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Highlights (3 to 5 bullet points (maximum 85 characters including spaces per bullet point)

- Water storage by the Three Gorges Dam (TGD) has completely changed the sediment transfer system of the Changjiang River
- The upper Changjiang River has changed from being a dominant sediment source zone before 2003 to a secondary source thereafter
- The middle-lower Changjiang River has shifted from being a sediment sink before 2003 to a sediment source thereafter

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

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Abstract

Knowledge of the transfer of sediment through river systems is essential for understanding a key control on the physical, chemical and biological processes on the Earth's surface. Based on a new analysis of long-term records of water discharge, sediment transport, riverbed morphology and estuarine hydrology, here we quantify and interpret fluvial sediment fluxes along the Changjiang River. We show that the establishment of the TGD has directly changed the fluvial sediment-transport process by annually trapping 1.23×10^8 t sediments. As a result of the loss of this trapped material the upper Changjiang reach has switched from being the main sediment source before 2003 to a depositional sink of fluvial sediment subsequently. Furthermore, 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 reach has switched to become the major source of sediment being transmitted downstream, now providing almost 50% of the material entering the estuary. Moreover, shoals in the estuarine channels and landward sediment transport from the sea have also become major new sediment sources for the river estuary following the construction of the TGD. We conclude that dams that are currently in preparation along the upper Changjiang reach and adjacent lakes may cause the cessation of sediment supply to downstream reaches. Meanwhile, rising sea levels and frequent storms may terminate landward sediment transport, aggravating estuary 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.

Keywords: Sediment discharge; river-estuary depositional system; sediment transfer; Changjiang River.

1 Introduction

The Earth's surface is a key interface over which many physical, chemical and biological processes that are associated with fluvial sediment transport can strongly shape the 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). The Industrial Revolution and associated human activities have significantly affected the Earth's surface, changing global sediment transport regimes across the planet (Milliman & Farnsworth, 2011; Syvitski & Green, 2005), with the potential to seriously disturb sedimentation and associated biogeochemical cycles on the Earth's surface. A fundamental question, therefore, concerns the extent to which sediment transport processes have been impacted by human interference in a range of fluvial sediment transfer systems around the world (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 parts 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). Meanwhile, sediment transfer pathways are much more complicated in estuarine areas compared to those in the ocean because of the complexity arising from the combined influence of river discharge, tidal flow, wave action, and associated gravitational circulation (Bianchi & Allison, 2009; Uncles & Stephens, 1997), tidal pumping (Mitchell et al., 2003) and flocculation because of mixing between salt and fresh water (Liu et al., 2016; Walling & Fang, 2003; Syvitski et al., 2005).

In recent decades there has been growing interest in quantifying the transfer of fluvial sediment from source to sink (Walsh et al., 2016; Liu et al., 2016; Blum et al., 2009; Allen, 2008). For example, Bentley et al. (2016) assessed the effects of tectonic, climatic, and anthropogenic influences on the fluvial-marine sediment-dispersal system of the Mississippi River and demonstrated that the upstream control of 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. Recent studies on the Waipaoa River (New Zealand) and Fly River (Papua New Guinea) also have provided a holistic perspective of the sediment transfer processes that have generated, transported and preserved sedimentary information since the Late Quaternary (Canestrelli et al., 2010, 2014; Kuehl et al., 2016). Related research on sediment transmission has also been conducted for the Amazon (Nittrouer & DeMaster, 1996; Jr et al., 2015), Mississippi (Meade & Moody, 2010), Eel

(Warrick, 2014), Ganges-Brahmaputra (Barua, 1990), Yellow (Liu et al., 2009; Wang et al., 2011; Saito et al., 2001), Red (Gao et al., 2015; Dang et al., 2010), Pearl (Luo et al., 2007; Wu et al., 2012), Colorado (Carriquiry et al., 2001), Danube (Matenco & Andriessen, 2013), Po (Fox et al., 2004), and Ebro (Rovira et al., 2015) River systems. Additionally, research has also been conducted on the transport of sediment from mountainous rivers to coastal zones, such as the Lanyang, Zhuoshui, and Gaoping rivers in Taiwan (Liu et al., 2008; Dadson et al., 2003; Liu et al., 2016).

While these previous studies have focused on a wide range of fluvial sediment transfer systems, 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 et al., 2009; Hu et al., 2009; Wang et al., 2011; Dai & Lu, 2014; Dai et al., 2016a). Previous work on the Changjiang has also investigated the influence of upstream reservoirs on downstream geomorphology and sedimentation (Luo et al., 2012; Dai & Liu, 2013a; Yang et al., 2014), 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). To date, however, a holistic synthesis of the fluvial sediment dispersal system of the Changjiang River has not been undertaken, especially in reference to the effects of intensive human activities. Such a synthesis is both necessary and vital to fully assess 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 interconnections between sediment transfer processes in the Changjiang River and estuarine morphodynamic processes.

The remainder of this paper is structured as follows. First, we provide a description of the Changjiang River in section 2 before summarizing the data sources and methods employed in section 3. In section 4 we analyze the sediment transition between the upper and middle Changjiang River, the exchange of sediments between the major lakes and river in the middle Changjiang River reach, and sediment transfer within the Changjiang estuarine area. In section 5 we seek to detect the influence of factors driving sediment transfer along the Changjiang River. Finally, we conclude by presenting an outlook of sediment transfer processes along the Changjiang River (section 6).

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 (Figure 1A). Generally, the upper reach of the Changjiang River is considered to end at Yichang, covering an area of 1×10^6 km^2; thereafter, the middle reach extends from Yichang to Hankou, encompassing the Hanjiang river as well as Dongting and Poyang Lakes, while the lower reach stretches from Hankou to the river mouth (Figure 1B-D). The hydrometric stations at Yichang, Hankou and Datong were, therefore, selected here to reflect the hydrological characteristics of the upper, middle and lower reaches of the Changjiang River, respectively (Figure 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 1950-2000 the river discharged 905×10^9 m^3 of water and 0.42×10^9 t of sediment to the estuary each year (BCRS, 2010, 2011, 2012, 2013 and 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 & Liu, 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 1950-2002 (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 (BRCS, 2010, 2011). Moreover, 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, alongside 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. Specifically, we collated monthly river runoff and Suspended Sediment Discharge (SSD) data for the period between

1950s-2014, alongside estimates of erosion and deposition of the Yichang-Nanjing reach between 1957-1980, 1980-2002, 2002-2010 as 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 (Figure 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 (Figure 1A). Chenglingji and Hukou indicate the contributions from Dongting Lake and Poyang Lake to the Changjiang River (Figures 1B and 1C), 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.

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 and Liu, 2013a; Dai et al., 2013b, 2016b). Occasional missing data were reconstructed through regression.

The sediment deposition/erosion volumes along the Changjiang River course was calculated from analyses of bathymetric map (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. When bathymetric charts were not available, the corresponding deposition/erosion volume was estimated through the sediment budget. 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 in reference to 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 of the ebb tidal currents (Simmons, 1955). When this coefficient is over 50%, the flow is ebb-dominated.

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

4.1. Suspended Sediment Discharge in the Upper Changjiang

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 (Figures 2A, 2C, and 2E), 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 (Figures 2B, 2D, and 2F). In terms of annual time series, there is no apparent trend in the water discharge during this period (Figures 2A, 2C, 2E, and 2G), but large variations were detected in the annual SSD, with an abrupt decline after 2003 (Figures 2B, 2D, and 2F). Specifically, 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, respectively, during the period 2003-2014, a reduction of 45%, 60% and 85% compared to the SSD values observed during the period 1951-2000 (Figure 2H).

Furthermore, Yichang is the most downstream of the three stations considered above and may therefore be regarded as a control station for the Upper Changjiang reach (Figure 1A). The total SSD being delivered to Yichang was therefore determined by summing the contributions from: (i) the upper stream from the river source to Pingshan; (ii) three major tributaries (Minjiang, Jialingjiang and Wujiang), and; (iii) riverbed sediment erosion along the Pingshan-Yichang reach (Figure 1A; Figure S1). 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 0.17×10^6 t/km yearly since 2003 (Figure 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 (Figure 3B). The upper Changjiang River has therefore 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 (Figures 3A and 3B).

The scale of change of SSD through Yichang can be illustrated by comparing the SSD at Yichang with that at Datong, the station located closest to the estuary. During the period 1951-2000 the SSD at Yichang varied between 83%-160% of that through Datong, with a mean value of 116% (Figure 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 (Figure 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 the main sediment source for the downstream area.

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, exchanging 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 (Figure 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%; meanwhile the contribution for the SSD has increased from 15% to 48% (Figure S2). Accordingly, the main SSD source for Dongting Lake has switched 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 (Figure 4A), albeit 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 (Figures 4A and 4B). Subsequently, this prior depositional state ceased entirely from 2003, after which date the lake shifted to an erosional status, exporting 0.4×10^6 t of sediment each year (Figure 4A). As Figure 4C indicates, the lake generally stored sediments during the flood season and provided sediment through erosion during the dry season; the accretion rate during the flood seasons being much larger than the erosion rate during the dry season (Figure 4C). Since 2003, however, the deposition rate during the flood season has decreased to only 0.067×10^8 t/yr, while the lake bed scouring rate during the dry season has increased to 0.072×10^8 t/yr. Furthermore, the proportional contribution of suspended sediment passing from Dongting Lake to the downstream area of the Changjiang River estuary has exhibited a downward trend since the 1950s, decreasing from 14% to 7% in 2002, but significantly increasing thereafter to 19% in 2014 (Figure 4D).

4.2.2. Poyang Lake

Exchanges of water between Poyang Lake and the Changjiang River have exhibited only slight variations in the pre-TGD (1960-2002) versus post-TGD periods, with both the output and input flows decreasing by only around 5% (Figures S3A, 3C, and 3E). However, Poyang Lake has undergone a dramatic change in its sediment budget (Figures S3B, 3D, and 3F). 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 (Figures S3B and 3D). 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: therefore the output flux is now almost double the input flux. In other words, while almost 4×10^6 t/yr of sediment was deposited in Poyang Lake during 1960-2002 (Figures 5A), since 2003 the lake has had to provide around 6.75×10^6 t/yr to maintain the sediment budget (Figure 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 only around the equivalent of 2% of the sediment load passing through Datong, but this proportion increased to 9% during the period 2003-2012 (Figure 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 (Figure 3). Thus, while the Changjiang's overall SSD 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 they were before.

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 & Liu, 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) (Figure S4), with no statistically significant changes over time. The annual sediment flux exported from the Hanjiang into the Changjiang, however, has experienced a significant declining trend with an overall reduction of 95% ($P<0.01$) during this time, with the maximum and minimum recorded values occurring in 1964 (2.61×10^8 t) and 2014 (0.007×10^8 t), respectively (Figure S4). Specifically, 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 during 1960-1969 and further to 0.245×10^8 t/yr during 1970-1979 (Figure S4). This decrease continued into the 2000s, by which time the annual mean sediment load was as low as 0.065×10^8 t/yr, just 5% of that observed during the 1950s (Figure S4).

In terms of its proportional contribution to sediment reaching the estuary, the sediment flux from the Hanjiang tributary was equivalent to around 15% of the sediment load passing through Datong during the 1960s, but it has significantly decreased afterwards, reaching a minimum of 6% in 2000. This proportional decline subsequently then reversed, with an increased value of 12% from 2000-2011. However, the sediment-contribution ratio from Hanjiang to Datong then abruptly declined to just 2% between 2012 and 2014, presumably as a result of a further increase, in the year 2013, in the Danjiakou reservoir's height on the Hanjiang River.

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 (Figure 1A). While 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 (Figures 6A, 6C, 6E, and 6G), the SSD has exhibited significant variations, with the most obvious changes occurring since 2003 (Figures 6B, 6D, 6F, and 6H). For example, compared to the period from the 1950s to 2000, the annual mean SSD along the main course has decreased by 80% at Jianli, 78% at Luoshan, 73% Hankou and 68% at Datong (Figures 6B, 6D, 6F, and 6H).

Furthermore, 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 (Figure 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 (Figure 7B). Thus, although the Luoshan-Hankou reach was in a depositional state before 2003, since that date it has subsequently switched to an erosional state and has supplied sediment to the downstream area. Moreover, the SSD budget along the Hankou-Datong reach is also erosional, with that reach providing 0.11×10^8 t/yr of in-channel sediment to the downstream area before 2003 (Figure 7C), 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 (Figure 8), the Luoshan-Hankou reach acted as a sediment-sink, and the Hankou-Datong reach intermittently received sediment while providing sediment in other years. 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 of downstream sediment transmission. The sediment contributions from these three reaches decreased as their distance to the upstream area increased (Figure 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 (Figures 6G and 9A). However, inter-seasonal variations in water discharge have become slightly more pronounced after 2003, with the overall proportion of flow passing during the flood season (May-October) decreasing slightly from 72% (1950-2002) to 68% (2003-2014), while the proportion of flow passing in the dry season has increased from 28% to 32% (Figures 9C and 9E).

In contrast to the water discharge trends, the fluvial suspended sediment discharge through Datong has exhibited a substantial decrease over recent decades (Figures 6H and 9B). This decline began around the 1970s but became more intense since the closure of the TGD in 2003 (Figure 10H) (Dai et al., 2016a). The annual mean SSD during the period 1950-1959 was around 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 (Figure 9B). In terms of seasonal variations in the SSD, during the flood season around 88% of the total annual SSD was previously (1950-2002) passed (Figure 9F), but since 2003 this has reduced to 80% of the total annual SSD.

4.4.2. Volume variations in the Changjiang Estuary

Volume variations in the Changjiang Estuary mainly occur in the submarine delta and estuarine channels, and these are now briefly analyzed. The Changjiang estuarine submarine delta (CESD) experienced net deposition during the period 1958-1997, with strong siltation of over 140×10^6 m^3/yr during the period 1958-1978, slow deposition of approximately 2×10^6 m^3/yr during 1978-1989 and 18×10^6 m^3/yr during 1989-1997, prior to the onset of slight erosion of around 40×10^6 m^3/yr during 1997-2002 (Figures 10A-10d). The CESD regained a depositional state during 2002-2013 (Figures 10E-H), during which time the -10-m isobath extended seaward at an accumulation rate of 25-50 cm/yr (Figure 10).

Furthermore, the channel volumes below the 0-m isobath for the NB (North Branch) and South Passage (SP) are described in Figure 11. The volume capacity of the SP gradually decreased during 1958-2012, with an overall loss of approximately 13% (Figure 11A). Specifically, the volume decreased from 0.69×10^9 m^3 in 1987 to 0.59×10^9 m^3 in 1994, a reduction of 14% (Figure 11), which suggests a period of infilling. During 1994-1996, the capacity increased by 0.04×10^9 m^3. After 1998, the capacity continued to decrease. During 2001-2006, the capacity increased again. However, the capacity drastically declined by 0.06×10^9 m^3 and then gradually but slightly increased during 2006-2008 (Figure 11A). Meanwhile, the channel volume below 0 m in the NB dramatically decreased by 53% from 1.17×10^9 m^3 in 1958 to 0.54×10^9 m^3 in 2013 (Figure 11B), at a mean deposition rate of 11.4×10^6 m^3/yr. Meanwhile, the channel volume below 0 m exhibited a statistically significant decrease ($p<0.05$) (Figure 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 364×10^3 km^2 during the 1950s (Shi, 1999; Zhang & Zhu, 2001), as a result of a decline of the forest cover in the catchment from 60-80% prior to the 1950s to just 22% in 1957 (Zhang & Zhu, 2001). This inappropriate land-use change 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 (Figure 7), when the annual mean SSD at Yichang reached 5.4×10^8 t/yr (Figure 2F).

Importantly, only a small number of reservoirs were present along the Changjiang River during the period 1950-1970, so the potential for trapping of riverine sediment was low at this time. During 1970-2002, however, the total reservoir storage capacity increased to 170×10^9 m^3 (Figure 12A), a sufficiently significant increase to retain large volumes of sediment behind the dams. Meanwhile, ongoing land use change resulted in the catchment area being affected by severe erosion increasing to 707×10^3 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, at this time without significant variations during 1950-2002 (Figures 2F and 12B). Accordingly, the basic sediment source-sink process within the Changjiang River itself did not significantly change over this period, when the upper reach was still the main sediment source, providing 115% of the SSD compared to that of the downstream area (Figure 13).

The dominant driver of recent sediment transfer variations along the Changjiang River is likely to have been the TGD, which is currently the world's largest hydrologic engineering project and was completed in 2003. 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 (Figure 12B). This cut off in the sediment supply from upstream sharply decreased the SSD observed at Yichang, from 2.28×10^8 t/yr in 2002 to 0.97×10^8 t/yr thereafter (Figure 2F), while the corresponding SSD at Datong was 2.06×10^8 t/yr (Figure 9B). During 2003-2005, the TGD stored 1.25×10^8 t/yr of sediment in the reservoir, when the SSD at Yichang was 0.91×10^8 t/yr, while the SSD at Datong dropped further to 1.89×10^8 t/yr (Figure 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 (Figure 6H). The huge amount of trapped sediment behind the TGD (Figure 12B) may be reflected in the SSD variation at Yichang, where the SSD was less than that at Datong in 2003.

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). Among the four outlets of the Changjiang Estuary, the North Passage (NP) has experienced erosion (Figure 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 and Liu, 2013b) (Figure 14A). 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 ongoing (Figure 14B), which is inconsistent with the dramatic decrease in fluvial sediment. Thus, the erosion along the NP was dominated by artificial dredging to maintain the DNC. The severe back siltation can be explained by landward sediment transport from the sea because the upstream area cannot easily provide such a large amount of sediment.

5.3. Local tidal forces in the Changjiang Estuary

The Changjiang experiences average tidal-current velocities in excess of 1 m/s (Figure 15). 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, a submarine delta of over 10000-km^2 exists around the river mouth, with the majority distributed shallower than -50 m (Chen et al., 1985), and the sediments stored in the 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).

According to Swenson et al. (2005), landward sediment transport may increase when the riverine water discharge decreases, which would induce submarine-delta siltation. For the Changjiang Estuary, the fluvial flood peak substantially decreased (Figures 9E and 9F), which increased the dynamic effects of tidal currents. As shown in Figure 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 well explain the deposition of a submarine delta in the Changjiang Estuary even under declining fluvial SSD (Dai et al., 2014). Meanwhile, the decrease in riverine flood discharge and associated land reclamation has also induced channel narrowing, which significantly strengthened the tidal currents (Figure 16A), resulting in gradual deposition along the tidally-dominant portions of the estuary, such as the NB, where the riverine SSD is less than 1% of the total sediment load entering the East China Sea (Dai et al., 2016b). Therefore, landward sediment transport from the sea area was another new sediment source. Additionally, deposition was detected in the SP as ebb flow increased, which can be explained by the sediment input from shoal erosion around the upstream opening of the SP (Figure 16B), indicating that the shoals in the Changjiang Estuary have also turned into new sediment sources.

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 now fundamentally changed the Changjiang's sediment transfer system (Figure 8). Specifically, the upper Changjiang River currently only 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 changed from being 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 (Figure 13). In addition, the Danjiangkou Reservoir, which was constructed in the Hanjiang River in 1973, and which was further heightened in 2012, also now intercepts additional sediment, decreasing the SSD contribution from the Hanjiang to the Changjiang Estuary to less than 2% (Figure 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 thus superseded the upper reach as the major source of sediment transmitted to the sea (Figure 13).

In the coming decades 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 (Figure 12B). This is because the sediment starved water released from the upstream reservoirs may well 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 (Figures 9C and 9E) 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, 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 may well continue to provide sediment to the estuary. Additionally, land reclamation in the Changjiang Estuary is continuing. 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

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Figure Captions

Figure 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.

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

Figure 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.

Figure 4. Sediment budget of Dongting Lake and its contribution to the Suspended Sediment Discharge (SSD) that enters the sea. A, B, and 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.

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

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

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

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

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

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

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

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

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

Figure 14. Dredging and siltation volumes along the North Passage.

Figure 15. Mean tidal-current variation in the Changjiang Estuary (Synchronous survey data: 22 Sept. 2002), also showing the variations in mean suspended sediment concentration (SSC)

Figure 16. Coefficient of flow dominance along the Changjiang Estuary

Cover letter

Dear Editor:

It is our great enthusiasms to submit the manuscript entitled "**Fluvial sediment transfer in the Changjiang (Yangtze) river-estuary depositional system**" to your journal. We confirm that the results reported herein are original and have not been submitted to other journals.

Knowledge of sediment source-to-sink systems is very significant to understand the physical, chemical and biological processes on the Earth's surface. River systems, which mark the transition zone between the land and the coastal ocean, are a critical interface for human resources and serve as key repositories of geological information, making these systems very important to fully understand the sediment-routing systems over the Earth's surface.

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. Meanwhile, the source-sink routes of sediment are much more complicated in estuarine areas compared to those in the ocean because of coupling between river discharge, tidal flow, and wave action, which is of particular concern globally.

While systematic and comprehensive research has examined the sediment-routing systems of large mountainous rivers and most fluvial systems (e.g. Mississippi river) around the world, a holistic understanding of the fluvial sediment dispersal system of the Changjiang River from source to sink has not been well documented, especially in reference to the effects of intensive human activities. Such an understanding is necessary and vital to fully assess the fluvial sediment transport from the Changjiang River to the East China Sea and the associated biogeochemical cycles.

Thereafter, in this paper thoroughly and systematically research is done on the sediment source-sink system of the Changjiang River, including a risk analysis of the sediment source-sink process against intensive human interferences. We firstly show that the water storage of the TGD operation in 2003 completely changed the sediment source-sink system of the Changjiang River. The upper Changjiang River changed from a dominate sediment source before 2003 to a secondary source. However, the riverbed of the main course of the middle-lower Changjiang reach provided a great volume of sediment to the downstream area after 2003. It is thereof argued that 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.

We hope that our findings support the aims of your journal.

Sincerely yours,

Zhijun Dai, Xuefei Mei, and Stephen E. Darby et al.

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Figure 1. Overview of the Changjiang River basin

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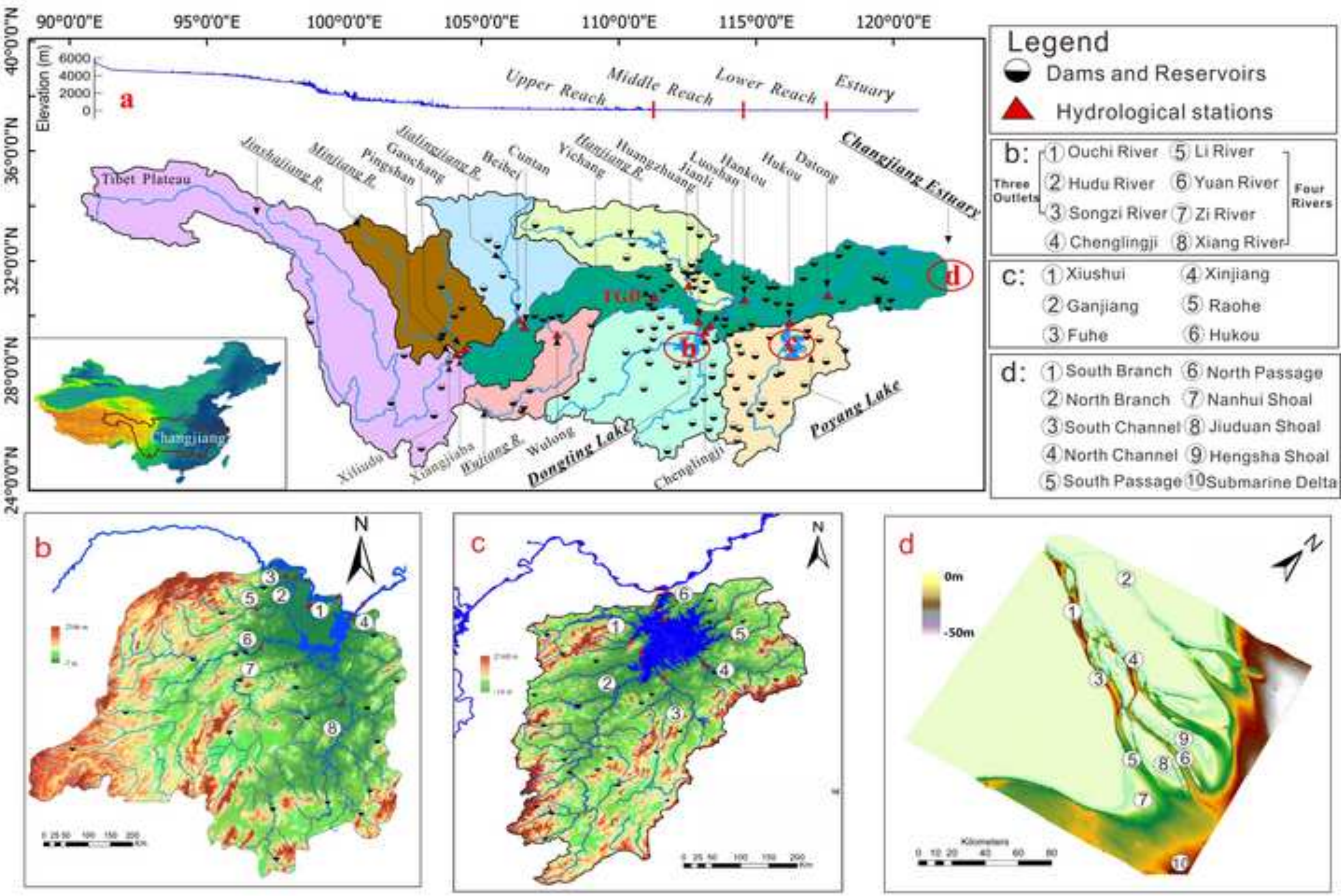

Figure 2. Variations in the water discharge and Sediment

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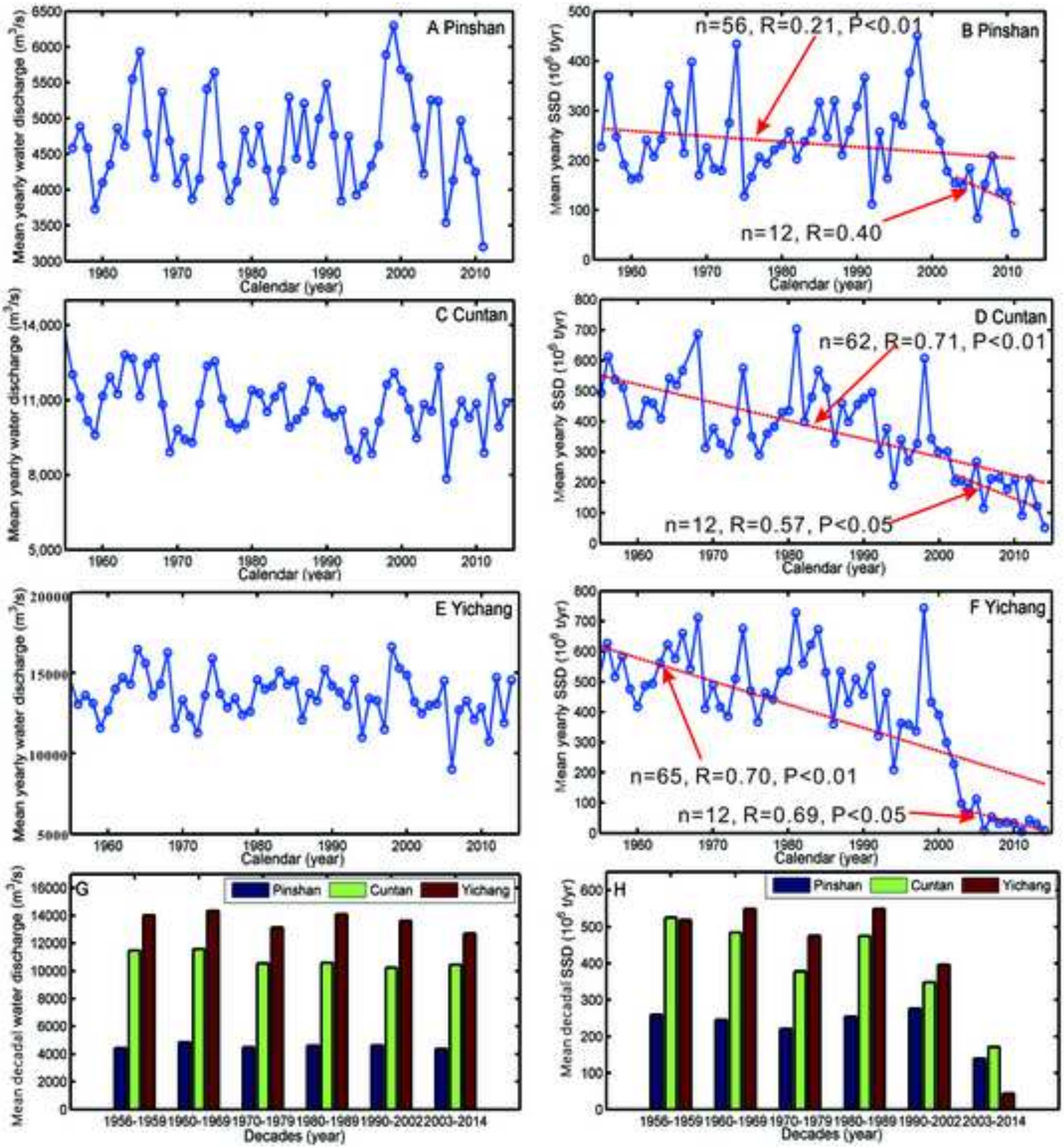

Figure 3 Yearly SSD in the upper Changjiang reach

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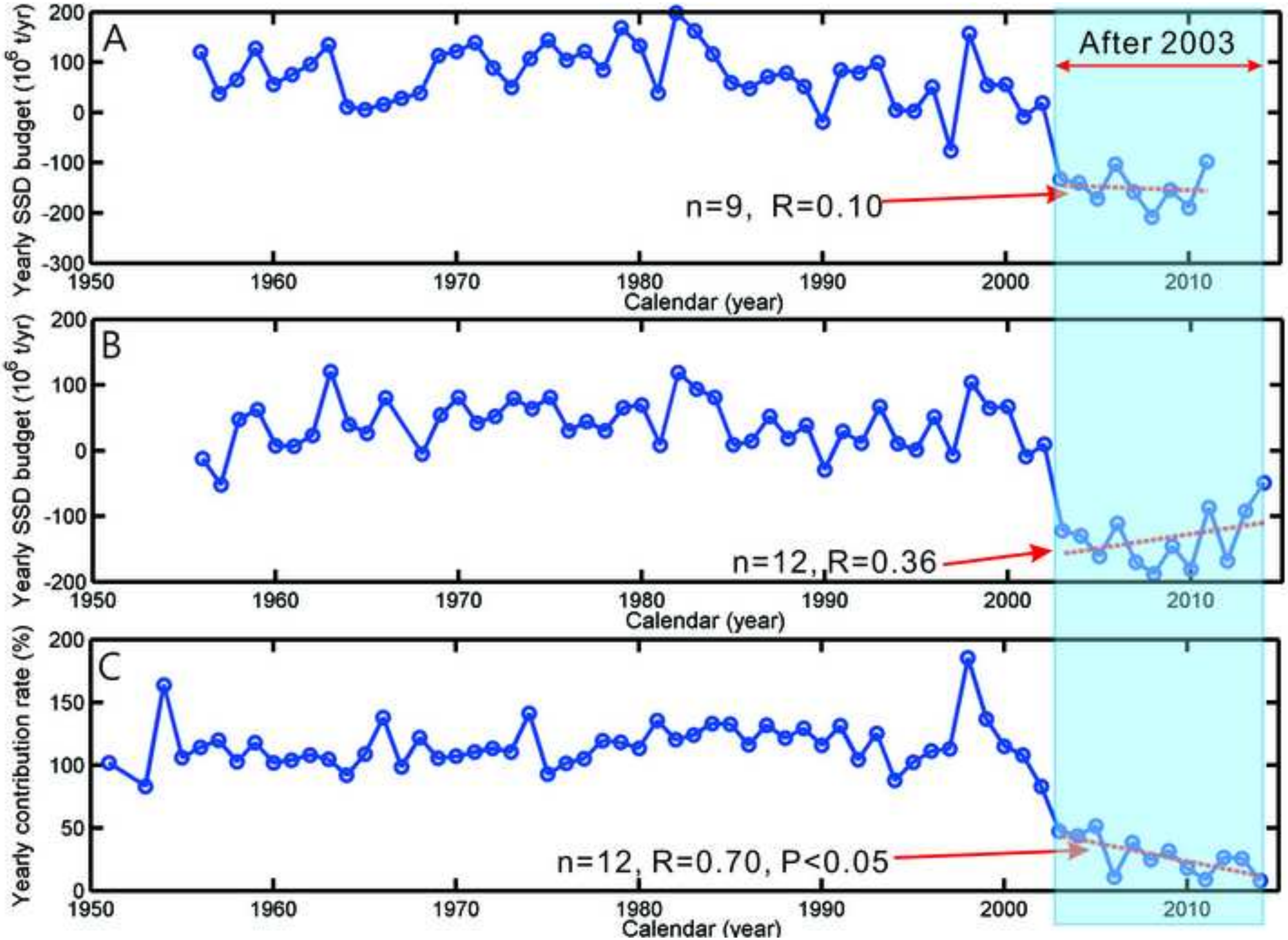

Figure 4. Sediment budget of Dongting Lake

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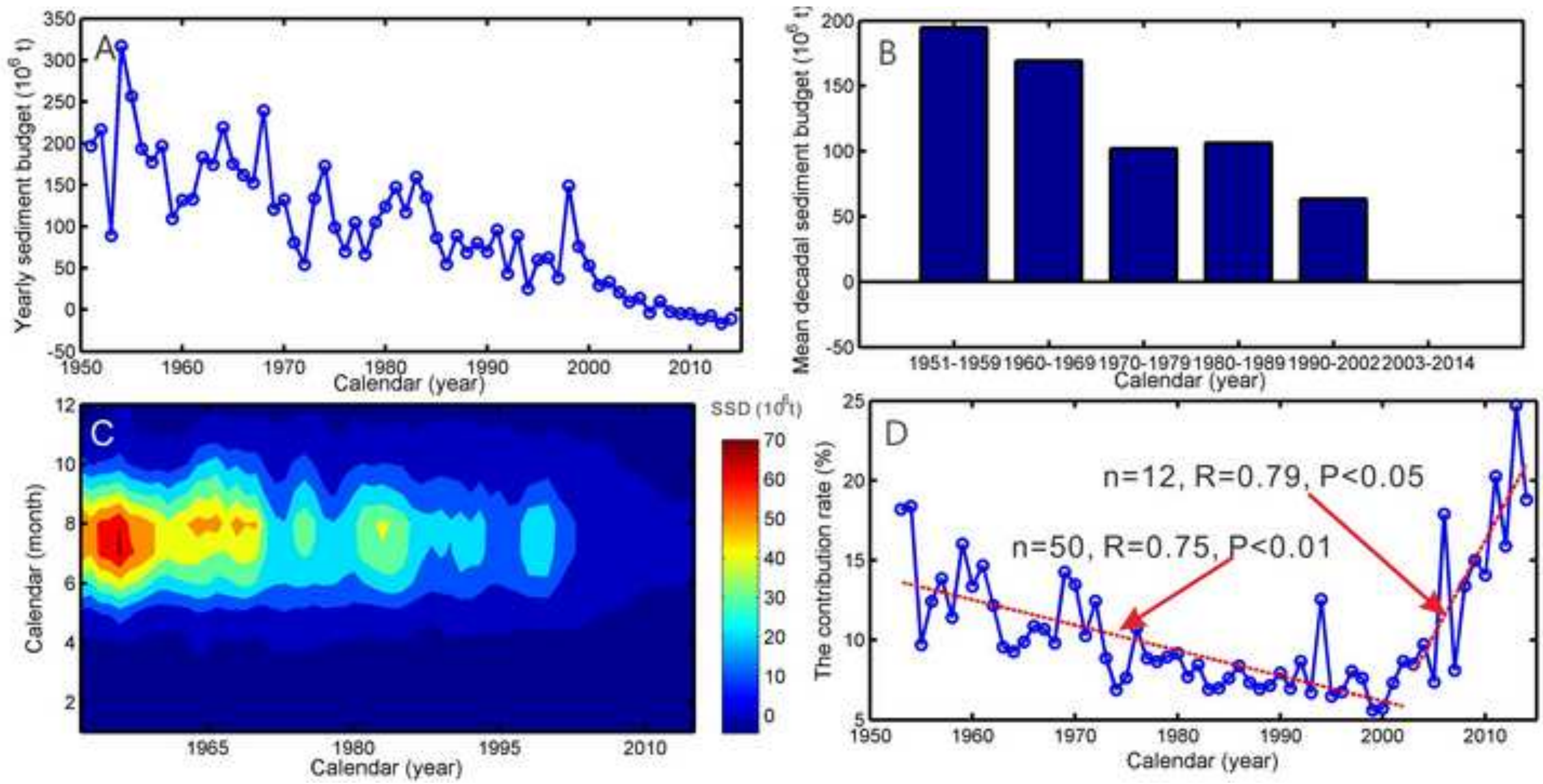

Figure 5. Sediment budget of the Poyang Lake

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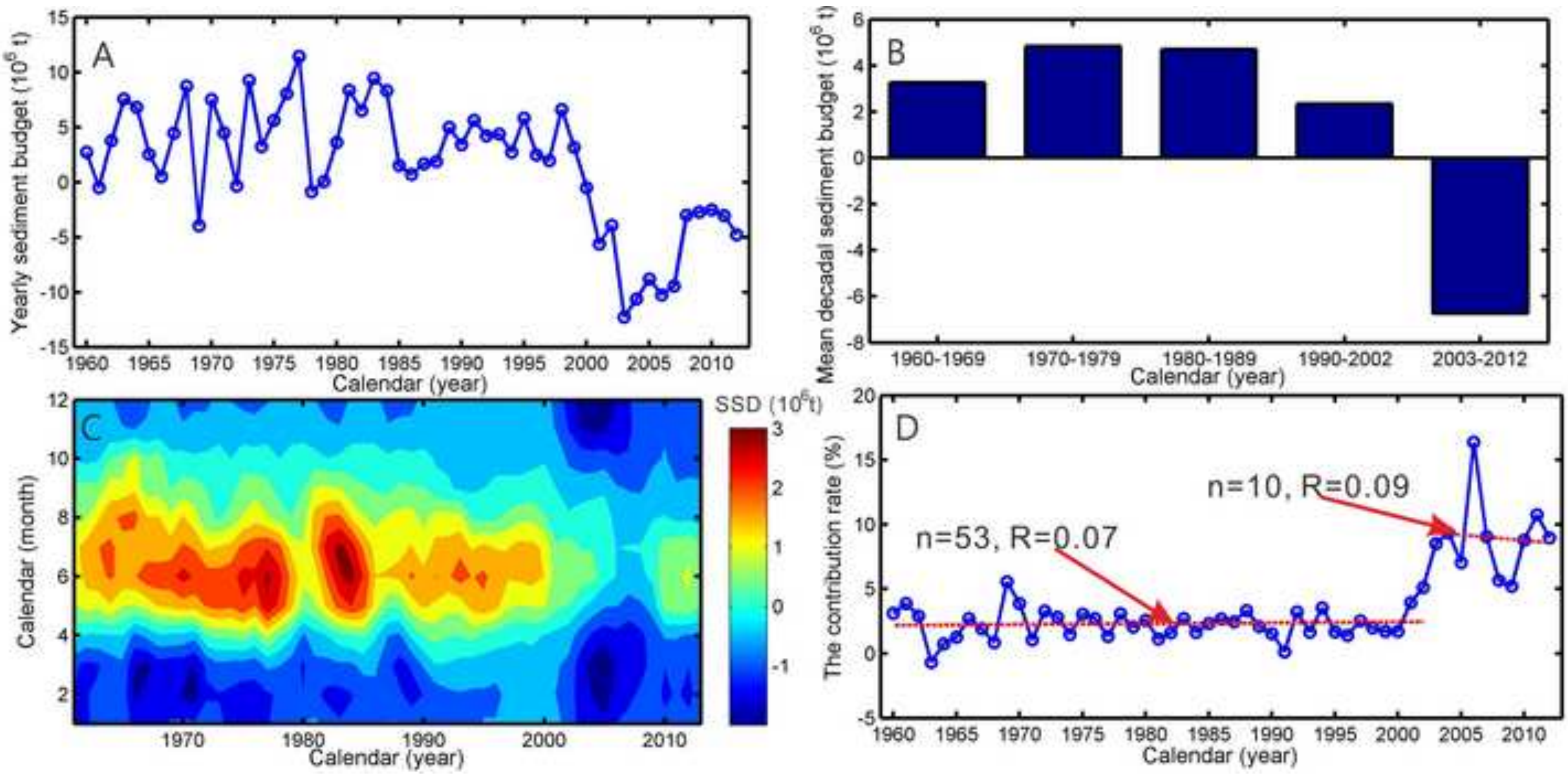

Figure 6. Changes in the water discharge and ssd

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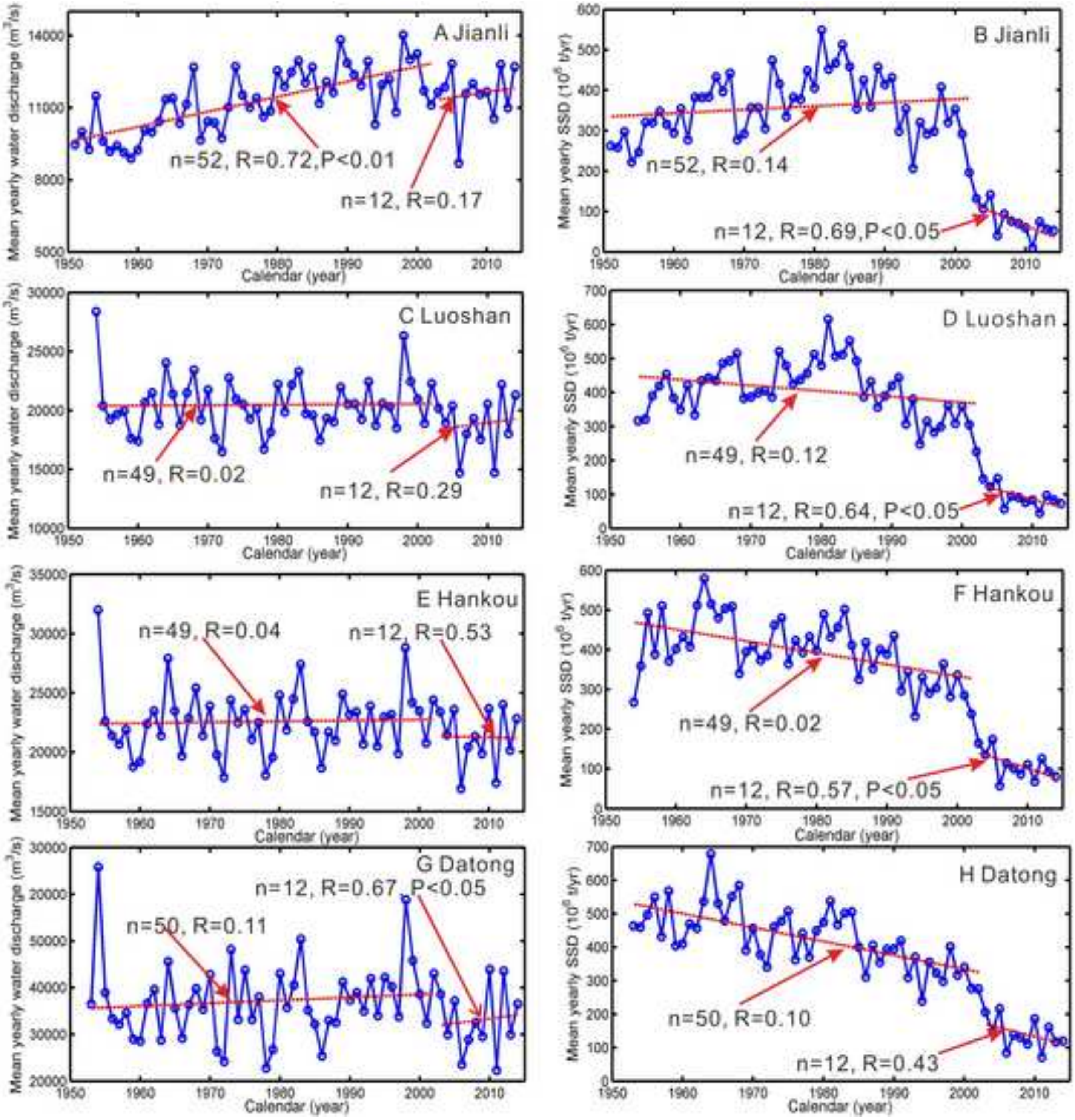

Figure 7. Sediment budget along the main stream of Changjiang
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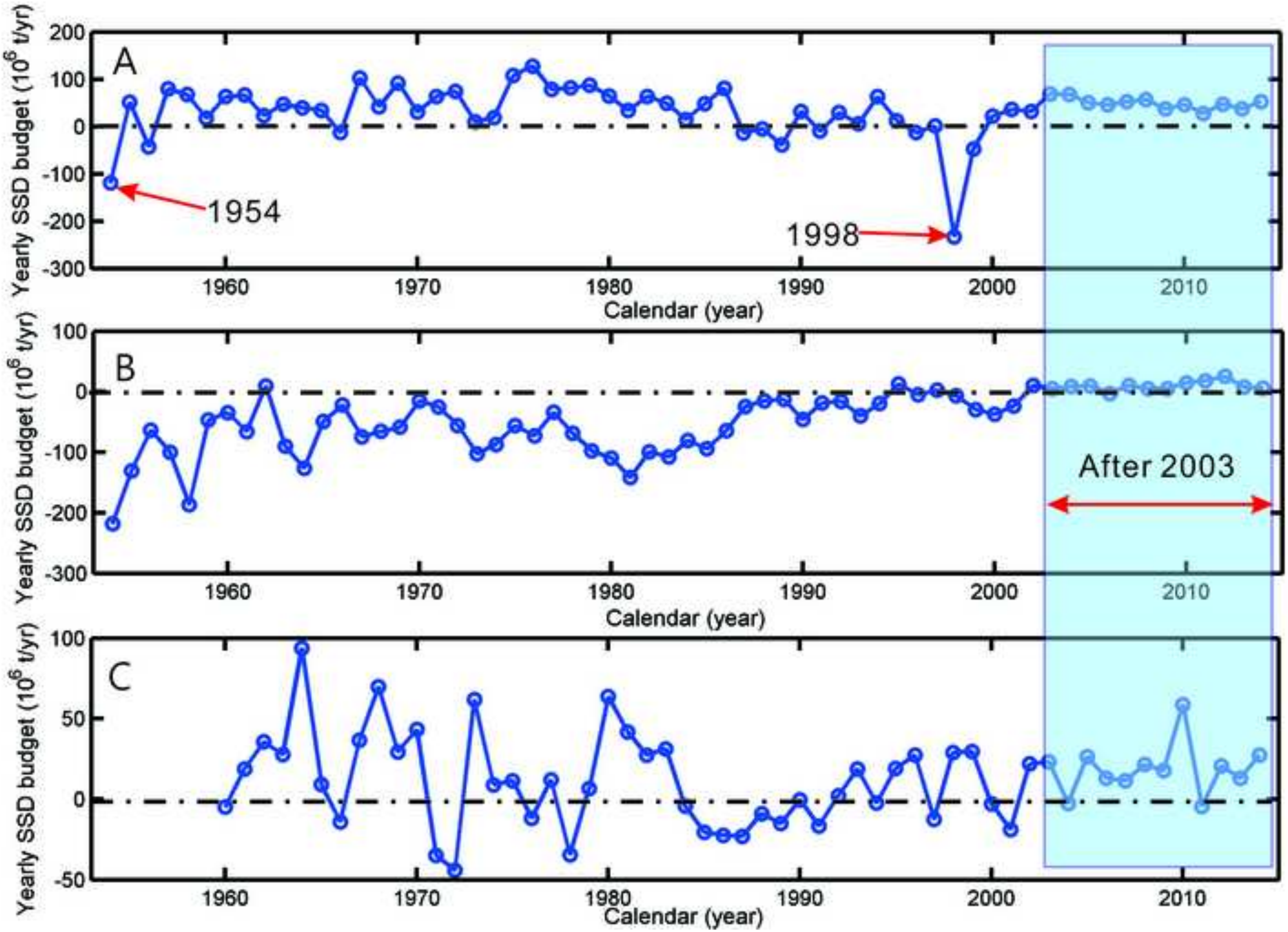

Figure 8. Sediment transfer shifts along mid-lower Changjian

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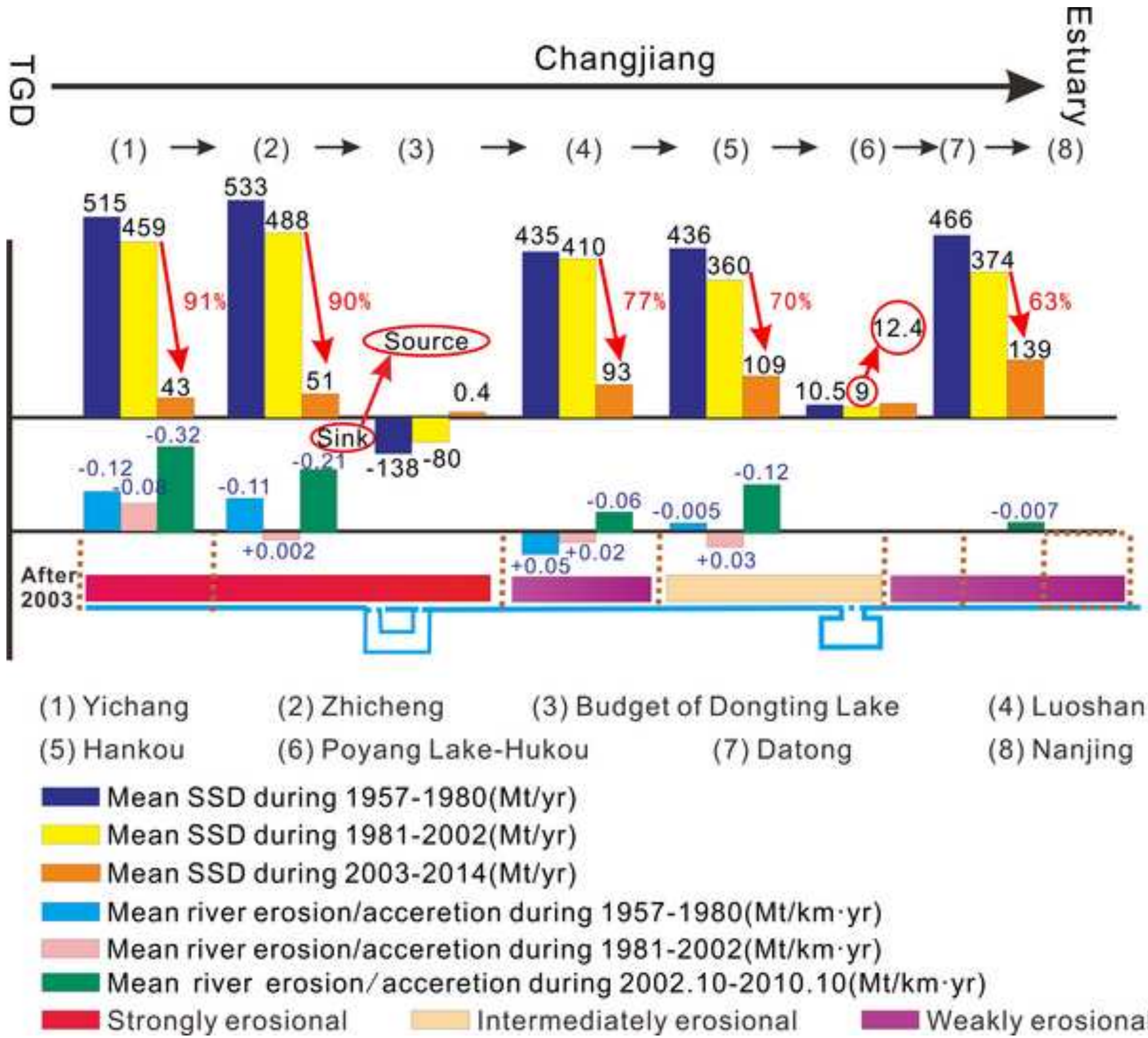

Figure 9. Variations in the water discharge and SSD

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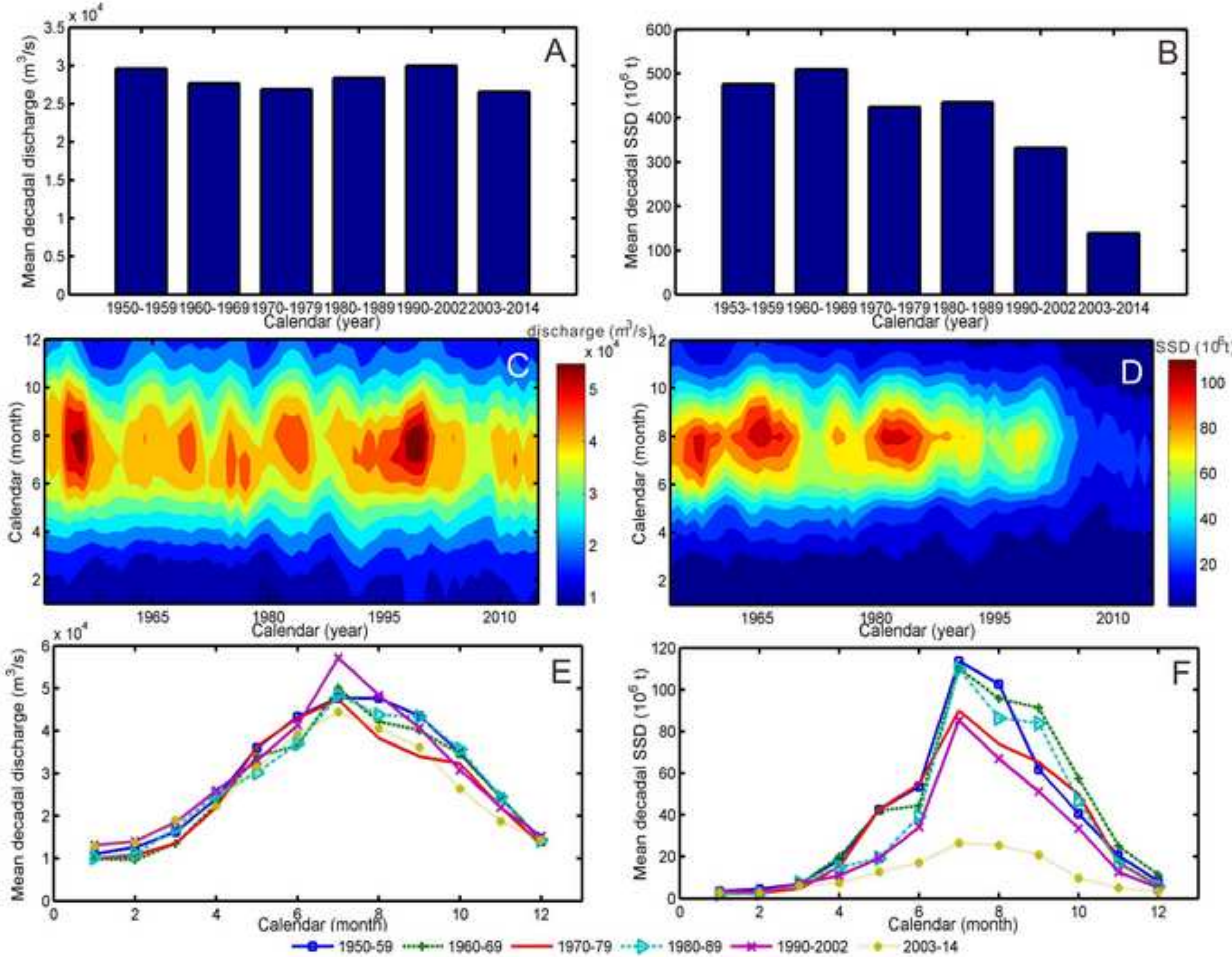

Figure 10. Erosion or accretions in the submarine delta
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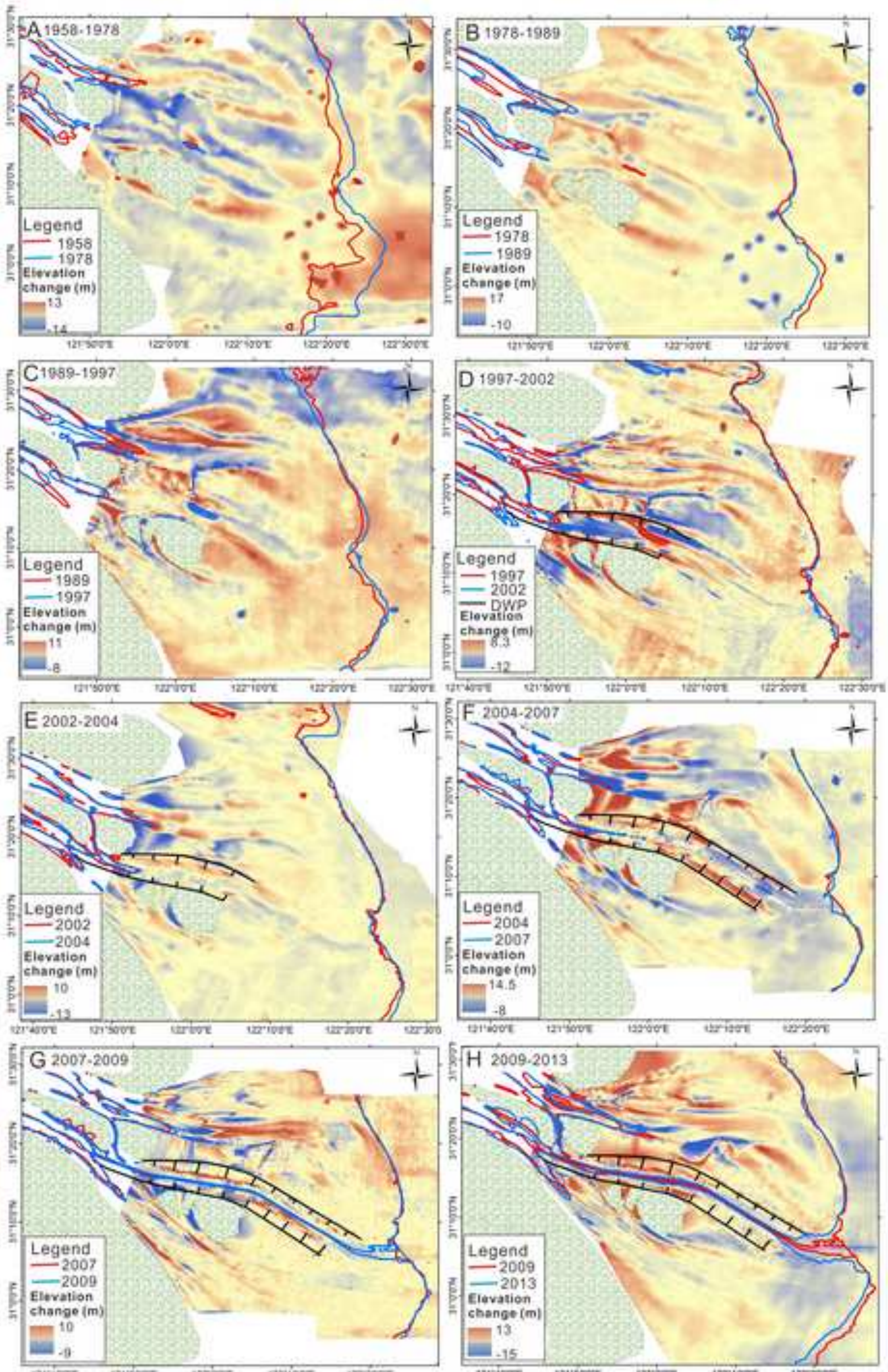

Figure 11. Volume variation in the North Branch and South Passag
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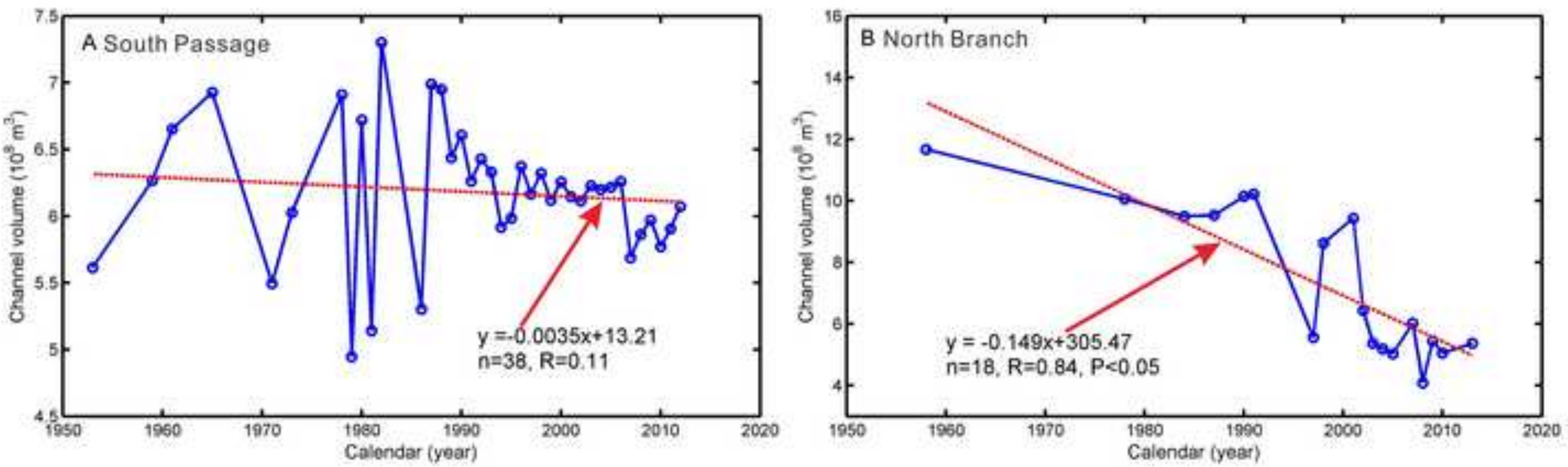

Figure 12. A. Reservoir capacity;B. trapped sediment of TGD

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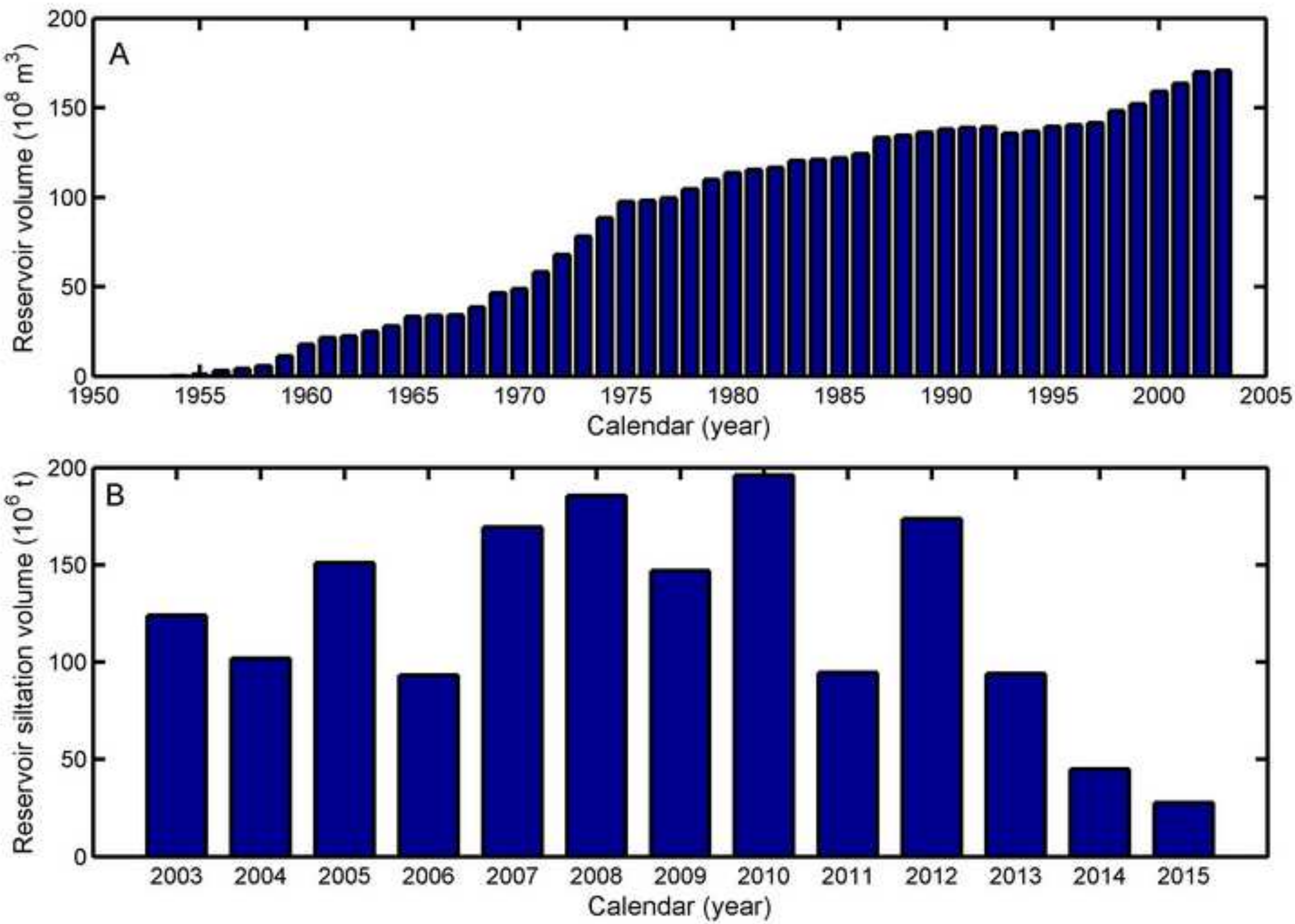

Figure 13. Sediment-contribution ratios

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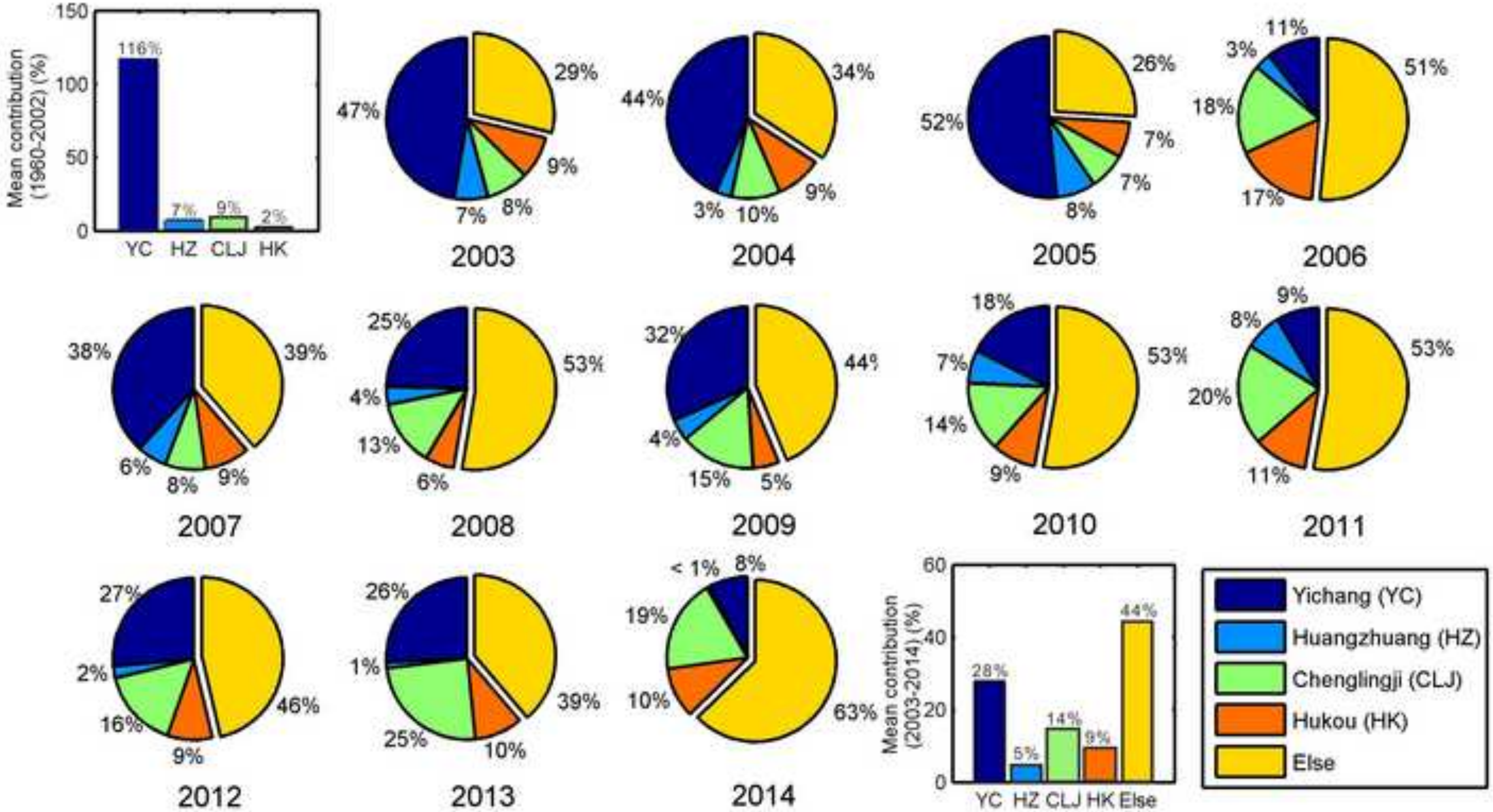

Figure 14. Dredging and siltation volumes along North Passage
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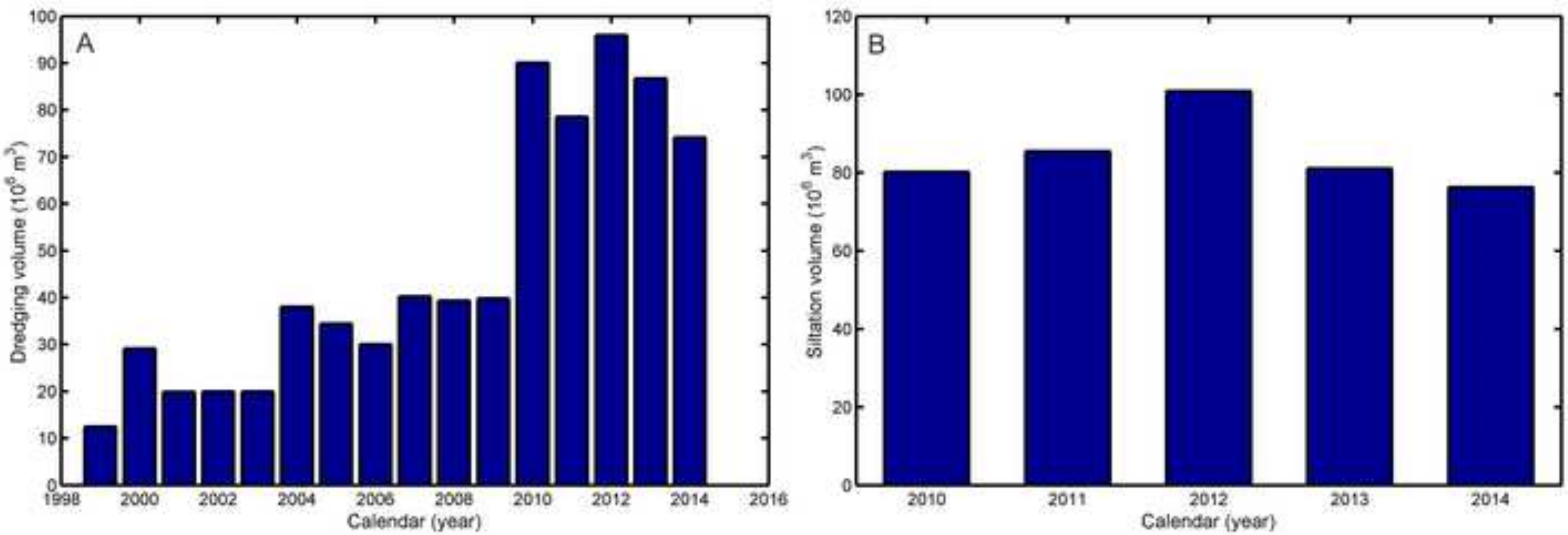

Figure 15. Mean tidal-current variation in the Changjiang Estua.

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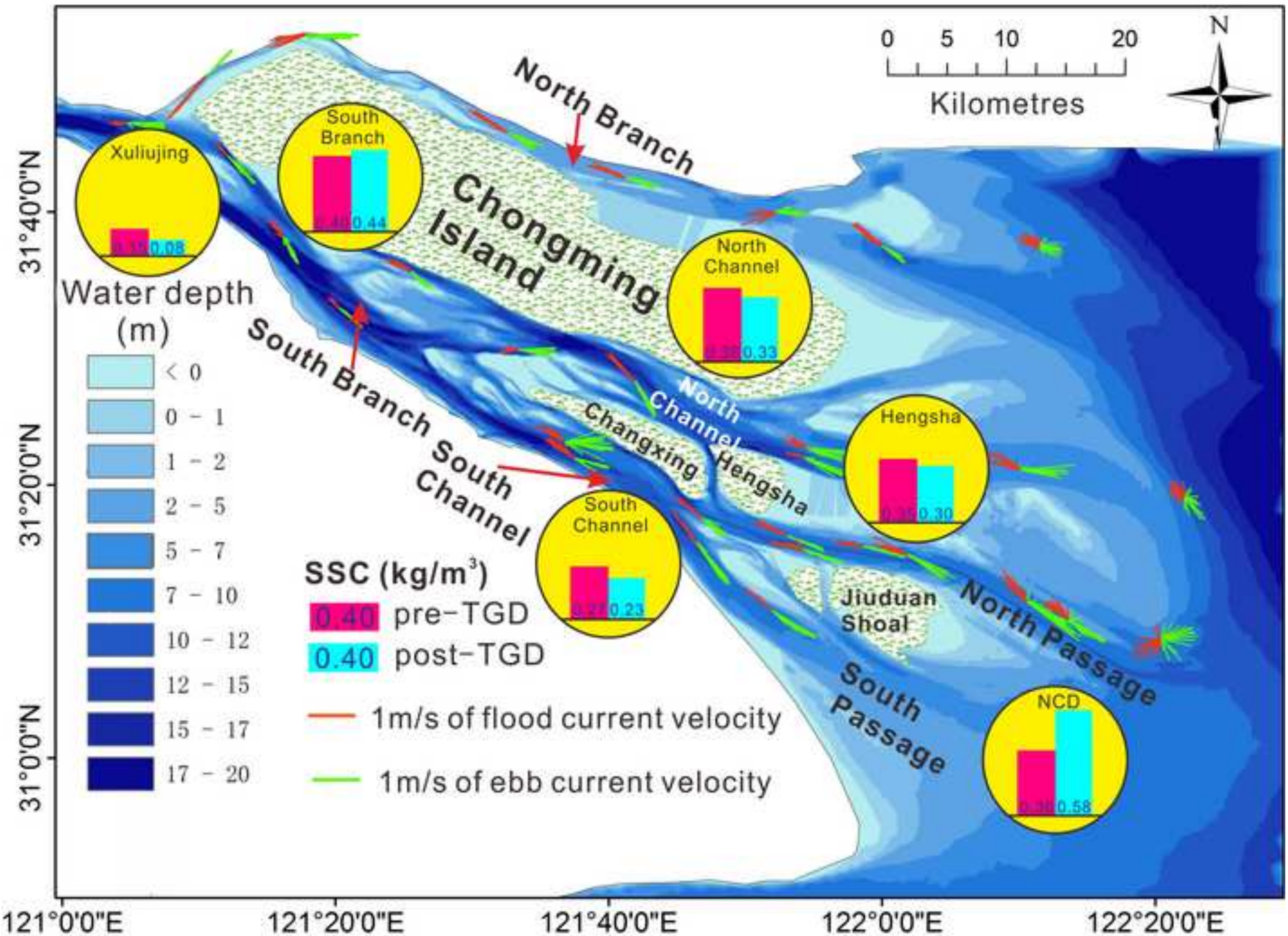

Figure 16. Coefficient of flow dominance along Changjiang Estua.
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