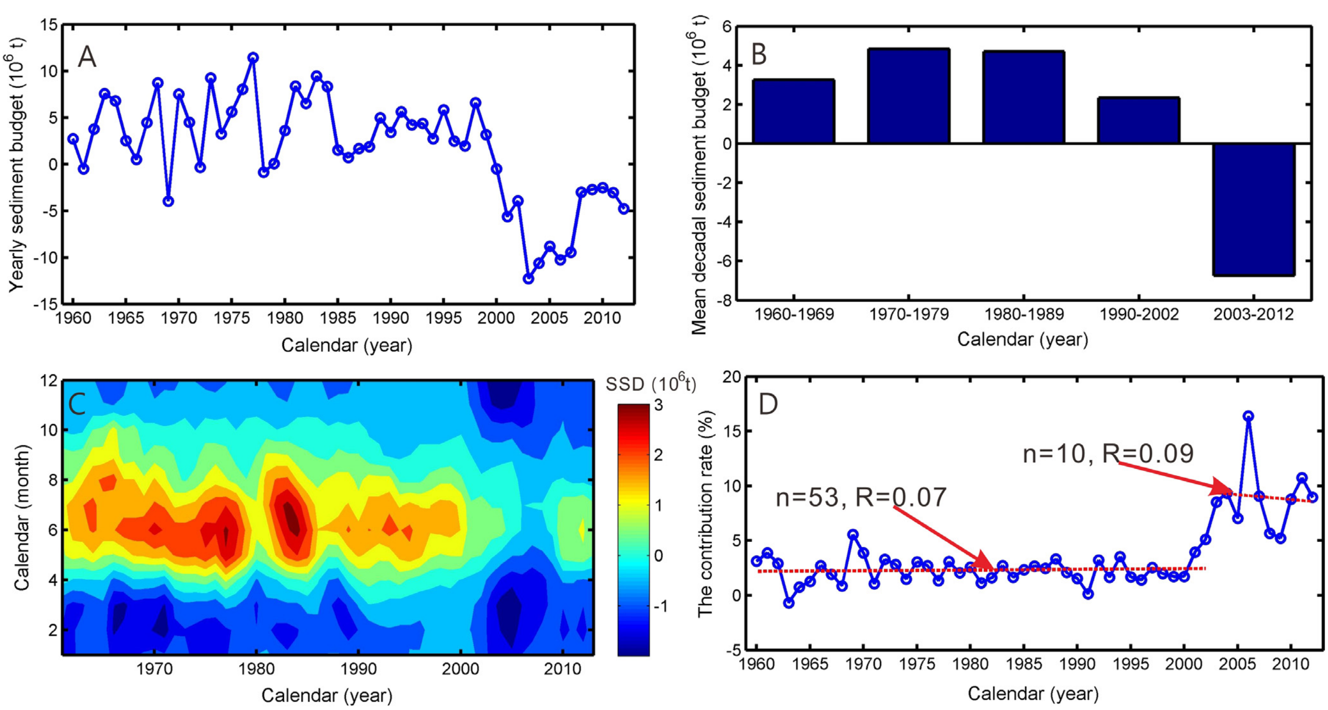

Fig. 5. Sediment budget of the Poyang Lake and its contribution to the Suspended Sediment Discharge (SSD) that entered the sea. A–C indicate the yearly, decadal and monthly SSD budgets, respectively; D denotes the ratio of the sediment contributions between Poyang Lake and Datong.

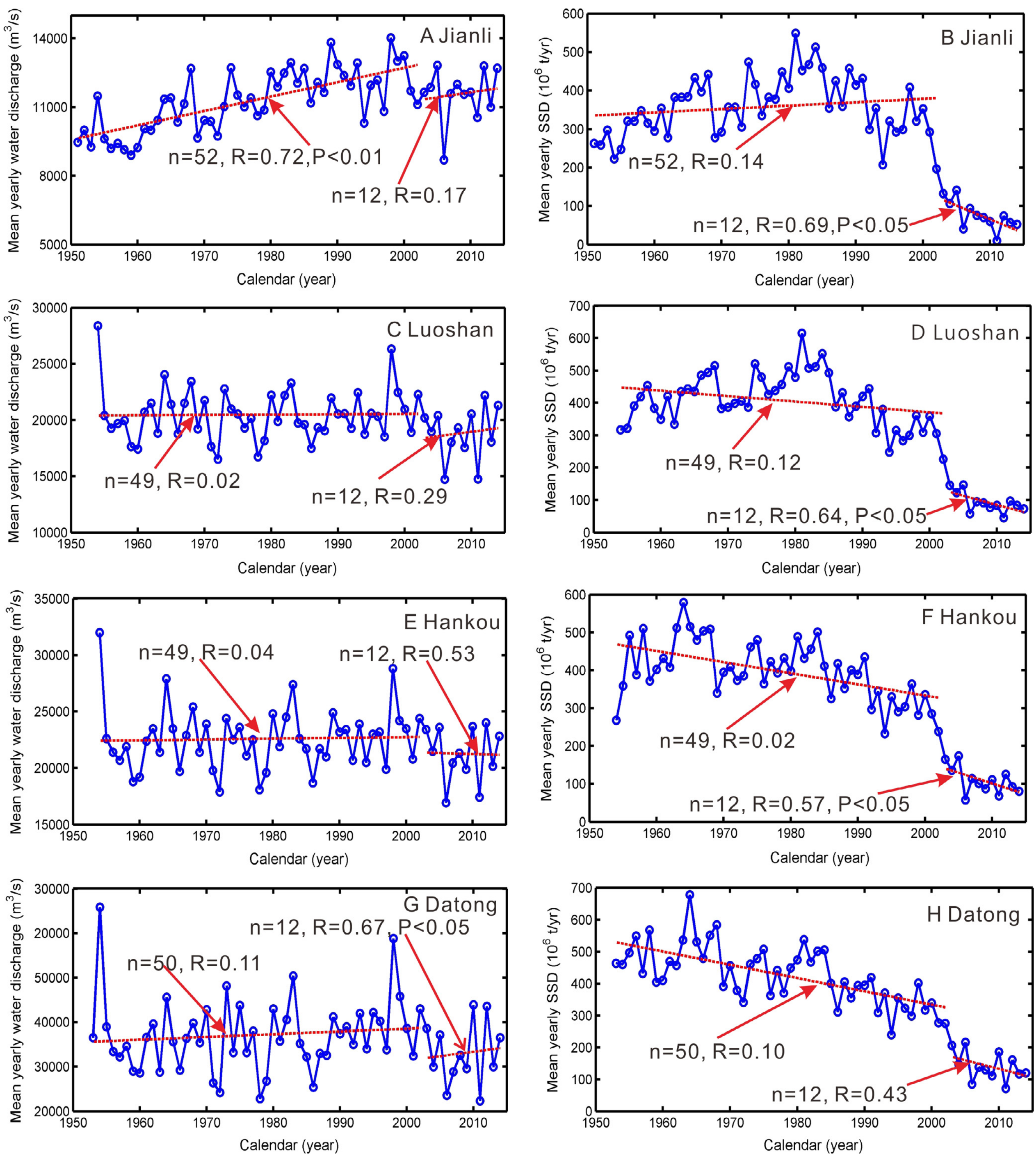

Fig. 6. Changes in the water discharge and Suspended Sediment Discharge (SSD) along the mid-lower Changjiang River.

during 1960–1969 and further to 0.245 × 10^8 t/yr during 1970–1979 (Fig. S3). This decrease continued into the 2000s, by which time the annual mean sediment load was 0.065 × 10^8 t/yr, just 5% of that observed during the 1950s (Fig. S3).

In terms of its proportional contribution to downstream area, the sediment flux from the Hanjiang tributary was around 15% of that at Datong during the 1960s, and then significantly decreased between 1970 and 2000 with a minimum of 6% in 2000. This proportional decline subsequently reversed, with an increased value of 12% from 2000 to 2011. The sediment-contribution ratio from Hanjiang to Datong declined to just 2% between 2012 and 2014.

4.3. Sediment transfer along the middle-lower Changjiang River course

The Changjiang downstream of Yichang first interacts with Dongting Lake, confluences with the Hanjiang and Poyang Lake, and eventually reaches the tidal limit of the river at Datong (Fig. 1A). It is apparent that the annual water discharge along the Changjiang River has experienced no major changes, as shown from the behavior of the control stations of Jiangli, Luoshan, Hankou and Datong (Fig. 6A, C, E,

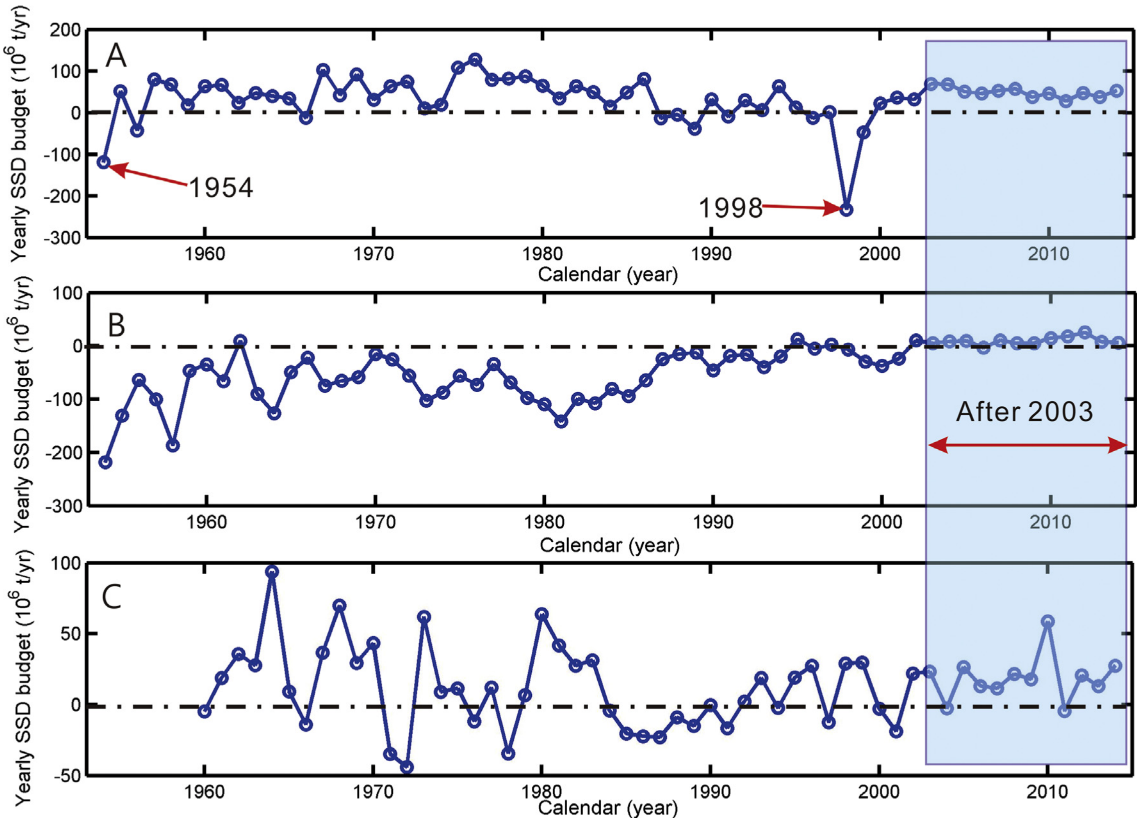

Fig. 7. Sediment budget along the main stream of the Changjiang River: A Yichang-Luoshan reach; B. Luoshan-Hankou reach; C. Hankou-Datong reach.

and G), and the SSD has exhibited significant variations with a clear decreased trend since 2003 (Fig. 6B, D, F, and H). For example, compared to the period from the 1950s to 2010s, the annual mean SSD decreased by 80% at Jianli, 78% at Luoshan, 73% Hankou and 68% at Datong (Fig. 6B, D, F, and H).

The SSD budget along the Yichang-Luoshan reach has clearly been in a net erosional status during most of this time, except during the extreme flood years of 1954 and 1998 (Fig. 7A). The SSD loss in the pre- and post-2003 periods was 0.41×10^8 t/yr and 0.47×10^8 t/yr, respectively, indicating that the reach provided slightly more sediment through riverbed erosion after 2003. The SSD budget along the Luoshan-Hankou reach shifted from a net depositional status of 0.6×10^8 t/yr before 2003 to a condition of mild net erosion (0.1×10^8 t/yr) thereafter (Fig. 7B). The SSD budget along the Hankou-Datong reach is also erosional, providing 0.11×10^8 t/yr of in-channel sediment to the downstream area before 2003 (Fig. 7C), and increasing to 0.3×10^8 t/yr thereafter.

Prior to 2003, the SSD budget along the main Changjiang stream between Yichang and Datong indicates that historically the Yichang-Luoshan reach continually provided sediment to the downstream area through channel erosion, the Luoshan-Hankou reach acted as a sediment-sink, and the Hankou-Datong reach intermittently received sediment while providing sediment in other years (Fig. 8). After 2003, however, the Yichang-Luoshan reach transmitted more sediment downstream, and both the Luoshan-Hankou and Hankou-Datong reaches have become net sediment sources to downstream waters. The sediment contributions from these three reaches decreased as their distance to the upstream area increased (Fig. 8).

4.4. Variations in water and sediment flows to the estuary and associated delta sedimentation

4.4.1. Variations in the fluvial water discharge and SSD to the sea

Datong, which is the most downstream hydrological station with long-term records, is representative of the variations in riverine water and sediment discharge being supplied to the head of the Changjiang estuary (BCRS, 2014). From 1950 to 2014, the fluvial water discharge supplied by the Changjiang catchment and passing through Datong showed no obvious variations, with an annual mean flow of 28000 m^3/s (Figs. 6G and 9A). However, inter-seasonal variations in water discharge have become slightly more pronounced since 2003. It can be shown that the overall proportion of water discharge during the flood season (May-October) decreased slightly from 72% (1950–2002) to 68% (2003–2014), and in the dry season increased from 28% to 32% (Fig. 9C and E).

In contrast to the water discharge trends, the fluvial suspended sediment discharge through Datong substantially decreased during recent decades (Figs. 6H and 9B). This decline began during the 1970s but became more intense since the closure of the TGD in 2003 (Fig. 10H) (Dai et al., 2016a). The annual mean SSD during the period 1950–1959 was approximately 4.76×10^8 t/yr, decreasing to 4.24×10^8 t/yr during 1970–1979 and falling again to just 1.4×10^8 t/yr during 2003–2014 (Fig. 9B). The proportion of SSD delivered during the flood season has declined from approximately 88% 1950–2002 (Fig. 9F), to 80% since 2003.

4.4.2. Volume variations in the Changjiang Estuary

Volume variations in the Changjiang Estuary mainly occur in the submarine delta and estuarine channels. The Changjiang estuarine submarine delta (CESD) experienced net deposition during 1958–1997, with strong siltation of over 260 m^3/yr during 1958–1978, slow deposition of approximately 2 m^3/yr during 1978–1987 and 18 m^3/yr during 1987–1997, and slight erosion of around 40 million m^3/yr during 1997–2002 (Fig. 10A–D). The CESD regained a depositional state during 2002–2013 (Fig. 10E–H), during which time the 10-m isobath extended seaward at an accumulation rate of 25–50 cm/yr (Fig. 10).

The channel volumes below the 0-m isobath for the NB (North

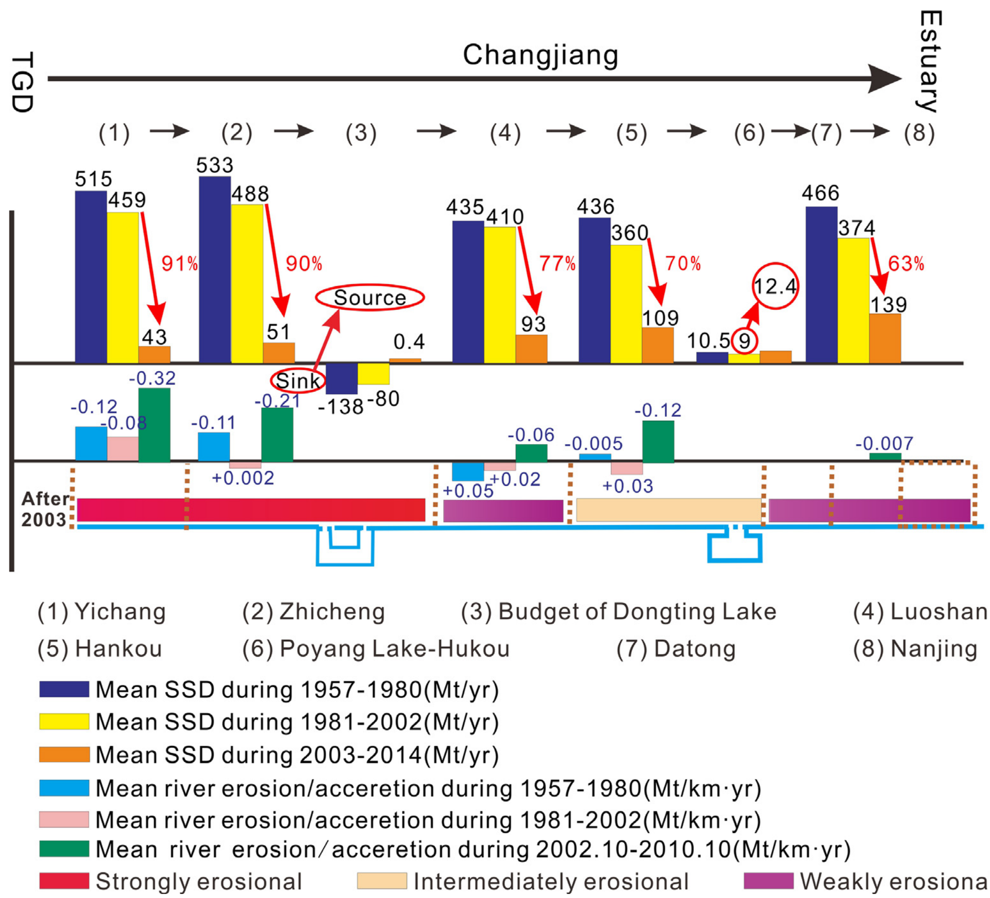

Fig. 8. Sediment transfer shifts along the middle-lower Changjiang reach (Revision after Dai and Liu (2013)).

Branch) and South Passage (SP) are described in Fig. 11. The volume capacity of the SP gradually decreased during 1958–2012, with an overall loss of approximately 13% (Fig. 11A). The volume decreased from $0.69 \times 10^9\,m^3$ in 1987 to $0.59 \times 10^9\,m^3$ in 1994, a reduction of 14% (Fig. 11), which suggests a period of infilling. During 1994–1996, the capacity increased by $0.04 \times 10^9\,m^3$. During 2001–2006, the capacity increased again. However, the capacity declined by $0.06 \times 10^9\,m^3$ and then gradually but slightly increased during 2006–2008 (Fig. 11A). Meanwhile, the channel volume below 0 m in the NB decreased by 53% from $1.17 \times 10^9\,m^3$ in 1958 to $0.54 \times 10^9\,m^3$ in 2013 (Fig. 11B), at a mean deposition rate of $11.4 \times 10^6\,m^3$/yr. The channel volume below 0 m exhibited a statistically significant decrease ($p < 0.05$) (Fig. 11B). This response is reflected in the elevation changes in the middle of the channel along the NB, which became shallower and flatter during the 2000s (Dai et al., 2016b).

It is noteworthy that, despite the obvious decline in riverine sediment load supplied from upstream, the Changjiang Estuary has exhibited no obvious responses such as shoreline erosion or channel down-cutting in the same period. Thus, the driver and sediment source for estuarine deposition/erosion likely changed, as discussed in the next section.

5. Influences on the Changjiang river-estuary sediment transfer system

5.1. Soil erosion and dam regulation along the Changjiang River

Soil erosion in the Changjiang's catchment is an important driver of sediment supply to the Changjiang River. Severe deforestation along the river is estimated to have caused a total soil loss of $364 \times 10^3\,km^2$ during the 1950s (Shi, 1999; Zhang and Zhu, 2001). This change in land-use resulted in 1.76×10^8 t/yr of SSD being delivered to the channel system during the 1950s (Yang et al., 2004), directly inducing sediment deposition in the upper Changjiang River with the annual mean SSD at Yichang reaching 5.4×10^8 t/yr (Figs. 2F, 7).

Between 1950 and 1970, only a small number of reservoirs were present along the Changjiang River, so the potential for trapping of riverine sediment was low. However, following the establishment of Danjiangkou Reservoir on the Hanjiang River in 1973, the sediment contribution from the Hanjiang River to the Changjiang dropped significantly from 1.31×10^8 t/yr during 1951–1959 to 0.245×10^8 t/yr during 1970–1979 and, as a result, fluvial sediment from Changjiang to the estuary started to decrease from the1970s. During 1970–2002, the total reservoir storage capacity increased to $170 \times 10^9\,m^3$ (Fig. 12A), which was a sufficiently significant increase to retain large volumes of sediment behind the dams. Ongoing land use change resulted in the catchment area being affected by severe erosion increasing to $707 \times 10^3\,km^2$ by 2001. The enhanced soil erosion triggered by land use change in the Changjiang basin between 1971 and 2002 could have partially mitigated the effects of sediment trapping by dams (Dai et al., 2016a). For example, the SSD at Yichang and Datong remained at roughly stable values of around 4.65×10^8 t/yr and 3.89×10^8 t/yr, respectively (Figs. 2F and 12B). Accordingly, the upper reach was still the main sediment source, providing 115% of the SSD compared to that of the downstream area (Fig. 13). The basic sediment source-sink process within the Changjiang River itself did not significantly change over this period.

The dominant driver of recent sediment transfer variations along the Changjiang River is likely to have been the TGD. In early 2003, the TGD's reservoir water level was 135 m, with an estimated 1.23×10^8 t/yr of sediment being trapped (Fig. 12B). This reduction in the sediment supply from upstream sharply decreased the SSD observed at Yichang,

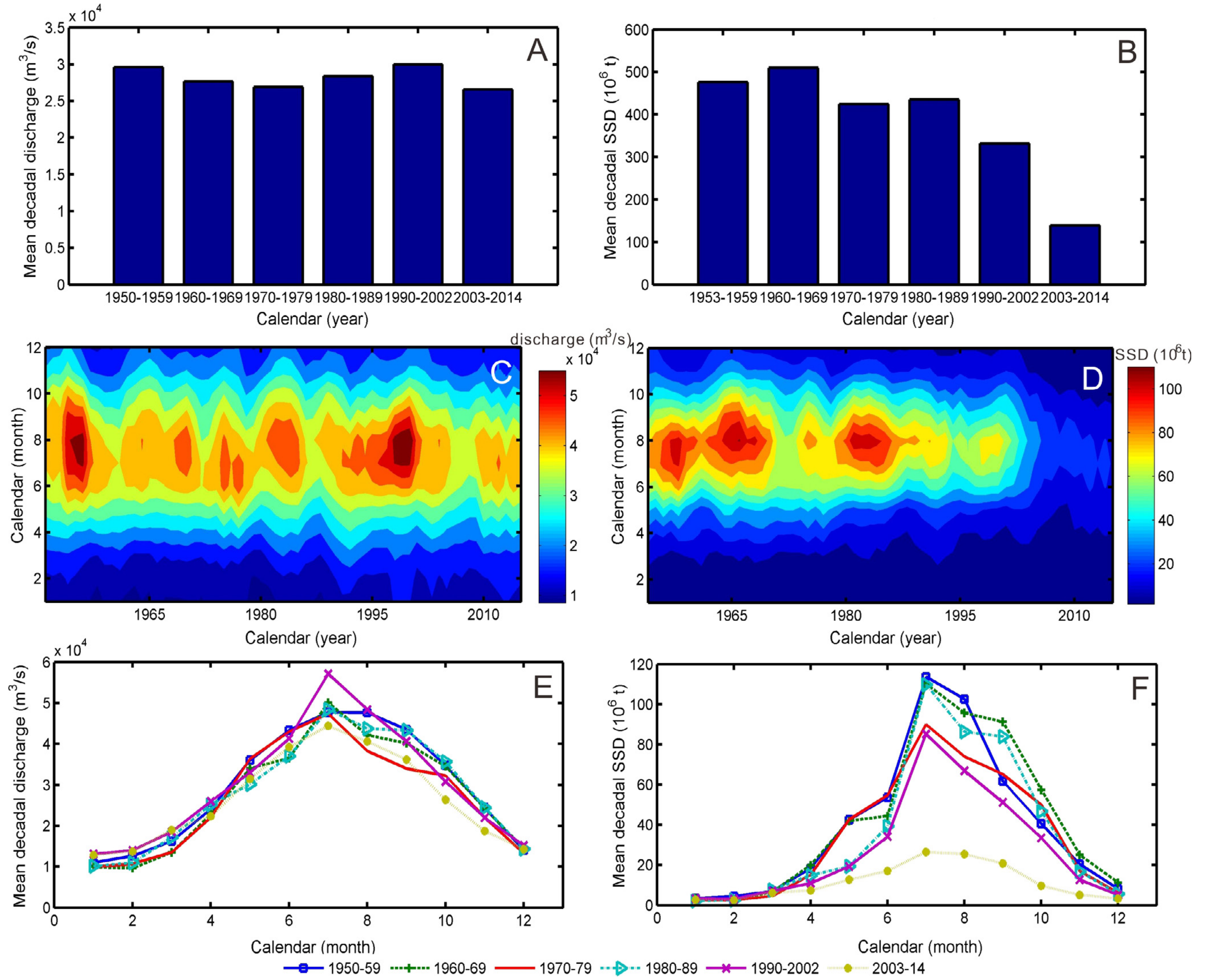

Fig. 9. Variations in the water discharge and Suspended Sediment Discharge at the Datong station.

from 2.28×10^8 t/yr in 2002 to 0.97×10^8 t/yr thereafter (Fig. 2F). The corresponding SSD at Datong was 2.06×10^8 t/yr (Fig. 9B). During 2003–2005, the TGD stored 1.25×10^8 t/yr of sediment in the reservoir, which induced the SSD of 0.91×10^8 t/yr at Yichang, and 1.89×10^8 t/yr at Datong (Fig. 6H). In 2006, the water level within the TGD rose to 156 m because of continuous water storage, and the SSD at Datong declined further to 0.85×10^8 t/yr (Fig. 6H).

Large scale sediment trapping behind the TGD caused river bed incision downstream (Fig. 8). Simultaneously, river bed material coarsening and slope variation also occurred (Luo et al., 2012; Yu et al., 2018), which led to changes in flow velocity. For instance, the flow velocity at Luoshan, Hankou and Datong in the post-TGD period are significantly higher than in the pre-TGD period (Fig. 14). The suspended sediment transport and erosion increased because of increasing flow velocity. In addition, channel straightening in the reach from Yichang to Luoshan in 1970s also increased the channel slope and flow velocity, and thereby increased the suspended sediment transport to Jiangli and Luoshan during this period (Fig. 6B, D).

5.2. Deepwater navigation channel project along the North Passage of the Changjiang Estuary

A major decrease in fluvial sediment entering the estuary could potentially induce estuary scouring (Syvitski et al., 2009). The variation of riverine sediment from the Changjiang River has vital effects on estuary morphological evolution (Milliman et al., 1985; Yang et al., 2007). Yang et al. (2007, 2011) indicate that the reduction of fluvial sediment from the Changjiang River induced estuarine wetland erosion and delta regression. However, recent works on the Changjiang Estuary show that both the sand bar zone and the submerged delta region are currently in a depositional state (Dai et al., 2014; Luan et al., 2016). The inconsistent conclusions of previous research can be attributed to the combination of variations in local morphology, human activities and dynamic conditions.

Among the four outlets of the Changjiang Estuary, the North Passage (NP) has experienced erosion (Fig. 10) (Luan et al., 2016), although this phenomenon had no direct relationship with the decrease in sediment supply from the upstream area (Dai et al., 2014). The riverbed erosion along the NP can instead be completely attributed to the artificial deep-water navigation channel project (DNC) (Jiang et al., 2012), which decreased the water depth from less than 7 m below the MLLWL (mean lowest low-water level) to 10.5 m below the MLLWL through intensive dredging (Dai et al., 2013b) (Fig. 15A). For example, 0.5×10^8 m^3 of sediment was dredged annually to maintain the DNC during the period 1999–2014. However, siltation of sediment in the DNC reached 0.8×10^8 m^3/yr during 2010–2014, even though there is manual dredging (Fig. 15B), which is inconsistent with the dramatic decrease in fluvial sediment. Thus, the erosion along the NP was

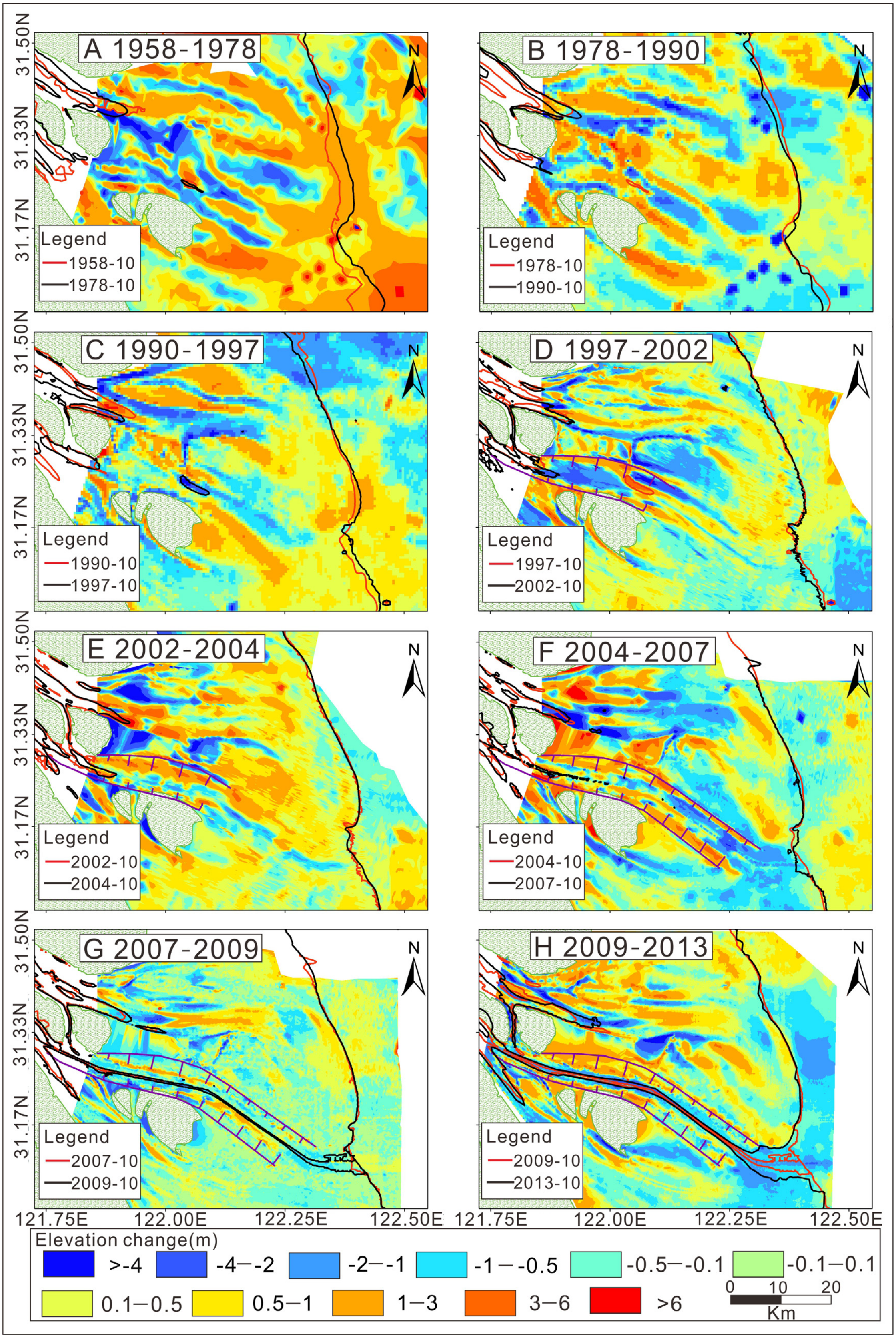

Fig. 10. Erosion/deposition variations in the submarine delta in the Changjiang Estuary.

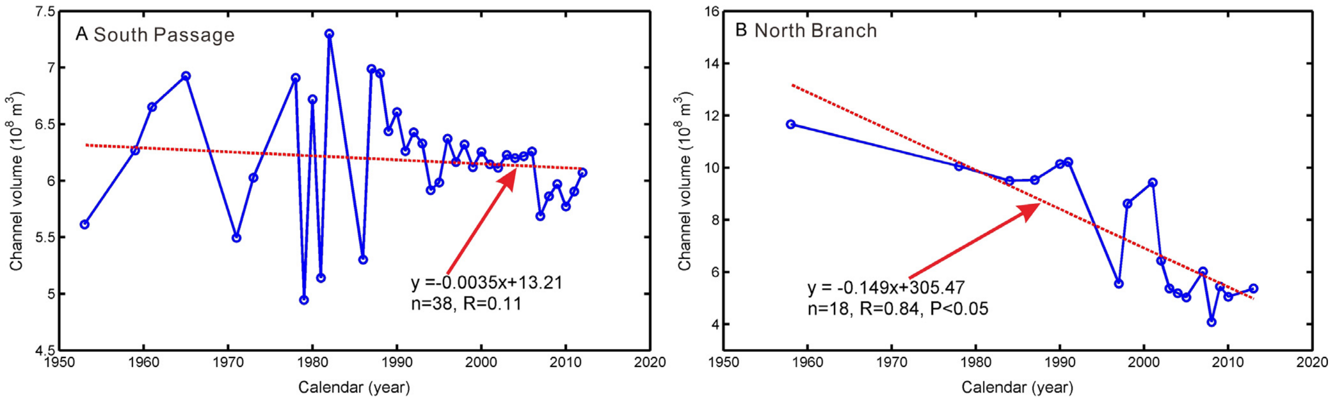

Fig. 11. Volume variation below the 0-m isobaths in the North Branch and South Passage.

dominated by artificial dredging to maintain the DNC.

5.3. Local tidal forces in the Changjiang Estuary

The Changjiang experiences average tidal-current velocities in excess of 1 m/s (Fig. 16). The four bifurcated estuaries have distinctive runoff and tidal-current interactions because of the geomorphological differences between them (Dai et al., 2013b, 2014, 2016b). Additionally, the sediments stored in the submarine delta may enter the Changjiang Estuary in cases when the transmission of sediment from upstream is insufficient, or under certain tidal conditions (Dai et al., 2014).

Previous research has indicated that landward sediment transport may increase when the riverine water discharge decreases, which would induce submarine-delta siltation (Swenson et al., 2005). For the Changjiang Estuary, the fluvial flood peak substantially decreased (Fig. 9E and F), which increased the dynamic effects of tidal currents. As shown in Fig. 15, the SSC in the inner side of the mouth bar decreased with the declining fluvial sediment loads from upstream, while the SSC around the mouth bar remained constant or even increased under the coupled effects of a turbidity maximum and an increase in waves and tidal currents. This phenomenon may explain the deposition of a submarine delta in the Changjiang Estuary even under declining fluvial SSD (Dai et al., 2014). The decrease in riverine flood discharge and associated land reclamation has also induced NB channel narrowing, which significantly strengthened the tidal currents (Fig. 17A), resulting in gradual deposition along the tidally-dominant NB (Dai et al., 2016b). Additionally, deposition was detected in the SP as the ebb flow increased, which can be explained by the sediment input from shoal erosion around the upstream opening of the SP (Fig. 17B). Therefore, landward sediment transport from the sea area and the shoals in the Changjiang Estuary have a new sediment sources.

5.4. Extreme storm events in the Changjiang Estuary

Extreme storms are an important driver of sediment source-sink variations in estuarine areas. Similar to how Hurricane Katrina posed a severe erosion threat to the Mississippi Delta (Törnqvist et al., 2006), the Changjiang Estuary has also exhibited deposition/erosion variations in response to typhoon events over the past 50 years. The submarine delta of the Changjiang River generally consists of relatively fine particles that are smaller than 0.063 mm (4φ), while those in the southern

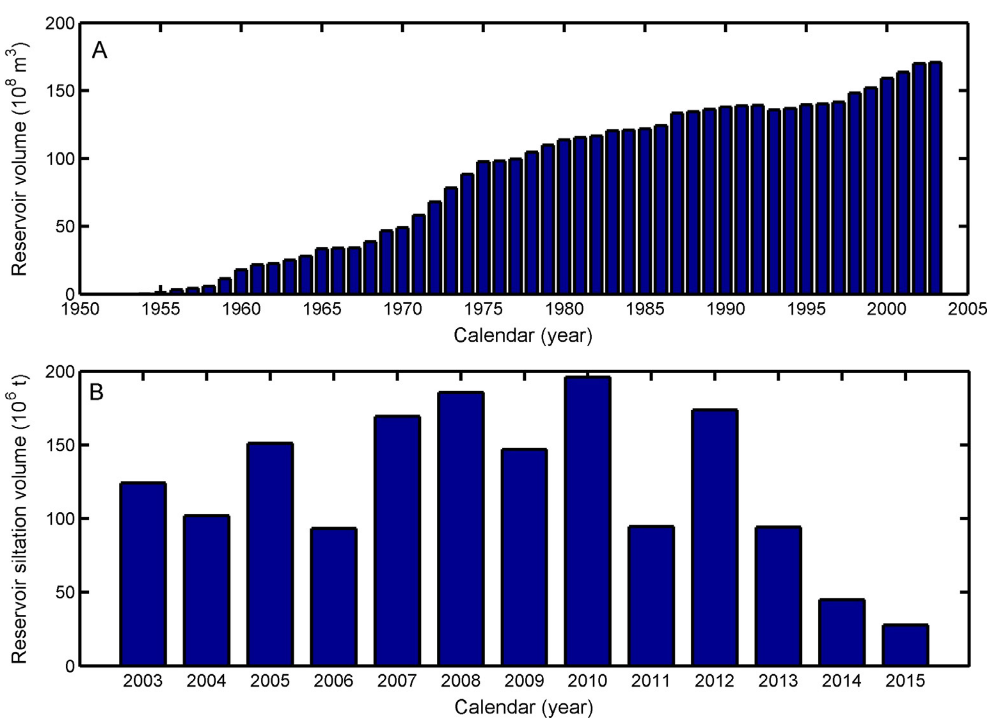

Fig. 12. A. Reservoir capacity of the Changjiang River; B. trapped sediment volume of the Three Gorges Dam.

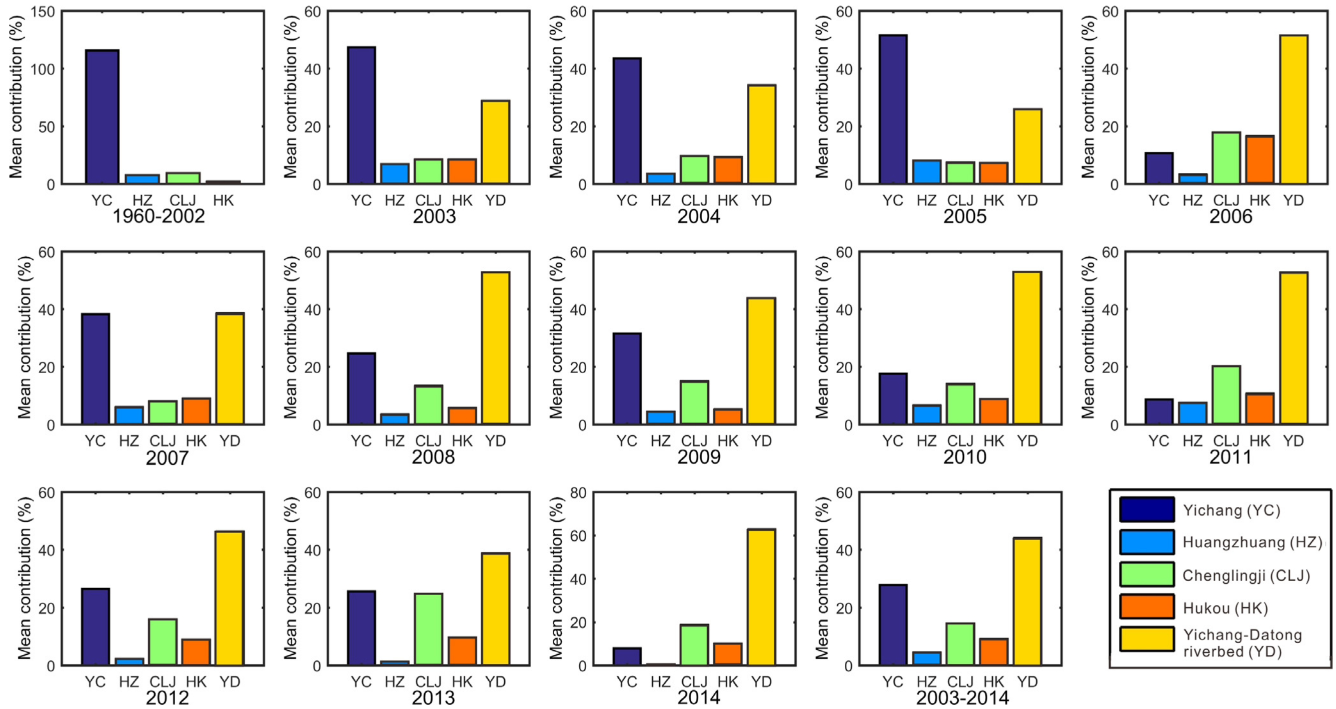

Fig. 13. Sediment-contribution ratios from various sediment sources to the total sediment that entered the sea.

area are even finer (around 7 ~ 8φ), which can be easily carried by base flow. Base flow in the outer side area of the mouth bar is relatively strong, with the current reaching speeds of 0.85 m/s even at a water depth of 40 m (Chen, 2007). Such strong flow currents can readily remove both silt and sand (Dai et al., 2014). Accordingly, large typhoons (e.g., 1997 and 2007) could have caused rapid deposition/erosion variations in the submarine delta, as documented in Fig. 10. Meanwhile, the Changjiang Estuary is mainly hit by typhoons from the northeast, which may lead to erosion along the northeastern delta, while the southeastern delta is less influenced. For instance, the 9711 Typhoon hit the Changjiang Estuary in August 1997, when the maximum tide level at Wusongkou was 5.99 m. The 9711 Typhoon induced strong erosion deeper than 10 m along the submarine delta and abundant landward sediment transport, which caused large-scale deposition where the water depth was less than 10 m (Fig. 10D) (Dai et al., 2014).

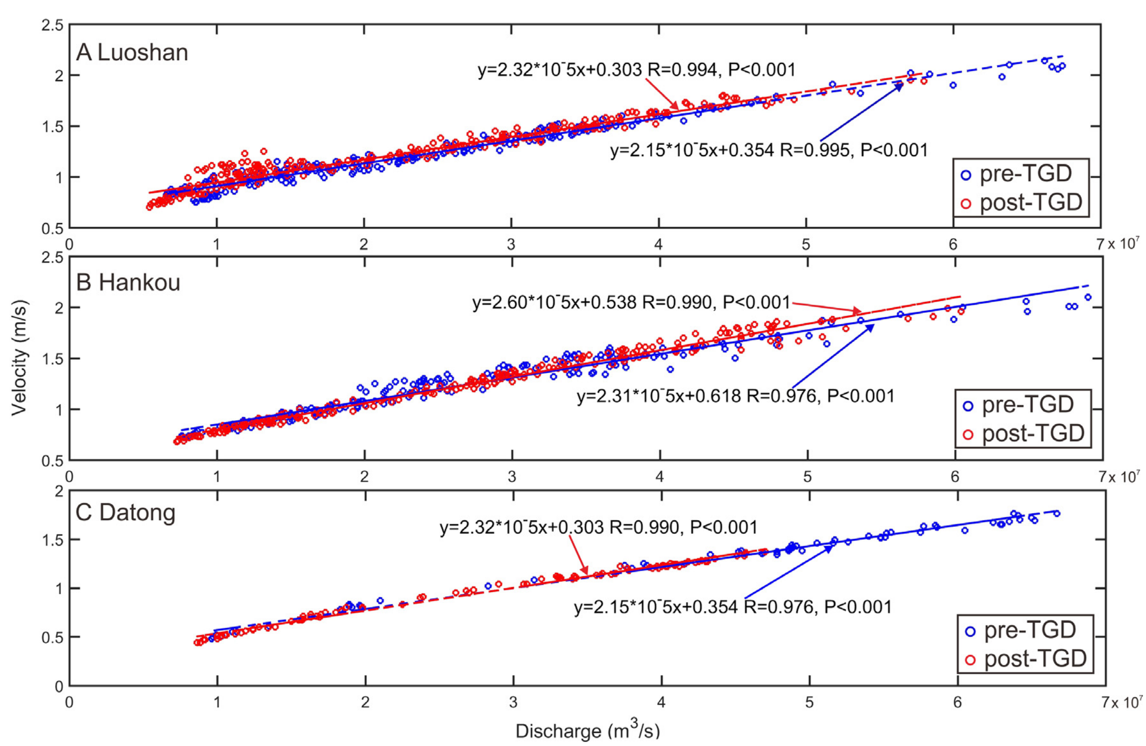

Fig. 14. Variations in water current velocity in different stations.

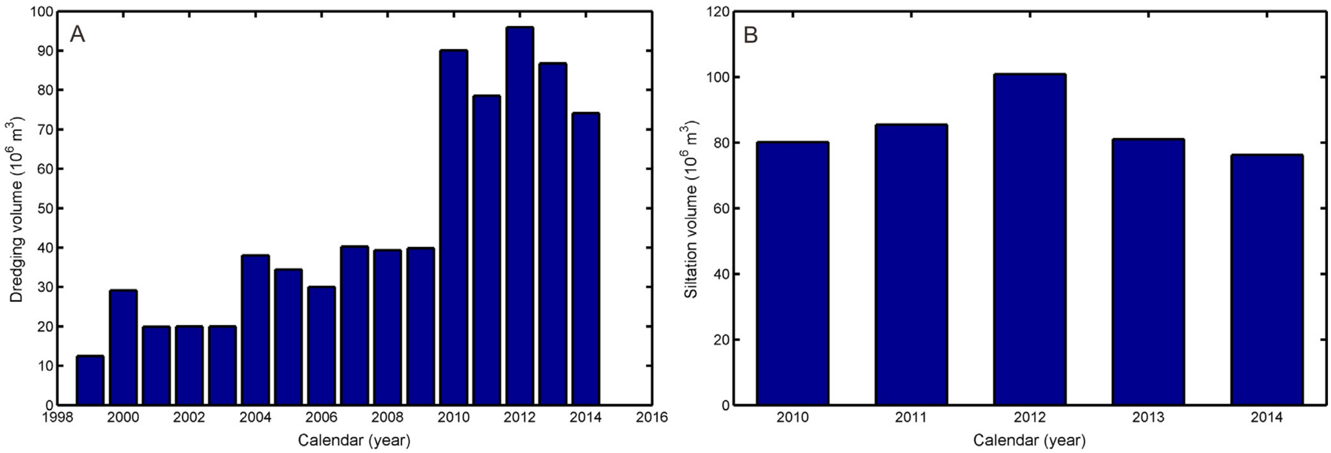

Fig. 15. Dredging and siltation volumes along the North Passage.

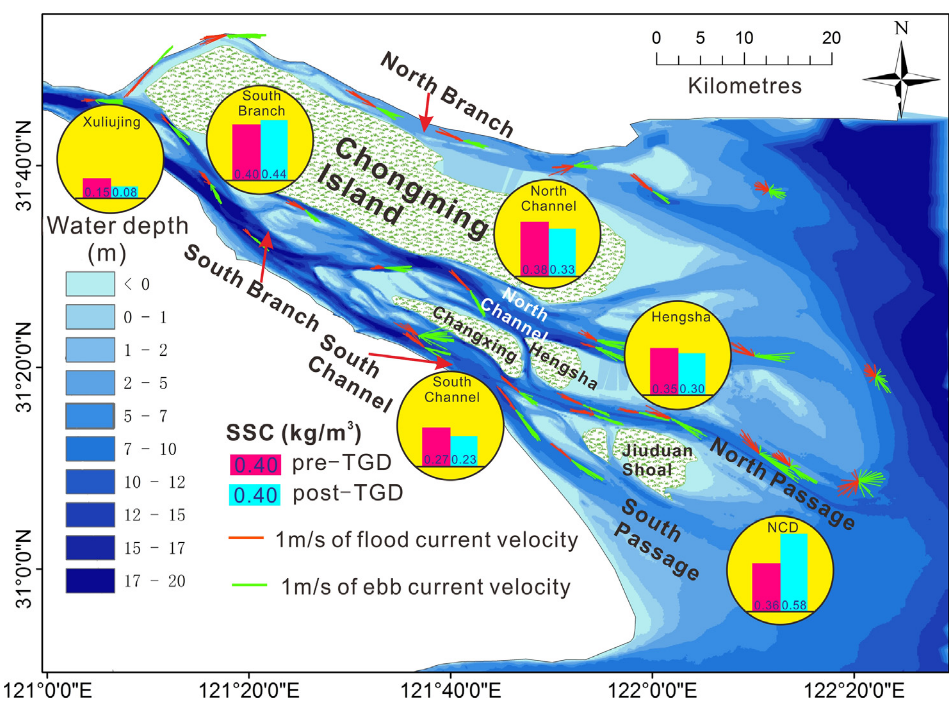

Fig. 16. Mean tidal-current variation in the Changjiang Estuary (Synchronous survey data: 22 Sept. 2002), also showing the variations in mean suspended sediment concentration (SSC).

6. Summary and prospects

The 6300-km-long Changjiang River links the Qinghan-Tibet Plateau to the East China Sea, delivering large volumes of water and sediment, which have vital significance to the estuarine ecosystem. While upstream soil erosion and deforestation have historically had some effect on the transmission of fluvial sediment along the Changjiang River, the regulation of the TGD since 2003 has changed the Changjiang's sediment transfer system (Fig. 8). Specifically, the upper Changjiang River currently provides less than 28% of the total sediment that enters the estuary and is no longer the main sediment source. In contrast, Dongting Lake has transitioned from a sediment sink to a source. Similarly, Poyang Lake previously transported the sediment load supplied by its major tributaries to the Changjiang but now, as a result of lake-bed erosion, Poyang Lake now transmits its own stored sediment to the river. Consequently the two lakes now provide 22% of the SSD passing through Datong (Fig. 13). In addition, the Danjiangkou Reservoir, which was constructed in the Hanjiang River in 1973 with further increase in height in 2012, alsodecreased the SSD contribution from the Hanjiang to the Changjiang Estuary to less than 2% (Fig. S4). As a result of major in-channel erosion, the middle-lower Changjiang River itself now contributes almost 50% of the SSD passing through Datong and has superseded the upper reach as the major source of sediment transmitted to the sea (Fig. 13).

Additional dams will likely be constructed in the Upper Changjiang, which may have the counter-intuitive effect of causing a decrease in sediment trapping behind the TGD (Fig. 12B). The sediment starved water released from the upstream reservoirs may cause channel erosion in the reach from Cuntan to the TGD, potentially providing sediment to the downstream area below the TGD. Nevertheless, the transmission of SSD along the main course of the Changjiang River would be further disrupted. Stronger flow discharge during dry seasons (Fig. 9C and E) and lower SSC (Dai et al., 2016a) would intensify riverbed erosion even further. Accelerated channel down-cutting along the Changjiang River would further decouple the Changjiang from Dongting and Poyang Lakes by enlarging the elevation difference between the lakes and river,

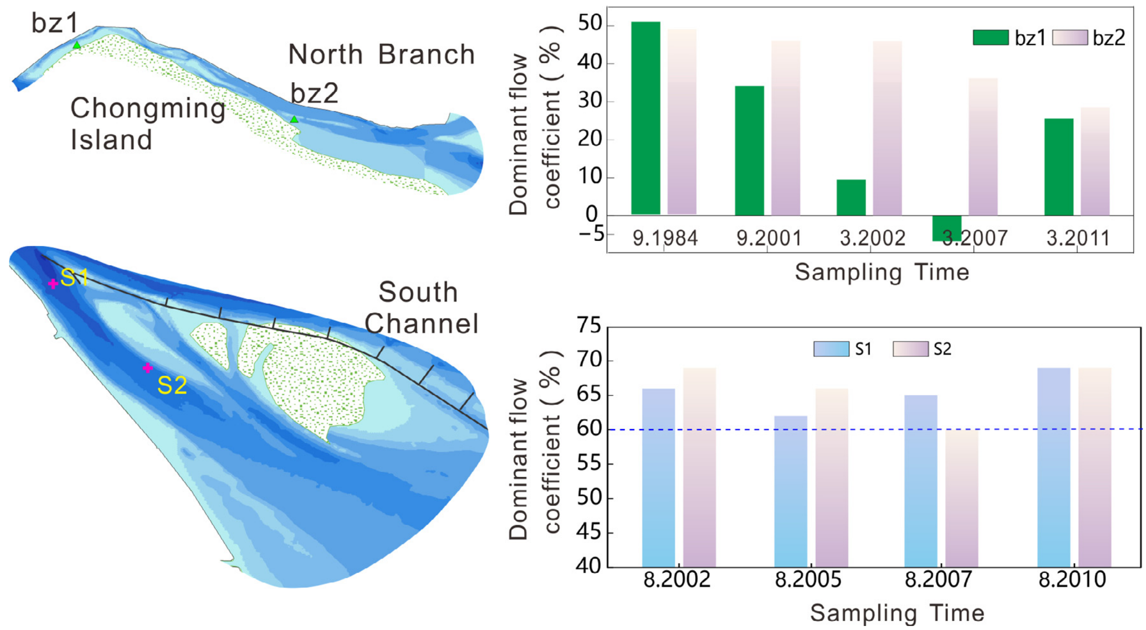

Fig. 17. Coefficient of flow dominance along the Changjiang Estuary.

forcing the lakes to discharge more water and sediment to the river. Decreased riverine SSD with a relatively constant water discharge would also seriously affect the SSC at the river estuary even if the adjacent sea area continues to provide sediment to the estuary. When the estuarine SSC can no longer support the channel and tidal-flat deposition, the Changjiang Estuary, which is currently experiencing a sediment source-sink transition, may be at risk of comprehensive erosion against a background of an annual sea-level rise of 3–4 mm and the occurrence of frequent storms.

Acknowledgments

This study was supported by the National Natural Science Foundation of China (NSFC) (41576087; 41706093; 41306085; 41471147). Yawen Yu, Jinjuan Gao and Jie Wang are thanked for their help with the preparation of the figures. Data can be requested from the corresponding author.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2018.09.019.

References

Allen, P.A., 2008. From landscapes into geological history. Nature 451 (7176), 274–276.
Bentley, S.J., Blum, M.D., Maloney, J., Pond, L., Paulsell, R., 2015. The Mississippi River source-to-sink system: perspectives on tectonic, climatic, and anthropogenic influences, miocene to anthropocene. Earth Sci. Rev. 153, 139–174.
Bi, L., Yang, S., Zhao, Y., Wang, Z., Dou, Y., Li, C., Zheng, H., 2017. Provenance study of the Holocene sediments in the Changjiang (Yangtze River) estuary and inner shelf of the East China sea. Quat. Int. 44A (16), 147–161.
Bianchi, T.S., Allison, M.A., 2009. Large-river delta-front estuaries as natural "recorders" of global environmental change. Proc. Natl. Acad. Sci. U.S.A. 106 (20), 8085–8092.
Blum, M.D., Roberts, H.H., 2009. Drowning of the Mississippi delta due to insufficient sediment supply and global sea-level rise. Nat. Geosci. 2 (7), 488–491.
Bulletin of China River Sediment (BCRS), 2010. Press of Ministry of Water Resources of the People's Republic of China. http://www.cjh.com.cn/.
Bulletin of China River Sediment (BCRS), 2011. Press of Ministry of Water Resources of the People's Republic of China. http://www.cjh.com.cn/.
Bulletin of China River Sediment (BCRS), 2012. Press of Ministry of Water Resources of the People's Republic of China. http://www.cjh.com.cn/.
Bulletin of China River Sediment (BCRS), 2013. Press of Ministry of Water Resources of the People's Republic of China. http://www.cjh.com.cn/.
Bulletin of China River Sediment (BCRS), 2014. Press of Ministry of Water Resources of the People's Republic of China. http://www.cjh.com.cn/.
Chen, J.Y., 2007. Research and Practices of the Estuary and Coast in China. China Higher Education Press, Beijing.
Chen, Z., Wang, Z., Finlayson, B., Chen, J., Yin, D., 2010. Implications of flow control by the Three Gorges Dam on sediment and channel dynamics of the middle Yangtze (Changjiang) River, China. Geology 38 (11), 1043–1046.
Dai, S.B., Lu, X.X., 2014. Sediment load change in the Yangtze River (Changjiang): a review. Geomorphology 215 (12), 60–73.
Dai, Z., Fagherazzi, S., Mei, X., Gao, J., 2016a. Decline in suspended sediment concentration delivered by the Changjiang (Yangtze) River into the East China Sea between 1956 and 2013. Geomorphology 268, 123–132.
Dai, Z., Fagherazzi, S., Mei, X., Chen, J., Meng, Y., 2016b. Linking the infilling of the North Branch in the Changjiang (Yangtze) estuary to anthropogenic activities from 1958 to 2013. Mar. Geol. 379, 1–12.
Dai, Z., Liu, J.T., Wei, W., Chen, J., 2014. Detection of the Three Gorges Dam influence on the Changjiang (Yangtze River) submerged delta. Sci. Rep. 4, 1–7.
Dai, Z., Liu, J.T., 2013a. Impacts of large dams on downstream fluvial sedimentation: an example of the Three Gorges Dam (TGD) on the Changjiang (Yangtze River). J. Hydrol. 480 (4), 10–18.
Dai, Z., Liu, J.T., Fu, G., Xie, H., 2013b. A thirteen-year record of bathymetric changes in the North Passage, Changjiang (Yangtze) estuary. Geomorphology 187 (4), 101–107.
Darby, S.E., Hackney, C.R., Leyland, J., Kummu, M., Lauri, H., Parsons, D.R., Nicholas, A.P., Best, J.L., Aalto, R., 2016. Fluvial sediment supply to a mega-delta reduced by shifting tropical-cyclone activity. Nature 539 (7628), 276–279.
Florsheim, J.L., Keller, E.A., Best, D.W., 1991. Fluvial sediment transport in response to moderate storm flows following chaparral wildfire, Ventura County, southern California. Geol. Soc. Am. Bull. 103 (103), 504–511.
Hu, B.Q., Yang, Z.S., Wang, H.J., Sun, X.X., Bi, N.S., Li, G.G., 2009. Sedimentation in the Three Gorges Dam and the future trend of Changjiang (Yangtze River) sediment flux to the sea. Hydrol. Earth Syst. Sci. 13 (11), 2253–2264.
Jiang, C., Li, J., De Swart, H.E., 2012. Effects of navigational works on morphological changes in the bar area of the Yangtze Estuary. Geomorphology s139–140 (2), 205–219.
Kuehl, S.A., Alexander, C.R., Blair, N.E., Harris, C.K., Marsaglia, K.M., Ogston, A.S., Bilderback, E.L., 2016. A source to Sink perspective of the Waipaoa River margin. Earth Sci. Rev. 153, 301–334.
Liu, J.P., Xu, K.H., Li, A.C., Milliman, J.D., Velozzi, D.M., Xiao, S.B., Yang, Z.S., 2007. Flux and fate of Yangtze River sediment delivered to the East China Sea. Geomorphology 85 (3–4), 208–224.
Liu, J.T., Hsu, R.T., Hung, J.J., Chang, Y.P., Wang, Y.H., Rendle-Bühring, R.H., Yang, R.J., 2016. From the highest to the deepest: The Gaoping River-Gaoping Submarine Canyon dispersal system. Earth Sci. Rev. 153, 274–300.
Luan, H.L., Ding, P.X., Wang, Z.B., Ge, J.Z., Yang, S.L., 2016. Decadal morphological evolution of the Yangtze Estuary in response to river input changes and estuarine engineering projects. Geomorphology 265, 12–23.
Luo, X.X., Yang, S.L., Zhang, J., 2012. The impact of the Three Gorges Dam on the downstream distribution and texture of sediments along the middle and lower Yangtze River (Changjiang) and its estuary, and subsequent sediment dispersal in the East China Sea. Geomorphology 179 (1), 126–140.
Meade, R.H., 1996. River-Sediment Inputs to Major Deltas. Springer Netherlands, London, pp. 63–85.
Mei, X., Dai, Z., Du, J., Chen, J., 2015. Linkage between Three Gorges Dam impacts and the dramatic recessions in China, largest freshwater lake, Poyang Lake. Sci. Rep.

5, 1–9.
Mei, X.F., Dai, Z.J., Darby, S.E., Gao, S., Wang, J., Jiang, W.G., 2018. Modulation of extreme flood levels by impoundment significantly offset by floodplain loss downstream of the Three Gorges Dam. Geophys. Res. Lett. 45, 3147–3155.
Milliman, J.D., Farnsworth, K.L., 2011. River Discharge to the Coastal Ocean – A Global Synthesis. Cambridge University Press, Cambridge, UK.
Milliman, J.D., Shen, H.T., Yang, Z.S., Mead, R.H., 1985. Transport and deposition of river sediment in the Changjiang estuary and adjacent continental shelf. Cont. Shelf Res. 4 (1), 37–45.
Mitchell, S.B., Lawler, D.M., West, J.R., Couperthwaite, J.S., 2003. Use of continuous turbidity sensor in the prediction of fine sediment transport in the turbidity maximum of the Trent Estuary UK. Estuar. Coast. Shelf Sci. 58 (3), 645–652.
Romans, B.W., Castelltort, S., Covault, J.A., Fildani, A., Walsh, J.P., 2016. Environmental signal propagation in sedimentary systems across timescales. Earth Sci. Rev. 153, 7–29.
Shi, D.M., 1999. Analysis of relationship between soil and water loss and flood disasters in Yangtze River basin. J. Soil Water Conserv. 5, 1–7 (in Chinese with English abstract).
Simmons, H.B., 1955. Some effects of upland discharge on estuarine hydraulics. In: Separate Paper No. 792. Proceedings ASCE Press, Reston VA, pp. 81.
Specifications for the Monitoring Riverine Suspended Matter (GB 50159-92), 1992. Compilation by Ministry of Water Resources of the People's Republic of China.
Specifications for the Observation of River Discharge (GB-50179-1993JRX), 1993.
Specifications for the Waterway Survey (SL257-2000), 2000. Compilation by Ministry of Water Resources of the People's Republic of China.
Swenson, J.B., Chris, P., Lincoln, P., Voller, V.R., Brad, M.A., 2005. Fluvial and marine controls on combined subaerial and subaqueous delta progradation: morphodynamic modeling of compound-clinoform development. J. Geophys. Res. 110 (110), 1–16.
Syvitski, J.P.M., Kettner, A.J., Overeem, I., Hutton, E.W.H., Hannon, M.T., Brakenridge, G.R., Giosan, L., 2009. Sinking deltas due to human activities. Nat. Geosci. 2 (10), 681–686.
Syvitski, J.P.M., Green, P.B.T., 2005. Impact of humans on the flux of terrestrial sediment to the global coastal ocean. Science (New York, N.Y.) 308 (5720), 376–380.
Törnqvist, T.E., Bick, S.J., Klaas, V.D.B., De Jong, A.F.M., 2006. How stable is the Mississippi Delta? Geology 34, 697–700.
Uncles, R.J., Stephens, J.A., 1997. Dynamics of turbidity in the tweed estuary. Estuar. Coast. Shelf Sci. 45 (6), 745–758.
Walling, D.E., Fang, D., 2003. Recent trends in the suspended sediment loads of the world's rivers. Global Planet. Change 39 (1), 111–126.
Walsh, J.P., Wiberg, P.L., Aalto, R., Nittrouer, C.A., Kuehl, S.A., 2016. Source-to-sink research: economy of the earth's surface and its strata. Earth Sci. Rev. 153, 1–6.
Wang, H., Saito, Y., Zhang, Y., Bi, N., Sun, X., Yang, Z., 2011. Recent changes of sediment flux to the western Pacific Ocean from major rivers in East and Southeast Asia. Earth Sci. Rev. 108 (1), 80–100.
Wei, W., Chang, Y., Dai, Z., 2014. Streamflow changes of the Changjiang (Yangtze) River in the recent 60 years: impacts of the East Asian summer monsoon, ENSO, and human activities. Quat. Int. 336 (12), 98–107.
Xu, K., Milliman, J.D., 2009. Seasonal variations of sediment discharge from the Yangtze River before and after impoundment of the Three Gorges Dam. Geomorphology 104 (3–4), 276–283.
Wang, B., Xu, Y.J., 2018. Decadal-scale riverbed deformation and sand budget of the last 500 km of the Mississippi River: insights into natural and river engineering effects on a large alluvial river. J. Geophys. Res. Earth Surf. 123. https://doi.org/10.1029/2017JF004542.
Yang, S.L., Shi, Z., Zhao, H.Y., Li, P., Dai, S.B., Gao, A., 2004. Effects of human activities on the Yangtze River suspended sediment flux into the estuary in the last century. Hydrol. Earth Syst. Sci. 8 (6), 1210–1216.
Yang, S.L., Milliman, J.D., Xu, K.H., Deng, B., Zhang, X.Y., Luo, X.X., 2014. Downstream sedimentary and geomorphic impacts of the Three Gorges Dam on the Yangtze River. Earth Sci. Rev. 138, 469–486.
Yang, S.L., Milliman, J.D., Li, P., Xu, K., 2011. 50,000 dams later: erosion of the Yangtze River and its delta. Glob. Planet. Change 75 (1), 14–20.
Yang, S.L., Zhang, J., Xu, X.J., 2007. Influence of the Three Gorges Dam on downstream delivery of sediment and its environmental implicationsYangtze River. Geophys. Res. Lett. 34 (10), 1–5.
Yu, Y.W., Mei, X.F., Dai, Z.J., Gao, J.J., Li, J.B., Wang, J., Lou, Y.Y., 2018. Hydromorphological processes of Dongting Lake in China between 1951 and 2014. J. Hydrol. 562, 254–266.
Zhang, S., Zhu, C., 2001. Soil loss and its effect on flooding catastrophe in Yangtze Drainage basin. J. Soil Water Conserv. 15, 9–13 (in Chinese with English abstract).
Zhu, L., Chen, J., Jing, Y., Dong, B., Hydrology, B.O., 2014. Sediment erosion and deposition in two lakes connected with the middle Yangtze River and the impact of Three Gorges Reservoir. Adv. Water Sci. 25 (3), 348–357.