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Variations in the characteristics of Changjiang sediment discharging into the sea due to human activities

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Abstract

The variations in sediment load and composition from tributaries of the Changjiang River by human activities were analyzed. The temporal-spatial variations in the sediment load in the main river of the Changjiang under the impact of dam emplacement were determined. We identified the grain size variation of the sediment in the accumulation areas (i.e., the estuarine and adjacent coastal waters) during different periods and, on such a basis, discussed about the environmental change signature in the sedimentary record. The results indicate that the timing of reduction in the sediment load of the main stream of the Changjiang was different from downstream to upstream sections, due to the variations in the sediment load of the sub-catchments, and four step-wise reduction periods were observed: 1956–1969, 1970–1985, 1986–2002, and 2003–2010. In addition, the proportion of the sediment load originating from the Jinsha River continuously increased before 2003, due to the sequential reduction in the sediment load of the Han and Jialing Rivers. After 2003, channel erosion of the main river of the Changjiang became a major source of the sediment discharging into the sea. Before 2003, the various sub-catchments as the sources of the sediment entering the sea may be evaluated by analyzing the sediment components in the deposition area, because the sedimentary materials were delivered directly from the upstream portions of the Changjiang; after 2003, although the clay component may be still originated mainly from the upstream areas, the silt and sand components have been derived to a large extent from the erosion of the mid-lower and estuarine reach main channel. Thus, the sediment source of the estuarine-coastal deposits associated with the Changjiang could not be represented by the upstream sources alone. This observation implies that caution should be taken in tracing the sediment sources, interpreting sediment records, and modeling the sediment dynamic processes over the estuary-coastal-continental shelf areas.

1 Introduction

Human activities in river catchments have exerted significant impacts on the eco-environmental changes in coastal oceans (Syvitski et al., 2005). Recently, the global sediment flux into the sea has drastically decreased under the influence of human activities (Vörösmarty et al., 2003; Walling, 2006), resulting in considerable changes in the geomorphology and eco-environment of estuarine, coastal and continental shelf regions (Gao and Wang, 2008; Gao et al., 2011). Thus, the source-sink processes and products of the catchment-coast system, including those associated with sediment transport pathways from catchment to continental margins under the impact of climate change and human activities, have received increasing attention (Driscoll and Nittrouer, 2002; Gao, 2006).

Because marine deposits consist of the materials from different sub-catchments, variations in the sediment characteristics at the deposition site should result from both sediment load reduction and alterations in sediment grain size and the proportion of the sediment originating from different tributaries. There have been studies about the impact of human activity (particularly large hydrologic project) on changes in the sediment discharge into the sea, by analyzing the long-term variation trends of representative rivers (i.e., Milliman, 1997; Syvitski, 2003; Syvitski and Saito, 2007; Milliman and Farnsworth, 2011; Yang et al., 2011). However, less attention has been paid to the variations in the grain size and composition of sediment in response to human activities, together with its effect. The importance of these two features lies in that they reflect the sediment contribution of different sub-catchments to the marine deposits and determine the mineralogy and geochemistry characteristics.

Sediment provenance tracing is a major method used to study the spatial-temporal distribution patterns of terrestrial sediments in continental margins; thus, constructing valid and accurate end-member components on the basis of the mineralogical and geochemical characteristics of catchment sediment is a prerequisite for such an analysis (Morton and Hallsworth, 1994; Svendsen and Hartley, 2002; Yang et al., 2009; He et al., 2013). However, variations in the composition of sediments supplied by a catchment modify the "end-member" characteristics. Therefore, knowledge about the variations in the catchment sediment composition during different periods is critical to the analysis of the change in the mineralogy and geochemical features and the selection of terrestrial sediment end-members. Furthermore, this knowledge is also meaningful for accurately analyzing the sediment origin and distribution of estuary coast-continental shelf regions and predicting the response of the marine sedimentary system to climate change, sea level change, and human activities.

The Changjiang is one of the largest rivers in the world. A portion of the sediment from the Changjiang catchment forms a large delta system (Milliman et al., 1985); and the other portions escape from the delta and are transported to the Yellow Sea, East China Sea, and Okinawa Trough, thereby exerting a considerable impact on the sedimentation and biochemistry of these areas (Liu et al., 2007; Dou et al., 2010). Recently, the sediment load of the Changjiang into the sea was reduced considerably in response to dam emplacement and soil/water conservation projects (Yang et al., 2002), of which the dam interception accounted for 90.10 % of the sediment load reduction (Gao et al., 2014). The Changjiang catchment consists of numerous branches, and its upper, middle and lower reaches have different rock properties and climate types; therefore, the physical and chemical properties of the sediment originating from different tributaries are highly variable (Wang et al., 2006). The varied spatial-temporal patterns of the sediment yield from the tributaries changes the sediment contribution of each tributary to the main river of the Changjiang during different periods (Lu et al., 2003). Therefore, the grain size and composition of the sediment might vary with decreases in the sediment load of the Changjiang River.

This paper aims to (1) study the temporal-spatial variations of sediment load of the main river of the Changjiang under the impact of dams emplacement, by systematically analyzing the variations in sediment load originating from tributaries within the Changjiang catchment; (2) identify the grain size and composition variations of the sediment entering the sea during different periods; and (3) discuss the significance of changes in sediment characteristics in the sedimentary environment.

2 Regional setting

The Changjiang, with a drainage basin area of approximately 1.80×10^6 km^2, originates in the Qinghai-Tibet Plateau and flows 6300 km eastward toward the East China Sea. The upper reach of the river, from the upstream source to the Yichang gauging station (Fig. 1), is the major sediment-yielding area of the entire catchment (Shi, 2008). The main upstream river has four major tributaries, i.e., the Jinsha, Min, Jialing, and Wu Rivers. The upper reach region is typically mountainous, with an elevation exceeding 1000 m a.s.l. (Chen et al., 2001). The mid-lower reach extends from Yichang to the Datong gauging station, with three large inputs joining the main stream in this section: the Dongting Lake drainage basin, the Hanjiang River, and the Poyang Lake drainage basin. The catchment area of this section mainly comprises alluvial plains and low hills with elevations of less than 200 m (Yin et al., 2007). The Dongting Lake is the second largest freshwater lake in China, and part of the main river flow enters Dongting Lake via five different entrances. Four tributaries enter Lake Dongting from the south and southwest, and water from Dongting Lake flows into the Changjiang main river channel at the Chenglingji gauging station (Dai et al., 2008). Poyang Lake is the largest freshwater lake in China, and it directly exchanges and interacts with the river. Poyang Lake receives runoff from 5 smaller tributaries (the Gan, Fu, Xin, Rao, and Xiu Rivers) and discharges freshwater into the Changjiang at Hukou (Shankmanet al., 2006). The estuarine reach of the Changjiang extends from Datong (tidal limit) to the river mouth. The local water and sediment supply from this part of river basin is much smaller in quantity in comparison with that from the upstream. Therefore, the Datong gauging station is a critical station; its records are often used to represent the sediment flux from the Changjiang to the East China Sea.

Most of the Changjiang drainage basin was developed in the Yangtz block. Aside from the complex Meso-Cenozoic tectonic activities, diverse lithologies ranging from Archean metamorphic rock, Paleozoic carbonate and clastic rocks, Meso-Cenozoic magmatic and clastic rocks, and Quaternary sequences can also be found within the system (Wu et al., 2005). These rocks are heterogeneously exposed from one region to another (Yang et al., 2004), and they are characterized by different mineralogy and geochemical characteristics (Table 1). Specifically, quaternary sediment is the predominant phase in the uppermost Tibet Plateau area, with some metamorphic rocks of green schist-amphibolite faces in South Qinghai Province, whereas adjacent districts in Southwest China are covered by various rocks, such as purple shale and carbonate rocks (the Yungui plateau and Sichuan Basin), Emeishan basalt (Yanyuan-Lijiang, Panxi, and Guizhou), and felsic and mafic intrusive rocks (Western Sichuan) (Zhou et al., 2006). Clastic rocks and felsic magmatic rocks are extensively distributed in the mid-lower portion of the Changjiang basin. In contrast, metamorphic rocks of low-intermediate grade were only sparsely observed in these regions (Zheng and Zhang, 2007).

3 Material and method

3.1 Data sources

Data for the annual sediment load and suspended sediment grain size of the Changjiang River are regularly collected by the Ministry of Water Resource of China, and we acquired the annual sediment load data for 26 hydrological stations distributed in the main reach and seven of the tributaries. The dataset for these gauging stations covers a 55 year period (1956–2010). Five gauging stations are situated in the main reach i.e., the Zhutuo, Cuntan, Yichang, Hankou, and Datong stations (from upstream to downstream). Four gauging stations are located at the upstream tributaries: the Pingshan station for the Jinsha River, the Gaochang station for the Min River, the Beibei station for the Jialing River, and the Wulong station for the Wu River. The Huangzhuang station is the control gauging station for the Han River. There are ten hydrological stations distributed in the Dongting Lake system: four stations are located at the four tributaries entering Lake Dongting i.e., the Xiangtan station for the Xiang River, the Taojiang station for the Zi River, the Taoyuan station for the Yuan River, and the Shimen Station for the Li River; and five stations are situated at the five different entrances where the Changjiang river discharges into Dongting Lake: the Mituoshi, Xinjiangkou, Shadaoguan, Ouchi (Kang), and Ouchi (Guan) stations; and the Chenglingji station monitors the Dongting Lake water entering the main river of the Changjiang. Six hydrological stations are distributed in the Poyang Lake system: the Waizhou station for the Gan River, the Lijiadu station for the Fu River, the Meigang station for the Xin River, the Wanjiabu station for the Xiu River, the Hushan station for the Rao River, and the Hukou station for where the Poyang Lake water discharges toward the main river of the Changjiang.

3.2 Analytical methods

The Mann–Kendall test (M–K test) is a nonparametric method, and it has been used to analyze long-term hydro-meteorological time serials (Mann, 1945; Kendall, 1955). This test does not assume any distribution form for the data and is as powerful as its parametric competitors (Serrano et al., 1999). Trend analysis of the sediment load changes was conducted based on this method. Before using the M–K test, the autocorrelation and partial autocorrelation functions were used to examine the autocorrelation of all hydrological data. The results indicated that there was no significant autocorrelation in the data. The modified M–K method was used to analyze variations in the sediment load data: $X_t = (x_1, x_2, x_3 \ldots x_n)$, where the accumulative number m_i for samples for which $x_i > x_j$ $(1 \le j \le i)$ was calculated, and the normally distributed statistic d_k was expressed as (Hamed and Rao, 1998)

$$d_k = \sum_{i=1}^{k} m_i \quad 2 \leq k \leq n \tag{1}$$

The mean and variance of the normally distributed statistic d_k were defined as

$$E[d_k] = \frac{k(k-1)}{4} \tag{2}$$

$$\mathrm{Var}[d_k] = \frac{k(k-1)(2k+5)}{72} \quad 2 \leq k \leq n \tag{3}$$

Then, the normalized variable statistical parameter UF_k was calculated as

$$\mathrm{UF}_k = \frac{d_k - E[d_k]}{\sqrt{\mathrm{var}[d_k]}} \quad k = 1,2,3\ldots n \tag{4}$$

where UF_k is the forward sequence, and the backward sequence UB_k was obtained using the same equation but with a retrograde sample. The C values calculated with progressive and retrograde series were named C_1 and C_2. The intersection point of the two lines, C_1 and C_2 ($k = 1,2\ldots n$) was located within the confidence interval, providing the beginning of the step change point within the time series. Assuming normal distribution at the significant level of $P = 0.05$, a positive Man-Kendal statistics C larger than 1.96 indicates an significant increasing trend; while a negative C lower than 1.96 indicates a significant decreasing trend.

4 Results

4.1 Stepwise reduction in the sediment load of the tributaries

As shown in Fig. 2, the sediment load of the seven tributaries exhibited a negative correlation with their cumulative reservoir storage capacity (CRSC), suggesting that dam emplacement caused a continuous decrease in the sediment load. The Jinsha River catchment, which suffers from the most serious water and soil erosion area in the Changjiang catchment, is the major sediment source of the upstream Changjiang (Shi, 2008). Due to reservoir construction, the CRSC drastically increased to 5.57 % in 1998, and the average sediment load decreased from 245 Mt yr^{-1} in 1956–1998 to 185 Mt yr^{-1} in 1999–2010. Although the CRSC of the Min River catchment is low (1.72 % in 2010), the sediment load still continuously decreased with increases in the CRSC. Due to the rapid increase in the CRSC of the Jialing River catchment to 4.49 % in 1985 and 9.29 % in 1998, the sediment load, in terms of the 154 Mt yr^{-1} value in 1956–1984, decreased sharply to 125 Mt yr^{-1} in 1985–1998 and 27 Mt yr^{-1} in 1999–2010. As the CRSC increased to 5.42 %, the average sediment load of the Wu River sharply decreased from 33 Mt (1956–1983) to 20 Mt (1984–1993) and then further reduced to 13 Mt (1994–2010) when the CRSC increased to 7.82 % in 1994.

The Han River was an important sediment source for the middle portion of the Changjiang before 1968. However, due to dam emplacement, the average CRSC of the Han River increased stepwise from 3.7 % in 1957–1967 to 45.8 % in 1968–1988 and then 55.4 % in 1989–2010. Currently, the Hanjing River has the highest CRSC of the seven tributaries contributing to the Changjiang. Thus, the average sediment load exhibited a stepwise reduction for the three aforementioned period, i.e., from 125 Mt yr^{-1} in 1957–1967 to 28 Mt yr^{-1} in 1968–1988 and then 9 Mt yr^{-1} in 1989–2010. In addition, the reduction in the sediment load entering the Dongting and Poyang Lakes was highly correlated with the increase in the CRSC.

The CRSC of the three mid-stream sub-catchments of the Changjiang exhibited rapid increasing trends after the 1960s, and the sediment load of the catchment of the Poyang Lake, Han River, and Dongting Lake began to decrease in 1963, 1968, and 1984, respectively (Fig. 3). However, the sediment loads of the four rivers of the upstream Changjiang began to decrease in the 1970s (with a significant reduction in the 1980s), and the sediment loads began to decrease in 1984 for the Wu River, 1985 for the Jialing River, 1994 for the Min River, and 2001 for the Jinsha River. The temporal-spatial variation trends of the sediment loads of the seven tributaries indicated that the sediment load began to decrease later at upstream locations compared to downstream locations.

4.2 Spatial-temporal sediment load variations of the main river

Due to discrepancies among the sediment load variations of the seven sub-catchments, the decreasing trends of the sediment load in the different sections of the main river were also inconsistent (Fig. 4): from downstream to upstream, the sediment load of the Datong, Hankou, Cuntan, Zhutuo, and Pingshan stations began to decrease in 1969, 1969, 1985, 1991, 1999, and 2001, respectively, suggesting that the downstream sediment load began to decrease earlier than the upstream sediment load. Although the sediment load of the Datong station, with an average value of 503 $\mathrm{Mt\,yr^{-1}}$, exhibited fluctuations from 1956 to 1969, the quantity generally remained at a high level. In contrast, the sediment load of the Datong station decreased to 445 Mt in 1970–1985 because the annual sediment load supplied by the Han River decreased by 95 Mt. Previous studies have suggested that the sediment load from the Changjiang entering the sea began to decrease in the 1980s (Yang et al., 2002); however, we demonstrate that this decreasing trend already occurred in 1970, and the impact of the reduced sediment load of the Han River on the sediment flux of the Changjiang into the sea was neglected in these previous studies. The sediment load of the upstream Changjiang began to decrease after 1985: the sediment load of the Yichang station decreased from 533 $\mathrm{Mt\,yr^{-1}}$ in 1956–1985 to 404 $\mathrm{Mt\,yr^{-1}}$ in 1986–2002; correspondingly, the sediment load of the Datong station further decreased to 340 $\mathrm{Mt\,yr^{-1}}$ in 1986–2002. Due to the Three Gorges Dam (TGD) emplacement in 2003, the sediment load of Yichang station decreased considerably to 55 $\mathrm{Mt\,yr^{-1}}$ in 2003–2010 and that of Datong station decreased to 152 $\mathrm{Mt\,yr^{-1}}$ in the same time period.

Overall, there were significant temporal-spatial differences in the sediment load variations of the Changjiang main river: the sediment load began to decrease later in upstream locations than in downstream locations, and four stepwise reduction stage periods were observed: 1956–1969, 1970–1985, 1986–2002, and 2003–2010.

4.3 Variations in the grain size of the sediment entering the sea

Because most of the coarse-grained sediment is intercepted by reservoirs, the sediment grains size downstream of the reservoirs become significantly finer (Xu, 2005). The variation in the medium grain size (D_{50}) of suspended sediments from the Yichang station (Fig. 5) indicated that the average D_{50} was 0.017 mm in 1960–1969, 0.012 mm in 1970–1985, 0.009 mm in 1986–2002, and 0.004 mm in 2003–2010, suggesting that the sediment grain size from the upstream Changjiang exhibited a continuous decreasing trend. In contrast, the decreasing trend of D_{50} from the Datong station was not as significant as that from the Yichang station during the four stages: the average D_{50} in 1960–1969 (0.12 mm) was similar to that in 1970–1985 (0.13 mm), and a slight decreasing trend was recorded in 2002 (0.09 mm) and 2003–2010 (0.10 mm).

In addition, the degree of inter-annual variation in the upstream sediment grain size continuously decreased during the four stages, i.e., the D_{50} variation interval gradually narrowed, and the distribution range of the data point of D_{50} and sediment load moved from the top left corner to the bottom right corner in the coordinate system; however, that of the Datong station generally shifted vertically downward. The sediment grain size variations of the Yichang and Datong stations in the four stages also indicated that the D_{50} of the Yichang station was greater than that of the Datong station in 1960–1969, and the two stations were similar in 1970–1985 and 1986–2002; after 2003, the D_{50} of the Yichang station was less than that of the Datong station. Furthermore, D_{50} ranged from 0.003–0.007 mm for Yichang station and 0.008–0.013 mm for Datong station in 2003–2010, suggesting that the D_{50} variation range of the two stations did not overlap after 2003.

The sand fraction of the Yichang station, ranging from 30 to 32 %, remained stable from 1960 to 2002. However, from 1960–1969 to 1985–2002, the clay content fraction increased from 14.2 to 31.8 % and the silt fraction decreased from 54.4 to 37.0 %.

Furthermore, after 2003, the clay content further increased to 49.5 %, and the sand fraction decreased to 10.4 % (Fig. 6). The variation in the sediment grain size of the Datong station could be divided into two stages: the content fractions for clay, silt, and sand reached 17.5, 57.7, and 24.8 %, respectively, in 1960–1985, and 32.4, 26.9, and 40.7 %, respectively, in 1986–2010. The above analysis suggests that although the average value of the grain size of the sediment entering the sea during the different periods exhibited no clear variations, the inter-annual variation range and sediment components changed considerably.

5 Discussions

5.1 Variations in the composition of sediment entering the sea during different periods

The sediment load from the Changjiang entering the sea mixes weathering products supplied by different sub-catchments. The temporal-spatial discrepancy among the sediment load variations of sub-catchments caused the sediment load entering the sea to decrease and resulted in changes to the sediment composition (Fig. 7). In 1956–1969, the sediment load of the Datong station mainly originated from the Jinsha, Jialing, and Han Rivers, and the three rivers contributed 35.0, 24.3, and 19.0 %, respectively, of the sediment to the Datong station. As the sediment load of the Han River decreased, the Jinsha and Jialing Rivers accounted for 46.7 and 27.6 %, respectively, of the sediment load at the Datong station during the 1970–1985 period, whereas the contribution of the Han River decreased to 5.8 %. During the 1986–2002 period, due to the reduced sediment yield in the Jialing River, the contribution of the Jinsha River to the sediment load of the Datong station further increased to 64.2 % and that of the Jialing River decreased to 15.0 %. The composition of sediment from the Changjiang entering the sea changed considerably during the 2003–2010 period due to the TGD emplacement: the sediment proportion due to channel erosion of the main river reached 48.0 % and that of the Jinsha River decreased dramatically to 24.1 %. In addition, the Jialing and Han Rivers only contributed 4.3 and 5.3 % of the sediment load of the Datong station, respectively.

The above analysis indicated that as the sediment load entering the sea decreased, although the average sediment grain size displayed no clear variations, the sediment composition changed considerably. Before 2003, the variations in the sediment composition were mainly determined by the changes in the sediment contributions of the Jinsha, Jialing, and Han Rivers i.e., with the sequential reduction in the sediment loads of the Han and Jialing Rivers, the proportion of the sediment load originating from the Jinsha River continuously increased, whereas the proportion of the sediment load from the other sub-catchments remained stable. Overall, during this period, the sediment load of the Datong station mainly originated from upstream of the Changjiang, and the mid-lower stream channel of the Changjiang was one of major sinks of the upstream sediment (Yang et al., 2011). However, after 2003, channel erosion of the mid-lower portion of the main river became the greatest source of sediment load of the Datong station.

Actually, the record of the Datong station is not the real sediment flux of the Changjiang into the sea, but merely the sediment delivery to estuary of the Changjiang, due to the adjustment of estuarine main river channel. Attributing to the upstream sediment load reduction, the estuarine river channel of the Changjiang stayed in sedimentation status before the late of 1990s, and then converted into erosion status (especially after 2003) (Li, 2007; Wang et al., 2009). In addition, the sedimentation/erosion status of the estuarine reach of the Changjiang was also correlated to the sediment load variation of the Datong station (Fig. 8). According to the relationship between the sediment load of Datong station and the sedimentation/erosion rate of the main river of estuarine reach, and assuming a sediment bulk density of 1.23 $\mathrm{t\,m^{-3}}$ (Li et al., 2011), the real sediment load of the Changjiang entering the sea, in terms of the quantity of 214 $\mathrm{Mt\,yr^{-1}}$, was underestimated 62 $\mathrm{Mt\,yr^{-1}}$ after 2003. Furthermore, the quantity of the erosive sediment of mid-lower and estuarine reach accounted for 63.0 % of the sediment load of the Changjiang entering the sea.

5.2 Implications of the changes in sediment composition for the sedimentary environment

Generally, catchment sediments into the sea contain rich catchment environmental change information, thereby becoming an important medium for identifying previous catchment changes (Brown et al., 2009). The variations in the sediment characteristics of the Changjiang entering the sea have traditionally been slow and gradual (Saito et al., 2001); however, the load, grain size, and composition of sediment entering the sea changed rapidly in recent decades, resulting in rapid changes in the mineralogy characteristics of the sediment entering the sea. As important tracers, detrital mineral and clay minerals are widely used to trace the provenance of fine and coarse grained sediments, respectively (Thiry, 2000; Garzanti and Andó, 2007). However, the tracing results concerning the sediment source of the Changjiang catchment during different periods were inconsistent (Wang et al., 2006), and these discrepancies correlated with the variations in the sediment composition. During 1970–1985, the contribution of the Jinsha and Jialing Rivers to the sediment load entering the sea reached 74.3 %; therefore, the results of the detrital and clay mineral analysis of this period indicated that the sediment from the Changjiang mainly originated from these two rivers (Lin, 1992). In 1986–2002, the Jinsha River became the major sediment yield source of the Changjiang catchment, accounting for 64.2 % of the sediment load entering the sea; thus, the detrital mineral tracing results of this period indicated that the sediment load of the upstream portion of Changjiang mainly originated from the Jinsha River, and the Jialing and Min Rivers provided less sediment to the mid-lower reaches of the Changjiang (Wang et al., 2006). Due to the clay fraction of the sediment was mainly supplied by the Jinsha and Jialings River (Lin, 1989), the Jinsha River is certain to be the major source of clay in the sediment of the upstream Changjiang during this period due to the drastic decrease in the sediment load of the Jialing River.

In addition, the different grain sizes of the sediment entering the sea also indicated that the clay, silt, and sand fraction of the Yichang station were greater than those of the Datong station during the 1960–1969, 1970–1985, and 1986–2002 periods (Table 2), which implied that the sediment fraction of clay, silt, and sand entering the sea mainly originated from the upstream Changjiang without regard to sediment exchange between the river water and the riverbed. Thus, the above analysis also demonstrates that because all of the sediment components were derived from a homologous source, although the mineralogy characteristics of the Changjiang catchment sediment changed continuously, the various sub-catchments as the sources of the sediment entering the sea may be evaluated by analyzing the sediment components in the deposition area.

After the emplacement of the TGD in 2003, the clay, silt, and sand fractions originating from the upstream Changjiang decreased dramatically. With regard to the amount of sediment originating from the Poyang Lake and Han River to the Changjiang main river, the erosive sediment of the main river channel (Yichang-Datong) and Dongting Lake contributed 13 Mt yr^{-1} of clay, 43 Mt yr^{-1} of silt, and 20 Mt yr^{-1} of sand to the sediment load of Datong station in 2003–2010, which accounted for 27.1, 55.8 and 74.1 % of the corresponding sediment component of Datong station (Table 2). Considering the contribution of strong erosion of the estuarine reach, the real proportion of silt, and sand fractions into the sea coming from the erosive sediment of main river channel, may be greater than 55.8 and 74.1 %. These data imply that the clay fraction of the sediment of Datong station mainly originated from the upstream of the Changjiang, and the silt and sand fractions largely comprised the erosive sediment of the mid-lower and estuarine reaches of the main river channel. The eroded “older” sediment also derived from the upstream of the Changjiang, and is characterized by the homologous mineralogy and geochemical characteristics of the upstream sediment (Kang et al., 2009). Therefore, after 2003, the tracing results of clay minerals merely reflect the fine-grained sediment origin (He et al., 2013), and that of the detrital mineral mainly reflects the information of the “older”, coarser sediment source. This phenomenon indicates that all sediment component sources from the Changjiang entering the sea could not be represented by a single sediment component origin when the different sediment components had different origins.

Briefly, due to the impact of human activities, which has intensified at an accelerated rate, the sediment load, component, composition, and mineralogy characteristics from the Changjiang changed considerably during different periods. Estuary-coastal-continental shelf areas are the final destination of catchment sediments; thus, variations in the sediment characteristics entering the sea will inevitably result in serious scientific problems when tracing sediment sources, interpreting records, and dynamically modeling estuary-coastal-continental shelf areas, which should be further investigated. As far as sediment provenance tracing is concerned, due to the variations in end-member components induced by changes of the sediment composition in the Changjiang catchment, the end-member components of one phase cannot be used to trace the sediment origin of another phase. For the sediment dynamic process, the sediment component variations entering the sea will inevitably change the sediment behavior of the Changjiang estuary and the Zhejiang-fujian coastal mud area, which should also be considered when the sediment transport process of these areas is calculated, modeled and predicted. In terms of the process of the catchment sediment going from the source to sink, one can pose the following questions: Could the response to variations in the sediment composition of the Changjiang catchment be observed in the sediment record of the East China Sea shelf area? Is the response hysteretic? What is the retardation time? Under the conditions of a complicated dynamic environment of the Changjiang estuary and East China Sea continental shelf, all these questions will have more uncertainty, and deserve to study further.

6 Conclusions

1. The patterns of sediment delivery from the sub-catchments of the Chnagjiang River have been changed, resulting in spatial-temporal changes in the sediment

load within the main stream, and four stepwise reduction stages were observed: 1956–1969, 1970–1985, 1986–2002, and 2003–2010.

2. Before 2003, the variations in the sediment composition at the marine sites were mainly determined by the changes in the sediment contribution made by the Jinsha, Jialing, and Han Rivers. After 2003, channel erosion of the main river of the Changjiang supplied around 63 % of the sediment load into the sea.

3. Before 2003, the clay, silt, and sand fractions entering the sea mainly originated from the upstream regions of the river. However, after 2003, only around 27 % of the clay component of the sediment was originated from the upstream areas; more than 55.8 % of silt and 74.1 % of sand were supplied by the eroding bed of the main river channel.

4. Before 2003, the various sub-catchments as the sources of the sediment entering the sea may be evaluated by analyzing the sediment components in the deposition area; after 2003, the sediment source of the estuarine-coastal deposits associated with the Changjiang could not be represented by the upstream sources alone.

5. Such changes indicate that caution should be taken in tracing the sediment sources, interpreting sediment records, and modeling the sediment dynamic processes over the estuarine, coastal and continental shelf areas.

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Table 1. Characteristic values and detrital and clay mineral compositions of different tributaries.

Tributaries	Length[a] (km)	Area[a] (10^4 km^2)	Ratio (%)	Characteristic of the detrital minerals	Clay mineral
Jinsha River	2316	34	60	metallic mineral-pyroxene-epidote-ilmenite-chlorite[b]	High illite content [e]
Min River	1062	16	12	metallic mineral-epidote-hornblende-garnet-leucoxene-pyroxene[b]	High illite and chlorite contents and low kaolinite content [e]
Jialing River	1119	16	28	metallic mineral-epidote-garnet[b]	High illite content[e]
Wu River	1018	9	6	metallic mineral-pyroxene-garnet[a]	High illite and chlorite contents and low kaolinite content[e]
Han River	1532	17	10	Hornblende-garnet[c]	High montmorillonite content[e]
Dongting Lake	–	26	7	zircon[d]	High kaolinite content[e]
Poyang Lake	–	16	4	–	High kaolinite content[e]

The ratio denotes the sediment load ratio of the different sub-watersheds and the Datong station. The sediment load of different sub-watersheds is the mean value of the 1956–2010 period. [a, b, c, d] and [e] represent data originating from Lin et al.(2010), Shao et al.(2010), Kang et al. (2009), Wang et al. (2006), and He et al.,(2013), respectively.

Table 2. Annual quantities of clay, silt, and sand at the Yichang and Datong stations during different periods.

Time Period	Clay ($\mathrm{Mt\,y^{-1}}$)		Silt ($\mathrm{Mt\,y^{-1}}$)		Sand ($\mathrm{Mt\,y^{-1}}$)	
	Yichang	Datong	Yichang	Datong	Yichang	Datong
1960–1969	78	78	297	291	172	134
1970–1985	105	86	257	257	159	102
1986–2002	128	113	212	174	63	50
2003–2010	27	48	25	77	3	27

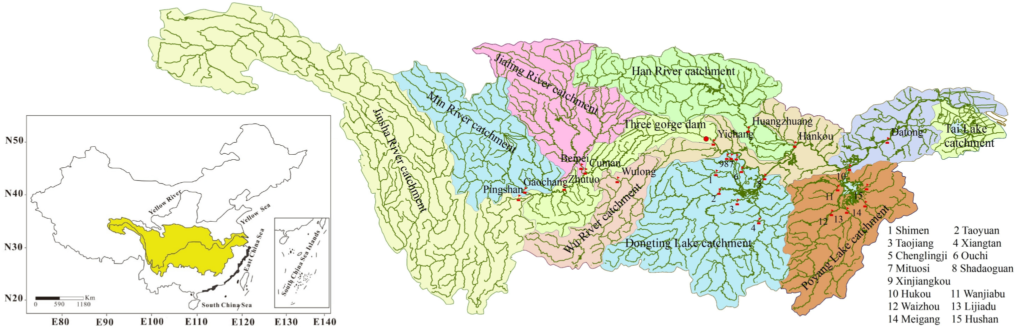

Figure 1. Sketch of the Changjiang catchment and location of the hydrologic stations for the Changjiang catchment.

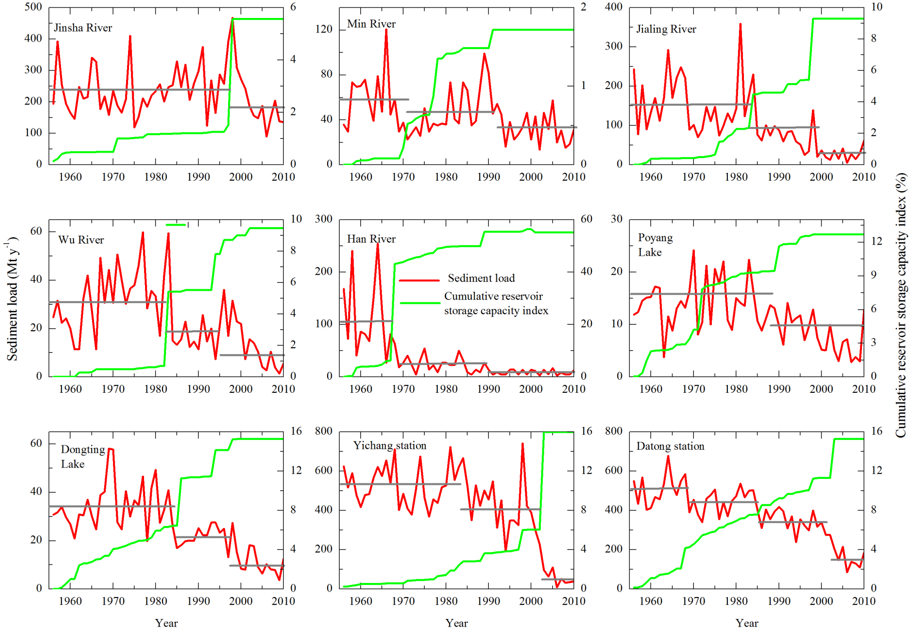

Figure 2. Relationship between the reduction in sediment load and cumulative reservoir storage capacity index in the tributaries and main river. The reservoir storage capacity index is defined as the ratio of the reservoir storage capacity and average annual water discharge of the contributed catchment. Data regarding reservoir construction originate from The Code For China Reservoir Name (Ministry of Water Resources of the People's Republic of China, 2001).

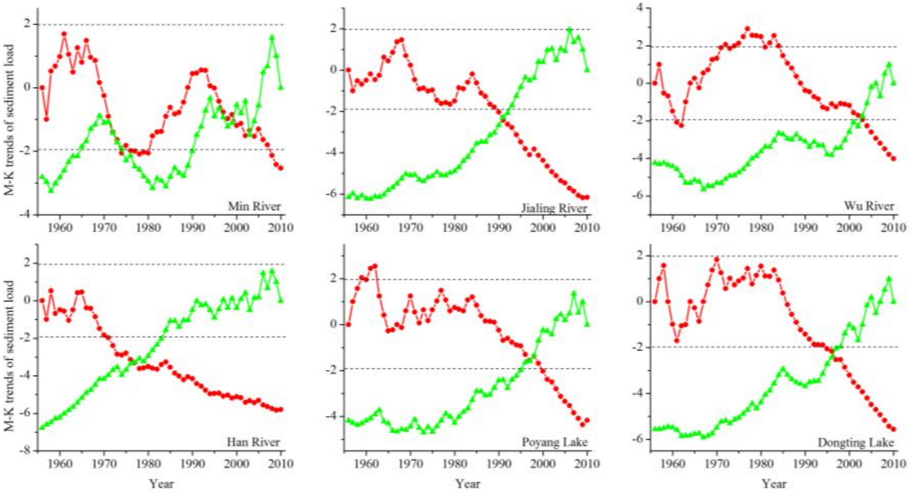

Figure 3. M–K trends of the sediment load for the Jinsha, Min, Jialing, Wu, and Han Rivers and the Poyang and Dongting Lake system.

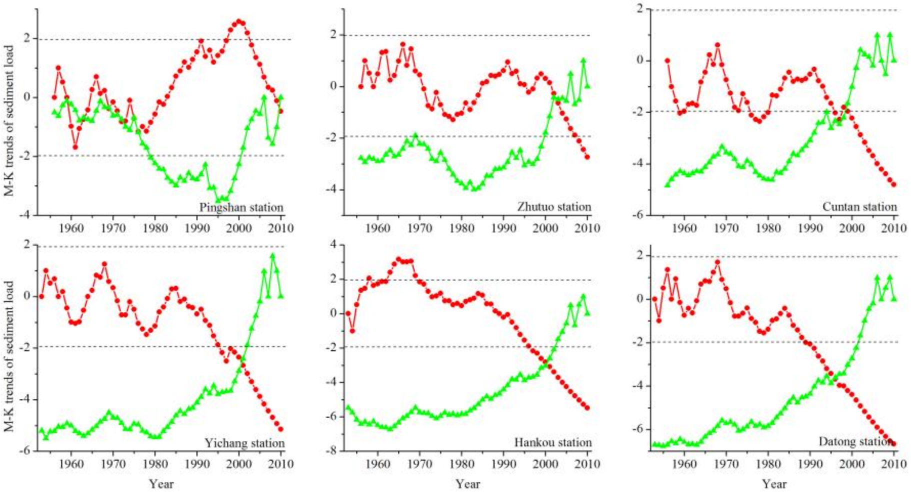

Figure 4. M–K trends of the sediment load for different gauging stations of the Changjiang main river.

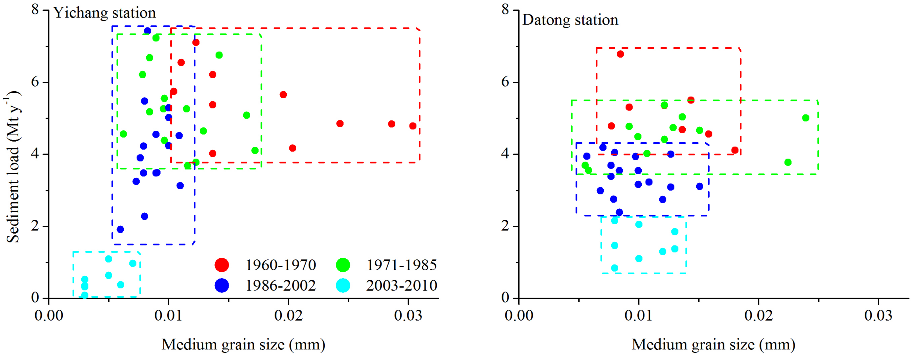

Figure 5. Relationship between the medium grain size of suspended sediments and the sediment load during different periods at the Yichang and Datong stations. Data are not available for the Datong station in 1968–1970, 1972–1973, and 1975.

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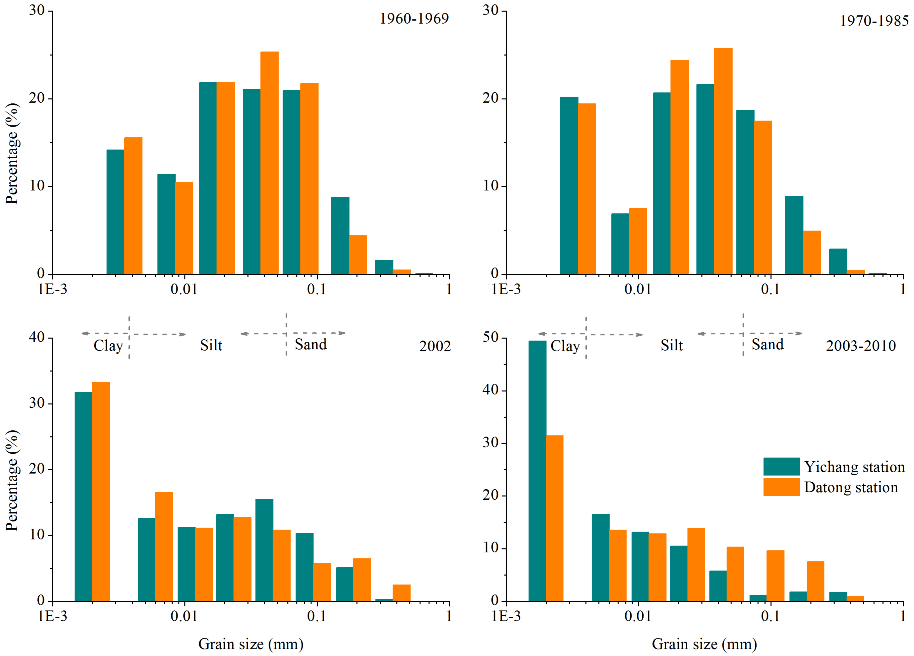

Figure 6. Distribution of the suspended sediment grain size of the Yichang and Datong stations in 1960–1969, 1970–1985, 2002, and 2003–2010.

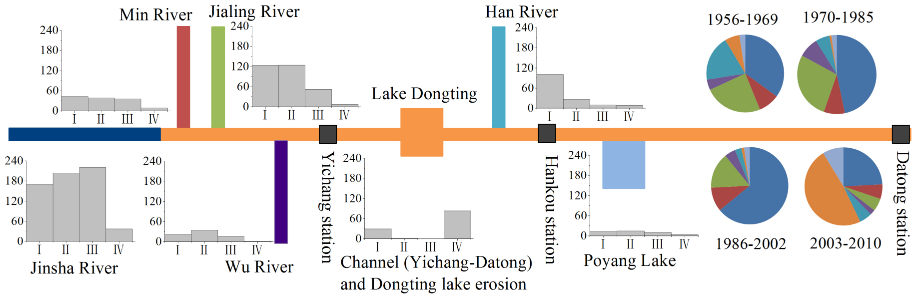

Figure 7. Contribution of different sub-catchments to the sediment load from the Changjiang entering the sea during different periods. Gray bars denote the sediment load variations from different tributaries during different periods, and the pie charts represent the sediment load contribution of the different tributaries to the Datong station.

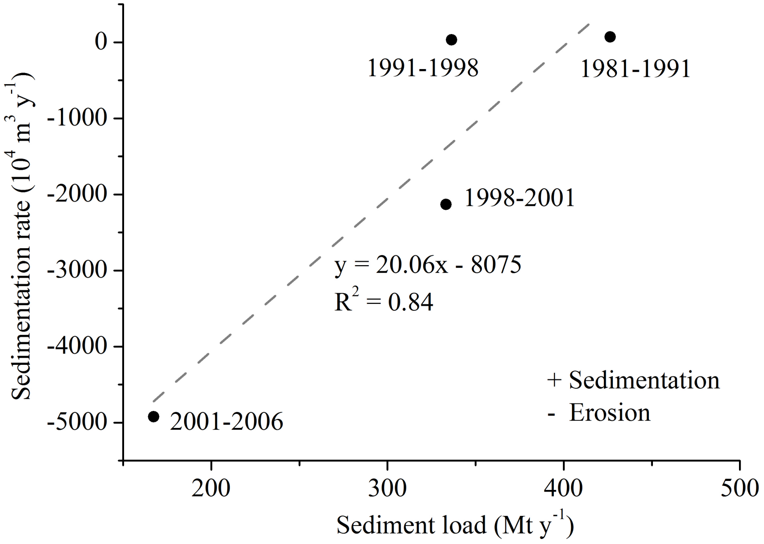

Figure 8. Relationship between the sediment load of Datong station and the sedimentation/erosion rate of the main river of estuarine reach (the data of the sedimentation/erosion rate from Li, 2007).