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Variations in quantity, composition and grain size of Changjiang sediment discharging into the sea in response to human activities

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Abstract: The impact of dam emplacement in terms of the spatial-temporal variations in the sediment load of different tributaries of the Changjiang was analyzed. We have identified the quantity, grain size and composition variations of the sediment entering the sea during different periods and within different tributaries. The results show that the timing of reduction in the sediment load of the main stream of the Changjiang was different from those associated with downstream and upstream sections, indicating the influences of the sub-catchments. Four step-wise reduction periods were observed, i.e., 1956-1969, 1970-1985, 1986-2002, and 2003-2010. Furthermore, 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 in the main stream of the Changjiang became a major source of the sediment discharging into the sea. Because of the dam construction, although mean grain size of the sediment entering the sea during the different periods did not greatly change, the inter-annual variability, in terms of range of fluctuations, sediment compositions and percentages of contributions of the tributaries changed considerably. Before 2003, the clay, silt and sand fractions of the materials entering the sea were supplied directly by the upstream parts of the Changjiang; after 2003, although the clay component may still be originated mainly from the upstream areas, the source of the silt and sand components have been shifted to a large extent to the erosion of the middle-lower reach valleys. These observations imply that caution should be taken in tracing the sediment sources, interpreting the sedimentary records, as well as modeling the sediment dynamic processes for the estuarine, coastal and continental shelf waters.

Keywords: grain size, sediment composition, sediment load, reservoir emplacement, Changjiang River

1. Introduction

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 (Syvitski et al., 2005; 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 different sediment types originating from different tributaries (which is referred to as “sediment composition” in the present study). With regard to the sediment load reduction, there have been studies about the impact of human activity (particularly large hydrologic projects) on changes in the sediment discharge into the sea, by analyzing long-term variation trends of representative rives (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 sedimentological and environmental effects. The importance of these two factors lies in that they reflect the sediment contribution of different sub-catchments to the marine deposits and determine the geochemical and sediment dynamic characteristics (Gao, 2007). Therefore, knowledge about the variations in the catchment sediment characteristics during different periods is critical for an accurate analysis of the sediment origin and distribution of estuary and coast-continental shelf regions and for the prediction of 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 part of the sediment from the Changjiang catchment has formed a large sub-aqueous delta system of around 10,000 km^2 (Milliman et al., 1985); and the remainder escapes from the delta, being 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). Dai et al. (2008) demonstrated that the contribution of dam construction and the water and soil conservative measures accounted for ~88% and 15±5% of the decline in sediment influx, respectively; and climate change is responsible for a slight increase in sediment load, approximately 3%. The Changjiang catchment consists of numerous branches, and these tributaries are characterized by different rock properties and climate types. On the other hand, the intensity and occurrence time of human activities of these tributaries is also varied, which directly lead to different spatial-temporal patterns of the sediment yield from these tributaries (Lu et al., 2003). Thus, the sediment contribution of each tributary to the main river of the Changjiang also changed during different periods. In addition, dam construction and land cover variation also exert an important impact on changes of sediment grain size of tributaries and main river of Changjiang (Zhang and Wen, 2004). Therefore, the sediment contribution of different tributaries to the sediment load entering the sea, the grain size and composition of the sediment might vary with decreases in the sediment load of the Changjiang River.

In order to reveal the impacts of human activities (mainly dam construction) on the quantity, composition and grain size of Changjiang sediment discharging into the sea, this paper aims to: (1) analyze the impact of dam emplacement on the sediment load of different tributaries; (2) study the temporal-spatial variations of sediment load of the main river of the Changjiang under the impact of dams emplacement; (3) identify the quantity, grain size and composition variations of the sediment entering the sea during different periods; and (4) systematically analyze the variations in sediment load originating from tributaries within the Changjiang catchment during different historical periods.

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 6,300 km eastward toward the East China Sea. The upper reach of the river, from the upstream source to the Yichang gauging station (Fig.1a), 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 1,000 m above sea level (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). Therefore, the sediment load of Dongting Lake System did not directly supply to the Changjiang main river, and exerted important impacts on the silting and erosion of Dongting Lake. However, due to sediment decreasing upstream of the Changjiang, the Dongting Lake has been converting from a strong sediment sink of its upstream to a weak sediment source to its downstream (Dai and Liu, 2013), and the great decreasing of sedimentation of Dongting Lake is beneficial to slowing down the atrophy of Dongting Lake area. 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.

Due to intensified human activities, the catchment forest vegetation was continuously destroyed, and the forest coverage rate of Changjiang River Catchment greatly reduced (Xu, 2000), thereby leading to the ecological environment seriously deteriorated (Lu and Higgitt, 2000). Starting from the late of 1980s, a large-scale soil conservation campaign was implemented in high sediment yielding regions of the upper Changjiang catchment. However, due to the natural conditions difference of the upstream Changjiang River Catchment, the effect of soil conservation campaign was discrepant in every upstream tributary. For example, the most of Jialing River watershed is hills areas, and mainly suffered from slope erosion (Zhang and Wen, 2004). In addition, its vegetation restoration rate is quite high due to the humid climate, and then the effect of vegetation recovery on reducing slope erosion is very prominent (Lei et al., 2006). Therefore, the sediment yield of Jialing River rapidly decreased since the soil conservation campaign carried out in 1980s (BSWC，2011), and the land cover variation exerted more important impact on the sediment load reduction. The downstream Jinsha River with 782 km in length is the main sediment yield area; although its area only account for 7.8% of upstream Changjiang, the average annual sediment load reach 35.50% of that of the Yichang station (Zhang and Wen, 2004). This reach with developed landslide and debris flow, is characterized by high and steep mountains, and deep valleys, which is not beneficial to vegetation restoration (Lei and Huang, 1991；Yang, 2004). Therefore, the water and soil erosion governing effect in Jinsha River was not as obvious as that in Jialing River (BSWC, 2011), reservoir interception is still the dominating factor leading to the sediment load reduction.

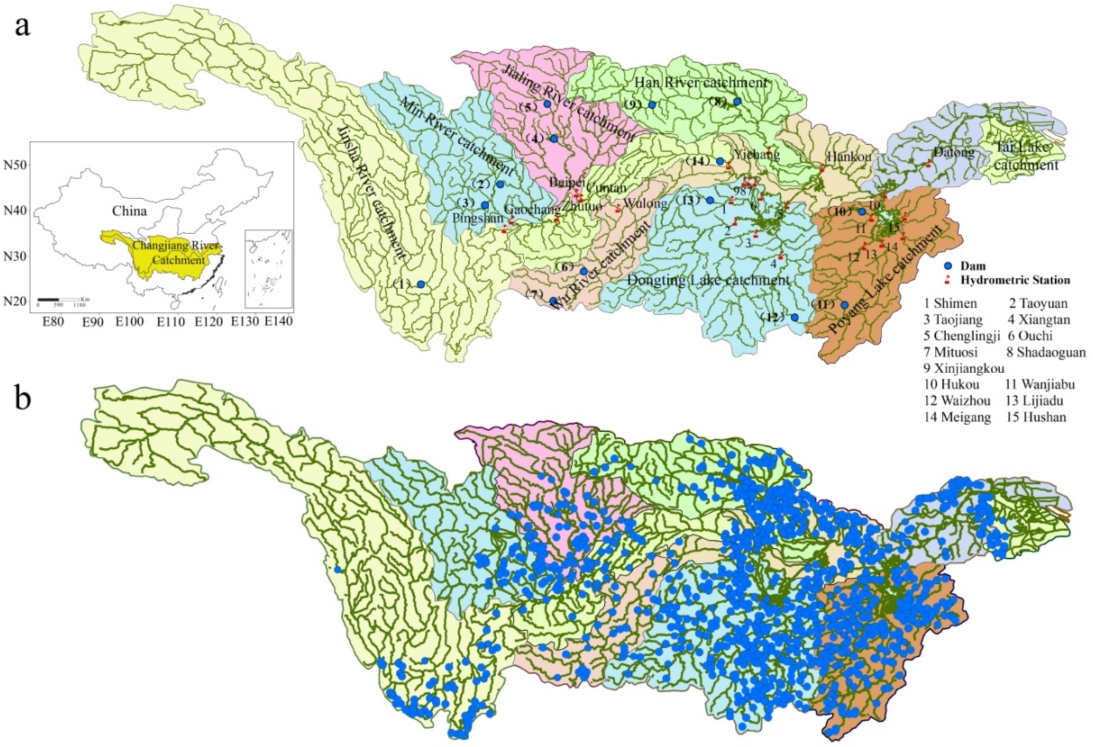

Figure 1. (a) Sketch of the Changjiang catchment and location of the hydrologic stations for the Changjiang catchment (the numeric symbols in the figure denote some important reservoir sites, including: (1) Er’tan; (2) Heilongtan; (3) Tongjiezi; (4) Shengzhong; (5) Baozhushi; (6) Wujiangdu; (7) Puding; (8) Danjiangkou; (9) Ankang; (10) Zhelin; (11) Wan'an; (12) Dongjiang; (13) Jiangya; and (14) Three Gorges Dam); and (b) major dams distributed within the Changjiang catchment.

3. Material and method

3.1 Data sources

3.1.1 Water discharge and sediment load data

The long-term discharge and sediment monitoring program over the entire catchment has been conducted since the 1950s, by the Changjiang Water Resource Commission (CWRC) under the supervision of Ministry of Water Resources, China (MWRC). These monitoring data of each station include field survey and measurement of discharge, suspended sediment concentration, suspended sediment load, and suspended sediment grain size, in accordance with Chinese national data standards (Ministry of Water Conservancy and Electric Power, 1962, 1975): 10-30 vertical profiles within the water column were selected for the measurements of each river cross-section, the number of profiles varying with the width of the river; For each profile, the water flow velocity (using a direct reading current meter) were measured at different depths (normally at surface, 0.2H, 0.6H, 0.8H and the bottom, where H is the height of the water column); Meanwhile, the water mass of the same depth were also sampled for measuring the suspended sediment concentration and grain size; the sediment grain size is measured using the settling of suspensions method. All above measurements are repeated daily at each station. The homogeneity and reliability of the hydrological data, with an estimated daily error of 16% (Wang et al., 2007), has been checked and firmly controlled by CWRC before its release. The data during the period of 1956-2001 was either published in the Yangtze River Hydrological Annals or provided directly by CWRC. After 2002, these hydrological data were posted in the Bulletin of China River Sediment published by the Ministry of Water Resources, China (BCRS, 2002-2010; available at: http://www.mwr.gov.cn/zwzc/hygb/zghlnsgb/).

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 reaches 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.

3.1.2 Dam data

In the present study, the reservoirs with a storage capacity > 0.01 km^3 (i.e., “large and medium sized reservoirs” according to the MWRC) are considered. Data on reservoir emplacement during 1949-2001 were obtained from the MWRC (2001), and those built during 2002-2007 were obtained from annual reports published by the MWRC (http://www.mwr.gov.cn/zwzc/hygb/slbgb/). In total, we count 1,132 large and medium sized reservoirs located within the Changjiang catchment, of which 1,037 reservoirs are situated upstream of the Datong station (Fig.1b). The database includes information on reservoir storage capacity, construction and impoundment time.

Here the reservoir storage capacity index (RSCI) is defined as the ratio of the reservoir storage capacity to the annual average water discharge of the contributed catchment; thus, the total RSCI of a catchment is the ratio of total capacity of reservoir to the annual average water discharge.

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 trend (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 $x_i > x_j$ $(1 \leq j \leq i)$ was calculated, and the normally distributed statistic d_k was expressed as (Hamed and Rao, 1998)

$$d_k = \sum_{i=1}^{k} m_i \qquad 2 \leq k \leq n \qquad （1）$$

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

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

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

Then, the normalized variable statistical parameter UF_k was calculated as

$$UF_k = \frac{d_k - E[d_k]}{\sqrt{\mathrm{var}[d_k]}} \qquad k = 1, 2, 3......n \qquad (4)$$

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....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 value with an absolute value of lower than 1.96 indicates a significant decreasing trend.

4. Results

4.1 Stepwise variations in the reservoir storage capacity of the tributaries

The total RSCI of the seven tributaries and main stream of the Changjiang reveal stepwise increasing trends (Fig. 2). The variations in reservoir storage capacity of the four tributaries upstream the Changjiang indicated that the total RSCI of the Min River catchment is low (1.72% in 2010) and those of the Jialing and Wu Rivers rapidly increased in 1985; in response to the construction of the Er’tan reservoir, the total RSCI of the Jinsha River also rose considerably in 1998. As a result of rising in the reservoir storage capacity of the above four rivers, the total RSCI of the Changjiang catchment, upstream of the Yichang station where there were increases by 2.8% in 1985 and 16.0% in 2003, also showed the stepwise patterns.

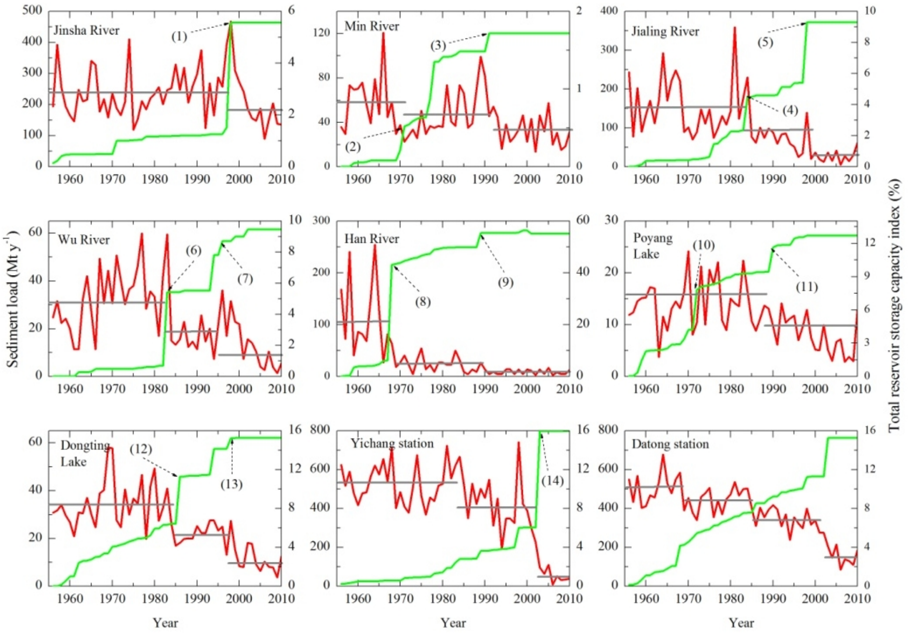

Figure 2. Relationship between the reduction in sediment load and the total reservoir storage capacity index in the tributaries and the main stream. Numeric symbols represent reservoirs listed in Figure 1a.

The middle-lower reaches of the Changjiang catchment consisted of three major tributaries, namely, the Han River, Dongting Lake and Poyang Lake. The total RSCI of Han River began to increase in 1966, and greatly rose in 1968. In addition, the rapid increment in the total RSCI of Poyang Lake and Dongting Lake were also observed in 1972 and 1985, respectively. Attributing to the dam construction of the seven tributaries of the Changjiang catchment, there has been a jump in the total RSCI of the Changjiang River upstream of the Datong station in 1969 and 2003, respectively.

The changes of the total RSCI and sediment load of tributaries and the whole Changjiang catchment indicate that the stepwise decrease of sediment load is highly related to the significant increase of the total RSCI. In addition, over the last few decades, the cumulative water and sediment discharge relation of each tributary continuously changed, with the slop of curve decreasing, and every turning point of the curve was closely related to dam construction (Fig. 3). The above two relationships reflected the impact dams have on sediment load.

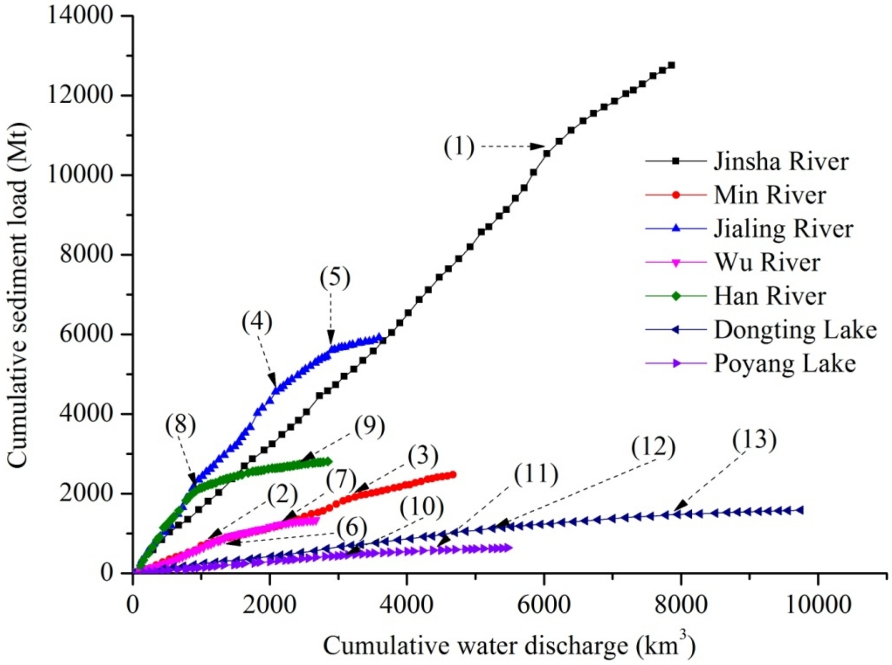

Figure 3. Cumulative water discharge–sediment load relations of the seven tributaries of the Changjiang catchment. Numeric symbols representing the reservoirs are the same as those in Figure 1a.

4.2 Spatial-temporal sediment load variations within the catchment

The trends, derived on the basis of the M-K method, of sediment load of the seven tributaries indicated that (Figs. 4 and 5): during the period of 1956-2010, the sediment load of Wu River, Jialing River, Min River and Jinsha River began to decrease in 1984, 1985, 1994 and 2001, respectively, suggesting that the downstream sediment load began to decrease earlier than the upstream sediment load in the upstream of Changjiang catchment. In addition, the M-K trends of sediment load of Jinsha River did not pass the 95% confidence test, and that of Wu River, Jialing River and Min River passed the 95% confidence test in 2004, 1990 and 2008, respectively, indicating that the sediment load variations of the three rivers appeared significant decreasing trends. In the mid-downstream of the Changjiang catchment, the sediment load Han River, Dongting Lake and Poyang Lake began to reduce in 1966, 1984 and 1985, respectively; and the M-K trends of sediment load of the three sub-catchments exhibited significant decreasing trends (passing the 95% confidence test) in 1970, 1995 and 2000, respectively.

Due to discrepancies among the sediment load variations of the seven sub-catchments, 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. As a result of the sediment load reducing of Jialing River and Wu River in 1985 and 1984, the sediment load upstream the Yichang station began to reduce in 1985, and passed the 95% confidence test in 1996. Impacted by sediment load decreasing of Han River beginning from 1966, the sediment load lessening trends of mid-lower reach of Changjiang main river (Hankou and Datong station) were observed in 1969. Furthermore, as a consequence of sediment load reducing of upstream and mid-lower tributaries in 1985, the sediment load of mid-lower reach of Changjiang main river began to further decrease in 1985. In addition, the M-K trends of sediment load of Datong, Hankou and Yichang station passed the 95% confidence test in 1989, 1997 and 1996, respectively, i.e., the statistical sediment load decreasing trends occurred qualitative change.

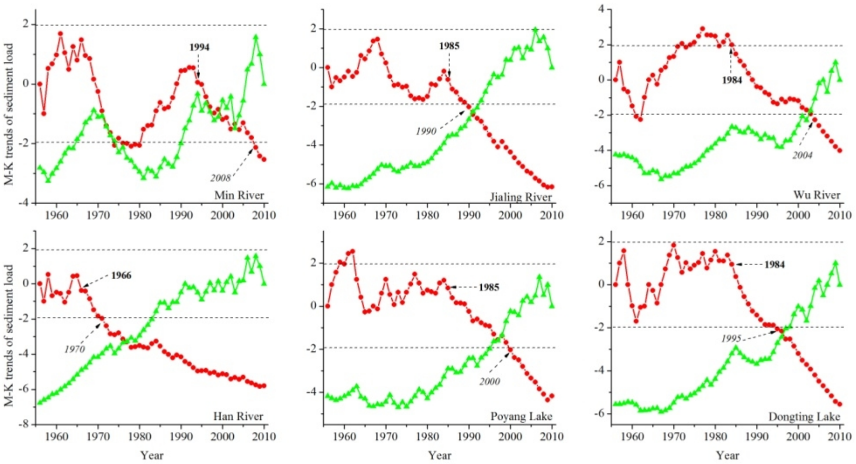

Figure 4. M-K trends of the sediment load for the Jinsha, Min, Jialing, Wu, and Han Rivers and the Poyang and Dongting Lake system. The symbol ● and ▲ denotes C_1 and C_2, respectively. The bold is the beginning time of sediment load decreasing; and the italics is the time when the M-K trends of the sediment load pass the 95% confidence test.

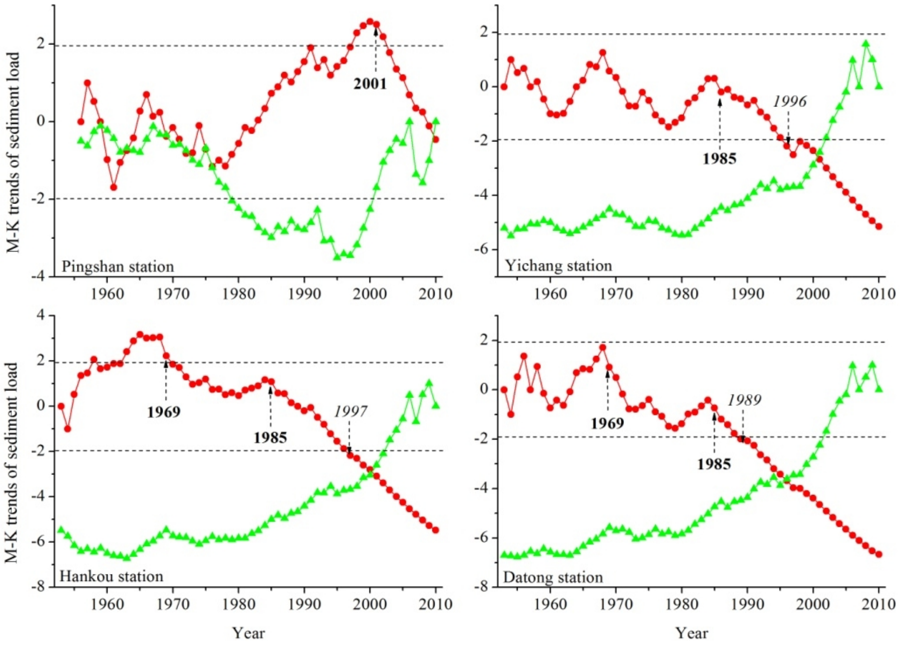

Figure 5.M-K trends of the sediment load for different gauging stations of the Changjiang main river. The symbol ● and ▲ denotes C_1 and C_2, respectively. The bold is the beginning time of sediment load decreasing;

and the number in italics denotes the time when the M-K trends of the sediment load pass the 95% confidence test.

4.3 Stepwise reduction of the sediment load entering the sea

The M-K trends of sediment load variation at Datong station show that, 1969 and 1985 are two important time nodes, reflecting the beginning time of sediment load decreasing. Due to the M-K trends of the sediment load passing the 95% confidence test occurred at 1989, another important time nodes (2003) is not reflected in the M-K trends of sediment load of Datong station. Taking into account the great impact of the Three Gorges Dam on the sediment load decreasing of the Changjiang main stream (Hu et al., 2011), the variations of the sediment load entering the sea of the Changjiang could be divided into four stepwise reduction stages, namely, 1956-1969, 1970-1985, 1986-2002, and 2003-2010.

The variations of sediment load discharging into the sea of the Changjiang (Datong station) indicated that, although the sediment load of the Datong station, with an average value of 503 Mt y^{-1}, exhibited fluctuations from 1956 to 1969, the quantity generally remained at a high level. Han River was ever the most important sediment source of middle reach of Changjiang main river (Yin et al., 2007); however, due to the annual sediment load supplied by the Han River decreased by 95 Mt, the sediment load of the Datong station reduced to 445 Mt in 1970-1985. 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. Due to the sediment load upstream Changjiang occurring decreasing trends in 1985, in term of the quantity reducing from

533 Mt y^{-1} during 1956-1985 to 404 Mt y^{-1} during 1986-2002, the sediment load entering the sea of the Changjiang lessened to 340 Mt y^{-1} during this period. With the emplacement of Three Gorges Dam in 2003, the sediment load upstream of the Changjiang decreased to 55 Mt y^{-1} during 2003-2010, and the sediment load entering the sea of the Changjiang was only 152 Mt y^{-1}.

Table 1. The mean value of sediment load of the Changjiang main river during different period

Time	Pingshan station Mt y^{-1}	Yichang station Mt y^{-1}	Hankou station Mt y^{-1}	Datong station Mt y^{-1}
1956-1969	232	547	461	503
1970-1985	226	521	426	445
1986-2002	275	404	331	340
2003-2010	151	55	118	152

Overall, four stepwise reduction stage periods of the sediment load discharging into the sea of the Changjiang were observed, namely, 1956-1969, 1970-1985, 1986-2002, and 2003-2010. In addition, the sediment load into the sea between adjacent time periods gradually decreased, attributing to the sediment load decreasing of different tributaries: the sediment load reduction entering the sea during 1970-1985 was mainly caused by Han River; upstream tributaries (mainly Jialing and Wu River), together the sub-catchment of mid-lower reach (mainly Poyang Lake) were responsible for the sediment load into the sea decreasing during 1970-1985; and the sediment load discharging into the sea lessening during 2003-2010 were mainly resulted from the emplacement of the Three Gorges Dam.

4.4 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).

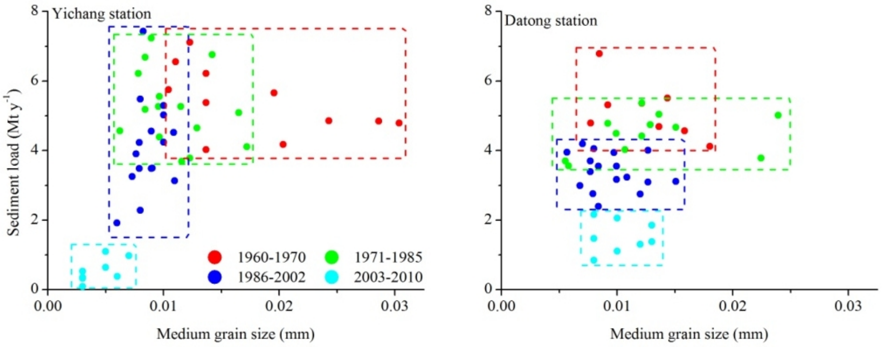

Figure 6. Relationship between the medium grain size of suspended sediments and the sediment load during different periods at the Yichang and Datong stations. Data are not available for the Datong station in 1968-1970, 1972-1973, and 1975.

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 and Datong station, ranging from 30-32% and 22%-27%, respectively, remained stable from 1960 to 2002. However, the clay content fraction of the two stations increased, and the silt fraction content decreased. After 2003, the clay and silt content of Yichang station greatly increased, and the sand fraction significantly decreased (Fig. 7); whereas, although the sand fraction of Datong station still had no obvious variation trends, the clay content increased, and the silt content reduced. In addition, before 2003, the silt and clay content appeared no obvious discrepancy between Yichang and Datong station, and the sand content fraction of Yichang station was slightly greater than that of Datong station; however, after 2003, the sand content fraction of Datong station was significantly greater than that of Yichang station, and the clay content of Datong station was less than that of Yichang station, which implied that other sediment sources (not the seven tributaries of Changjiang) supplied sand fraction to Yichang-Datong reach of the Changjiang. The above analysis suggests that although the average value of the grain size of the sediment entering the sea during the different periods did not greatly alter, the inter-annual variation range and sediment components and origin changed considerably.

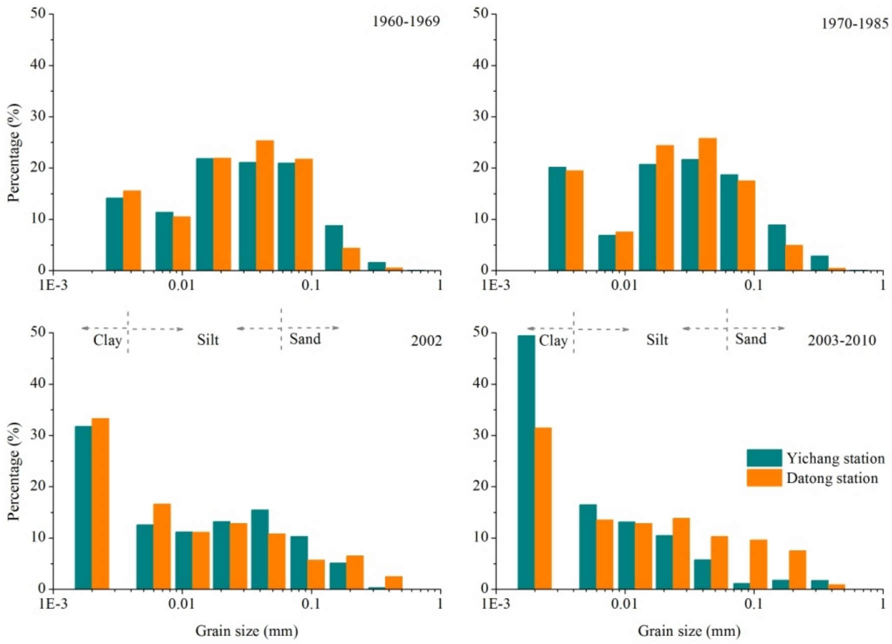

Figure 7. Distribution of the suspended sediment grain size of the Yichang and Datong stations in 1960-1969, 1970-1985, 2002, and 2003-2010.

5. Discussion

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. According to the concept of Sediment Budget (Houben, 2012), the flowing equation is used to calculating the sediment discharge balance of Changjiang main river:

$$\sum S_{input} = \Delta S + S_{output} = S_{Jinsha} + S_{Min} + S_{Jialing} + S_{Wu} + S_{Han} + S_{Poyang} \tag{5}$$

where $\sum S_{input}$ is the sediment contribution of tributaries to the sediment load of the Changjiang main stream, S_{output} is the sediment load entering the sea of the Changjiang (Datong station), ΔS is the quantity of deposited (+) / erosive (-) sediment of the Changjiang main stream and Dongting Lake. Therefore, the sediment contribution proportion of different tributaries to the sediment load entering the sea of the Changjiang can be expressed as:

$$\frac{S_{Jinsha}}{S_{output}} + \frac{S_{Min}}{S_{output}} + \frac{S_{Jialing}}{S_{output}} + \frac{S_{Wu}}{S_{output}} + \frac{S_{Han}}{S_{output}} + \frac{S_{Poyang}}{S_{output}} - \frac{\Delta S}{S_{output}} = 1 \qquad (6)$$

The calculated results indicated that (Tab.2), 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 48.3% and that of the Jinsha River decreased dramatically to 24.1%. In addition, the Jialing and Han Rivers only contributed 5.3% of the sediment load of the Datong station, respectively.

Table 2. The sediment contribution proportion (%) of different tributaries to the sediment load entering the sea of the Changjiang.

River/Catchment	1956-1969	1970-1985	1986-2002	2003-2010
Jinsha River	35	46.7	64.2	24.1
Min River	8.8	8.6	10.1	6.1
Jialing River	24.3	27.6	15	5.3
Wu River	4.4	8.2	4.5	2.2
The total of the upstream four rivers	72.5	91.1	93.8	37.7
Han River	19	5.8	2.8	5.3
Channel erosion	6.1	0.9	1.1	48.3
Poyang Lake	2.4	2.2	2.3	8.7

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 four rivers of the upstream Changjiang was the dominating sediment source to the sediment load entering the sea, and their total contribution was 72.5% during 1956-1969, 91.1% during 1970-1985, and 93.8% during 1986-2002, respectively. In addition, during this period, 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. However, after 2003, the sediment contribution of the upstream to the sediment load of the Datong station greatly decreased. The mid-lower stream channel of the Changjiang was one of major sinks of the upstream sediment (Yang et al., 2011); after 2003, channel erosion of the mid-lower portion of the main river became the greatest source of sediment load of the Datong station.

Apart from dams interception effect, the soil conservation campaign starting from 1989 and implemented for the high sediment yielding regions of the upper Changjiang basin (Hu et al., 2011), may be another factor accelerating the decreasing trend of the sediment grain size of Yichang station. The different grain sizes of the sediment of Yichang and Datong station indicated that, the clay, silt, and sand fraction of the Yichang station were greater than those of the Datong station during 1960-1969, 1970-1985, and 1986-2002 periods (Tab. 3), 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. 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, we still use the sediment budget concept, calculate different sediment fraction balance of Changjiang main river between Yichang-Datong reach:

$$S_{Yichang} + S_{Han} + S_{Poyang} = \Delta S + S_{datong} \tag{7}$$

The results show that, the erosive sediment of the main river channel (Yichang-Datong) and Dongting Lake contributed 13 Mt y^{-1} of clay, 43 Mt y^{-1} of silt, and 20 Mt y^{-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. Considering the contribution of strong erosion of the estuarine reach (Li, 2007), 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 reaches of the main river channel.

Table 3. Annual quantities of clay, silt, and sand at the Yichang and Datong stations during different periods.

Time Period	Clay (Mt y^{-1})		Silt (Mt y^{-1})		Sand (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

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 characteristics of the sediment entering the sea. 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). Estuary-coastal-continental shelf areas are the final destination of catchment sediments; however, the gross sedimentary flux, terrestrial material tracing, sedimentary records interpreting, and sediment dynamically modeling of these areas are closely correlated to the sediment load entering the sea, the sediment composition and sediment grain size (Gao, 2013). Therefore, above changes will bring about more uncertainty, which deserves further investigations.

6. Conclusions

(1) The increment of reservoir storage capacity is significantly correlated with the decrease in the sediment load, which reflected the impact of dams on the sediment load of tributaries and the entire Changjiang catchment.

(2) The patterns of sediment delivery from the sub-catchments of the Chnagjiang River have been changed, with significant spatial-temporal differences in the sediment load variations of the Changjiang main stream: four stepwise reduction stages were identified, i.e., 1956-1969, 1970-1985, 1986-2002, and 2003-2010. There was a lag of the decrease in the sediment load at upstream locations compared with those at downstream locations.

(3) Before 2003, the variations in the sediment composition in the marine areas were mainly determined by the changes in the sediment contribution made by the Jinsha, Jialing, and Han

Rivers. However, after 2003, channel erosion of the main stream of the Changjiang supplied around 48.3% of the sediment load into the sea.

(4) Impacted by dam construction, although mean grain size of the sediment entering the sea during the different periods did not show clearly-defined variations, the inter-annual variation in terms of the range, sediment components and source areas, changed considerably.

(5) Before 2003, the clay, silt, and sand fractions entering the sea mainly originated from the upstream regions of the river. In contrast, after 2003, the origin of the clay component of the sediment was dominated by the upstream areas, whilst the silt and sand component were mainly supplied by the eroding bed of the main channel.

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