Revised.

Title page

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

Jian Hua Gao[a*], Jianjun Jia[b], Ya Ping Wang[a*], Yang Yang[a], Jun Li[c], Fenglong Bai[c], Xinqing Zou[a], Shu Gao[a]

a Ministry of Education Key Laboratory for Coast and Island Development, Nanjing University, Nanjing 210093, China

b Key Laboratory of Submarine Geo-Sciences, Second Institute of Oceanography, State Oceanic Administration, Hangzhou 310012, China

c Qingdao Institute of Marine Geology, Qingdao 266071, China

[*]Corresponding author. Tel.: +86 025 83686010; fax: +86 025 83595387.
Email-address: jhgao@nju.edu.cn (J.H., Gao)
[*]Corresponding author. Tel.: +86 025 83686010; fax: +86 025 83595387.
Email-address: ypwang@nju.edu.cn (Y.P., Wang)

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

Jian Hua Gao[a*], Jianjun Jia[b], Ya Ping Wang[a*], Yang Yang[a], Jun Li[c], Fenglong Bai[c], Xinqing Zou[a], Shu Gao[a]

a Ministry of Education Key Laboratory for Coast and Island Development, Nanjing University, Nanjing 210093, China

b Key Laboratory of Submarine Geo-Sciences, Second Institute of Oceanography, State Oceanic Administration, Hangzhou 310012, China

c Qingdao Institute of Marine Geology, Qingdao 266071, China

Abstract: In order to evaluate the impact of human activities (mainly dam building) on the Changjiang River sediment discharging into the sea, the spatial-temporal variations in the sediment load of different tributaries of the river was analyzed to reveal the quantity, grain size and composition patterns of the sediment entering the sea. 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 identified, i.e., 1956-1969, 1970-1985, 1986-2002, and 2003-2010. The proportion of the sediment load originating from the Jinsha River continuously increased before 2003; after 2003, channel erosion in the main stream provided a major source of the sediment discharging into the sea. In addition, in response to dam construction, although mean grain size of the suspended sediment entering the sea did not change greatly with these different periods, the inter-annual variability for sediment composition or the relative contributions from the various tributaries changed considerably. Before 2003, the clay, silt and sand fractions of the river load 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 river bed erosion of the middle reach of the river. These observations imply that the load, grain size and sediment composition deposited over the coastal and shelf water adjacent to the river mouth may have changed rapidly recently, in response to the catchment changes.

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, as well as the proportion of the sedimentary materials from different tributaries (which will be 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 activities (particularly large hydrologic projects), analyzing long-term variation trends for a number of representative rivers (e.g., 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 sediment composition in response to human activities, and to their sedimentological and environmental consequences. The importance of these two aspects 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 catchment sediment characteristics for different periods is critical for an accurate analysis of the sediment source/distribution pattern over the estuary and coast-continental shelf regions, and for an improved 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, the East China Sea, and the Okinawa Trough, thereby exerting a considerable impact on the sedimentological and biochemical conditions 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) estimated 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. The Changjiang catchment consists of numerous tributaries, which are characterized by different rock properties and climate conditions. On the other hand, the intensity and duration of human activities of these tributaries are also varied, which leads to different spatial-temporal patterns of the sediment yield of the sub-catchments (Lu et al., 2003). Thus, the sediment supply of each tributary to the main stream of the Changjiang also changed with time. Furthermore, dam construction and land cover changes also have an important impact on changes in sediment grain size for the tributaries and main stream of the Changjiang (Zhang and Wen, 2004). Therefore, the sediment contribution made by the different tributaries to the sea-going sediment load, the grain size and sediment composition may vary at the same time for the decrease in the total sediment load of the Changjiang River.

In order to evaluate the impact of human activities (mainly dam construction) on the quantity, composition and grain size of the Changjiang sediment discharging into the sea, we attempt to: (1) analyze the effect of dam emplacement on the sediment load of different tributaries; (2) identify the spatial-temporal variation patterns of sediment load within the main stream of the Changjiang associated with dam emplacement; (3) reveal the quantity, grain size and composition features of the sea-going sediment during different periods; and (4) delineate the variations in sediment load originating from the tributaries of the Changjiang for different historical times.

# 2. Regional setting

The Changjiang, with a drainage basin area of approximately $1.80\times10^6$ $km^2$, 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.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 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 Dongting Lake 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). The Dongting Lake was a major sink of the upstream sediment of the Changjiang and, due to sediment decrease from the upstream Changjiang, has become a weak sediment source to its downstream sections (Dai and Liu, 2013). 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 Datong gauging station is the last station along the Changjiang before going to the sea, and its hydrological records are often used to derive a represent sediment flux of the Changjiang into the adjacent East China Sea.

Due to intensified human activities, the catchment forest vegetation degenerated continuously, with a large-scale reduction of forest cover in the Changjiang catchment (Xu, 2000), resulting serious deterioration of the ecological environment (Lu and Higgitt, 2000). Starting from the late 1980s, a major soil conservation campaign was implemented in high sediment yielding regions of the upper Changjiang catchment. However, due to the highly variable natural conditions of the tributaries, the effect of this campaign was different in every upstream tributary. For example, most of the Jialing River catchment is characterized by hills areas, with potential severe slope erosion (Zhang and Wen, 2004), yet its vegetation restoration rate is quite high due to the humid climate; hence, the effect of vegetation recovery on the reduction of slope erosion is prominent (Lei et al., 2006). As such, the sediment yield of these parts of the Jialing River catchment has rapidly decreased since the soil conservation campaign carried out in the 1980s (BSWC，2011). However, the downstream Jinsha River has a different situation. This section, 782 km in length, is the main sediment yield area; although its area only accounts for 7.8% of the upstream Changjiang, the average annual sediment load reaches 35.50% of the quantity at the Yichang station (Zhang and Wen, 2004). The high and steep mountains here are characterized by landslides and debris flow, reducing the effect of vegetation restoration (Lei and Huang, 1991；Yang, 2004). Therefore, the water and soil erosion prevention scheme does not work in the Jinsha River as well as in the Jialing River (BSWC, 2011); in the former case, reservoir interception is still the dominant factor of the sediment load reduction.

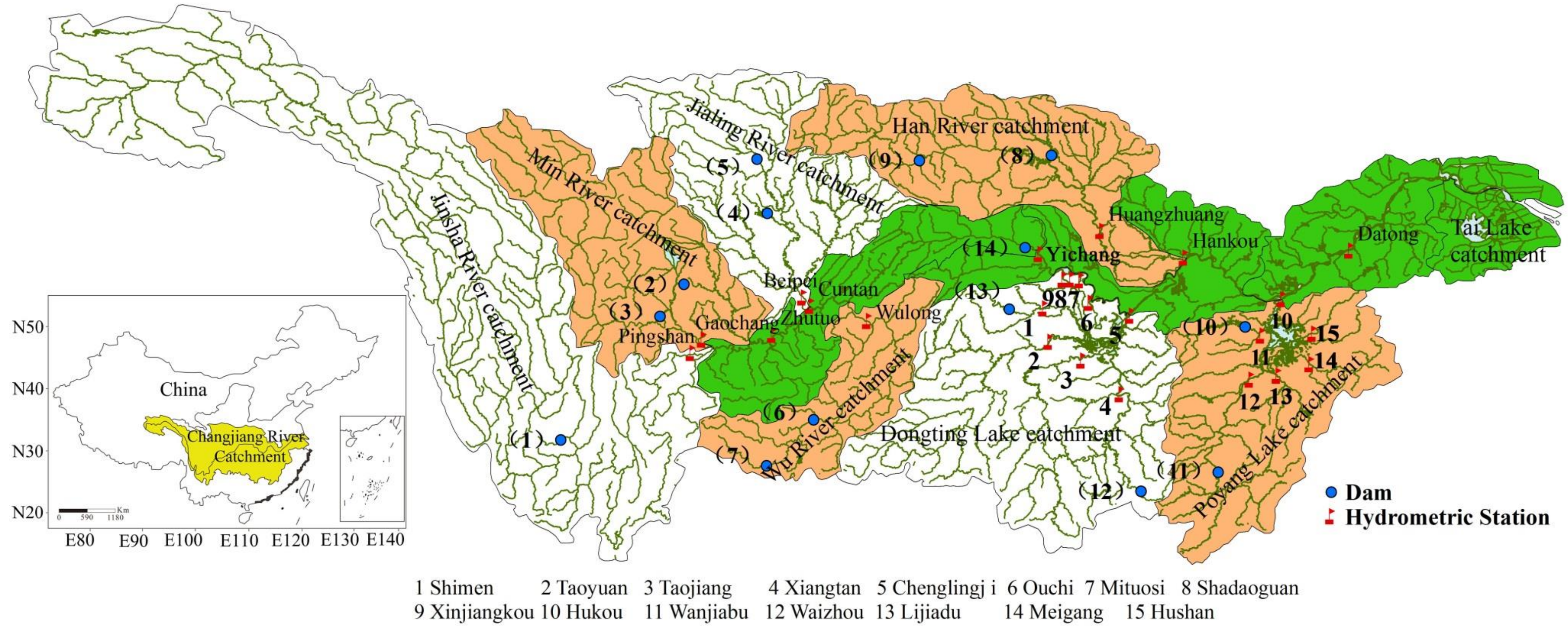


**Figure 1**. The Changjiang catchment and location of the hydrologic stations for the Changjiang catchment. The numeric symbols in the figure denote some important reservoir sites, including: (1) Er'tan; (2) Heilongtan; (3) Tongjiezi; (4) Shengzhong; (5) Baozhushi; (6) Wujiangdu; (7) Puding; (8) Danjiangkou;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

# 3. Material and method

## 3.1 Data sources

### 3.1.1 Water discharge and sediment load data

A long-term discharge and sediment monitoring program for the entire catchment has been implemented since the 1950s, by the Changjiang Water Resource Commission (CWRC) under the supervision of the Ministry of Water Resources, China (MWRC). These monitoring data of each station include field survey and measurement of water discharge, suspended sediment concentration, suspended sediment load, and suspended sediment grain size, in accordance with China's national data standards (Ministry of Water Conservancy and Electric Power, 1962, 1975): 10-30 vertical profiles within the water column were established for the measurements of each river cross-section, with the number of profiles varying with the width of the river. For each profile, the flow velocity are measured (using a direct reading current meter) at different depths (normally at surface, 0.2H, 0.6H, 0.8H and the bottom, where H is the water depth). Meanwhile, the water mass of these layers is sampled for the measurements of the suspended sediment concentration (using filtration) and grain size (using the suspension settling method). Such 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 strictly examined by the CWRC before release. The data for the period of 1956-2001 were either published in the Yangtze River Hydrological Annals or provided directly by the CWRC. After 2002, these hydrological data were reported 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 from 26 hydrological stations distributed in the main reach and seven of the tributaries (for the location of these stations, see Fig.1). The dataset for these gauging stations covers a 55-year period (i.e., 1956-2010).

### 3.1.2 Dam data

In the present study, the reservoirs with a storage capacity of greater than 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 the 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.

In the present study, 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, which has been used to analyze long-term hydro-meteorological temporal series (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 the 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: $X_t$ = ($x_1$, $x_2$, $x_3$ ....$x_n$), 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 statistical variable $d_k$ 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

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

where $UF_k$ is the forward sequence. 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 as $C_1$ 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 a normal distribution at the significant level of P=0.05, a positive Man-Kendal statistics C larger than 1.96 indicates a significant increasing trend, whilst 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 values of the seven tributaries and the main stream of the Changjiang reveal stepwise increasing trends (Fig. 2). The variations in reservoir storage capacity of the four upstream tributaries 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 these four rivers, the total RSCI of the Changjiang catchment, upstream of the Yichang station with increases by 2.8% in 1985 and 16.0% in 2003, also showed the stepwise patterns. The middle reaches of the Changjiang catchment consisted of three major tributaries, namely, the Han River, Dongting Lake and Poyang Lake. The total RSCI of the Han River began to increase in 1966, and greatly rose in 1968. In addition, the rapid increment in the total RSCI of the Poyang and Dongting Lakes were also present for 1972 and 1985, respectively. Generally, as a consequence of dam construction, the total RSCI of the Changjiang upstream of the Datong greatly increased in 1969 and 2003, respectively.

The changes of the total RSCI and sediment load of the tributaries and the whole Changjiang catchment indicate that the stepwise decrease of sediment load is apparently related to the significant increase of the total RSCI. In the case of the Yichang and Datong stations, over the last few decades, there is significant negative correlation between average sediment load and total RSCI at both the Yichang and Datong stations (Fig.3), which reflected the impact dams have on the sediment load.

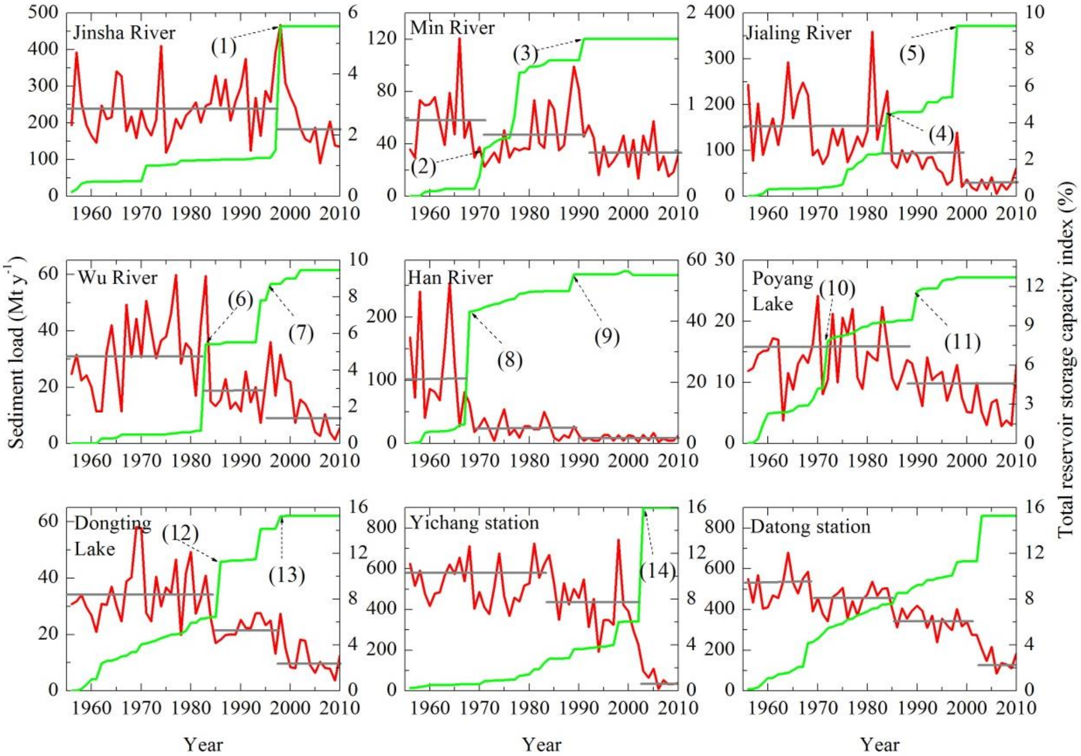


**Figure 2.** Relationship between the reduction in sediment load (red line) and the total reservoir storage capacity index (green line) in the tributaries and the main stream. Numeric symbols represent reservoirs listed in Figure 1.

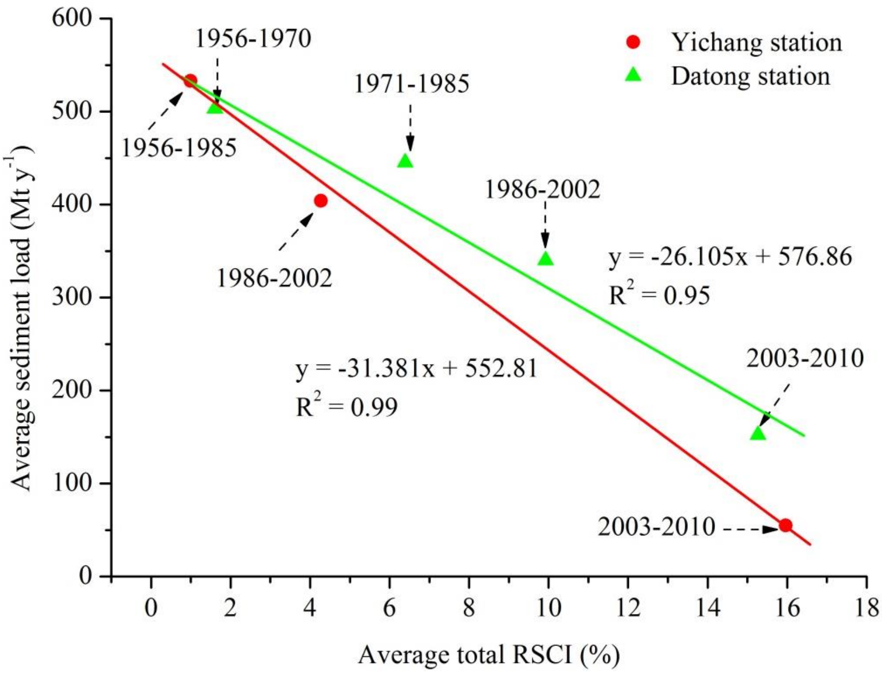


**Figure 3.** The relationship between average sediment load and total RSCI of different periods at Yichang and Datong station.

## 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 (Figs. 4 and 5) indicate that the downstream sediment load began to decrease earlier than the upstream sediment load. Due to the sediment load reduction of the Jialing and Wu Rivers, the total sediment load of the four upstream rivers began to decrease in 1984. In the middle stream of the Changjiang, the sediment load for the Han River and Dongting - Poyang Lakes began to reduce in 1966, 1984 and 1985, respectively; the M-K trends of sediment load of the three sub-catchments exhibited significant trends of decrease (at the 95% confidence level) in 1970, 1995 and 2000, respectively.

Due to the different patterns of sediment load variations of the seven sub-catchments, there were significant spatial-temporal differences in the sediment load variations of the mainstream

Changjiang: the sediment load began to decrease later at upstream locations than at downstream locations. The sediment load upstream of the Yichang station began to reduce in 1985, with a 95% confidence level for the year of 1996. Impacted by sediment load decreasing of the Han River, beginning from 1966, the sediment load reduction trends of the middle reach (Hankou - Datong stations) were observed in 1969. Furthermore, as a result of sediment load reducing of upstream and middle reach tributaries in 1985, the sediment load of the middle reach of the Changjiang began to further decrease in 1985. The M-K trends of sediment load of the Datong, Hankou and Yichang stations are associated with a 95% confidence level in 1989, 1997 and 1996, respectively.

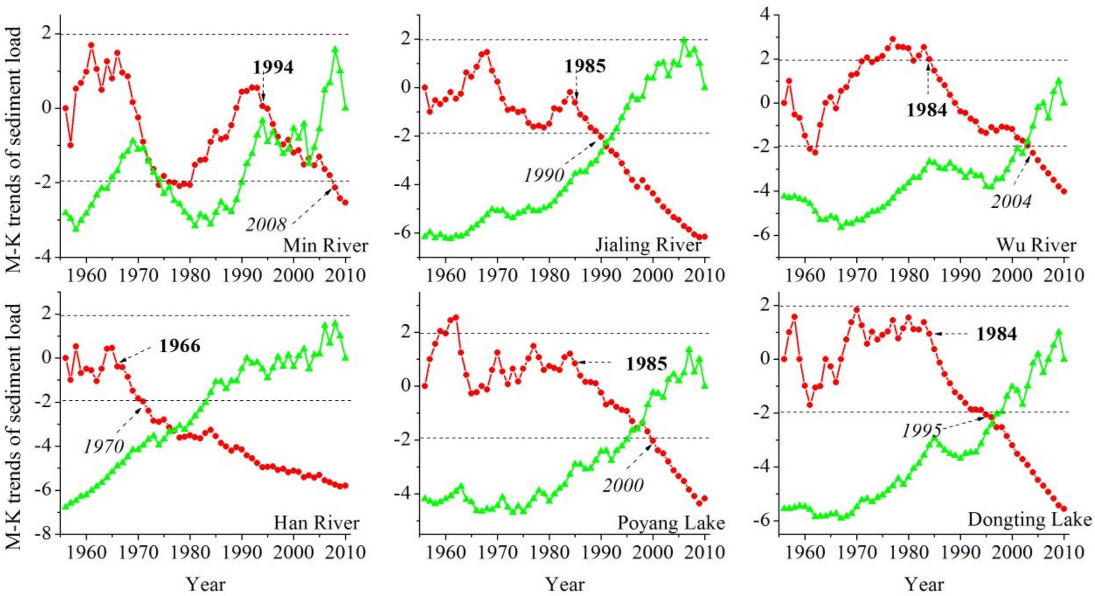


**Figure 4.** M-K trends of the sediment load for the Jinsha, Min, Jialing, Wu, and Han Rivers and the Poyang and Dongting Lake system. The symbol ● and ▲ denotes $C_1$ and $C_2$, respectively. The bold is the beginning time of sediment load decreasing; and the italics is the time when the M-K trends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

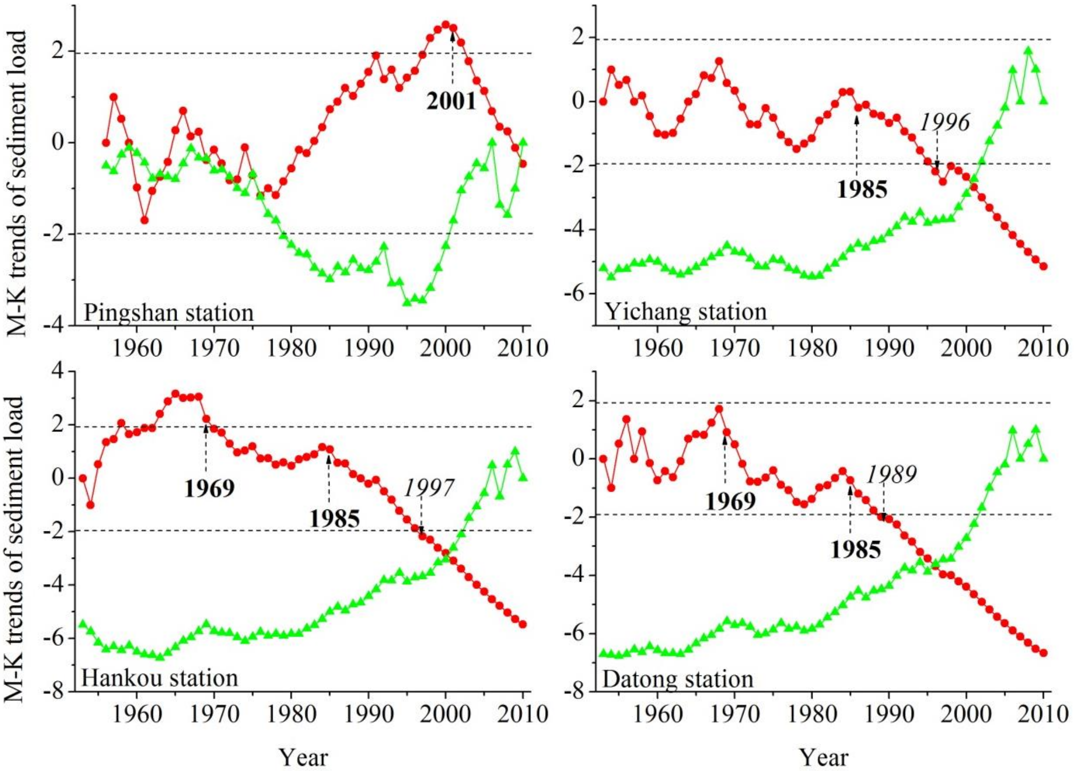


**Figure 5.** M-K trends of the sediment load for different gauging stations of the Changjiang main river. The symbol ● and ▲ denotes $C_1$ and $C_2$, respectively. The bold is the beginning time of sediment load decreasing; and the number in italics denotes the time when the M-K trends of the sediment 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 the Datong station show that 1969 and 1985 are two critical temporal nodes, reflecting the beginning time of sediment load decrease. While the M-K trends of the sediment load passes the 95% confidence test for 1989, another important time node (2003) is not shown in the M-K trends of sediment load of the Datong station. Taking into account the great impact of the Three Gorges Dam on the sediment load decrease of the main stream Changjiang (Hu et al., 2011), the variations of the sediment load entering the sea 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, measured at the Datong station, indicated that although the sediment load of the Datong station, 503 Mt $y^{-1}$ on average, exhibited fluctuations from 1956 to 1969, with the quantity generally remaining at a high level (Tab.1). The Han River was once the most important sediment source of the middle reach Changjiang (Yin et al., 2007); however, because the annual sediment load supplied by the Han River decreased by 95 Mt, the sediment load of the Datong station was reduced to 445 Mt in the period of 1970-1985. Previous studies elsewhere have suggested that the sediment load from the Changjiang entering the sea began to decrease in the 1980s (Yang et al., 2002); however, we would propose that such a decreasing trend already occurred in as early as 1970, and the impact of the reduced sediment load of the Han River on the overall sediment flux of the Changjiang was neglected in these previous studies. The sediment load for the upstream Changjiang had a decreasing trend starting from 1985; in term of the quantity, there was a reduction from 533 Mt $y^{-1}$ during 1956-1985 to 404 Mt $y^{-1}$ during 1986-2002. The sea-going sediment load of the Changjiang became less than 340 Mt $y^{-1}$ during this period. With the emplacement of the Three Gorges Dam in 2003, the sediment load upstream of the Changjiang decreased to 55 Mt $y^{-1}$ during 2003-2010, with the sediment discharge into the sea being around 152 Mt $y^{-1}$ (Tab. 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 sea-going sediment load were observed, namely, 1956-1969, 1970-1985, 1986-2002, and 2003-2010. Further, the sediment load decrease may be related to sediment load decrease of different tributaries: the reduction during 1970-1985 was correlated with the Han River, whilst the upstream tributaries (mainly the Jialing and Wu Rivers), together with the sub-catchment of the middle reach (mainly the Poyang Lake), were responsible for the decrease during 1970-1985. The sediment load decrease during 2003-2010 resulted mainly 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 grain size downstream of the reservoirs becomes significantly finer (Xu, 2005). The variation in the medium grain size ($D_{50}$) of suspended sediment at the Yichang station (Fig. 6) indicates that the average value of $D_{50}$ 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 $D_{50}$ for the Datong station was not as significant as that for the Yichang station during these four stages: the average $D_{50}$ in 1960-1969 (0.12 mm) was similar to that in 1970-1985 (0.13 mm), with a slight decrease for the year of 2002 (0.09 mm) and for the period of 2003-2010 (0.10 mm).

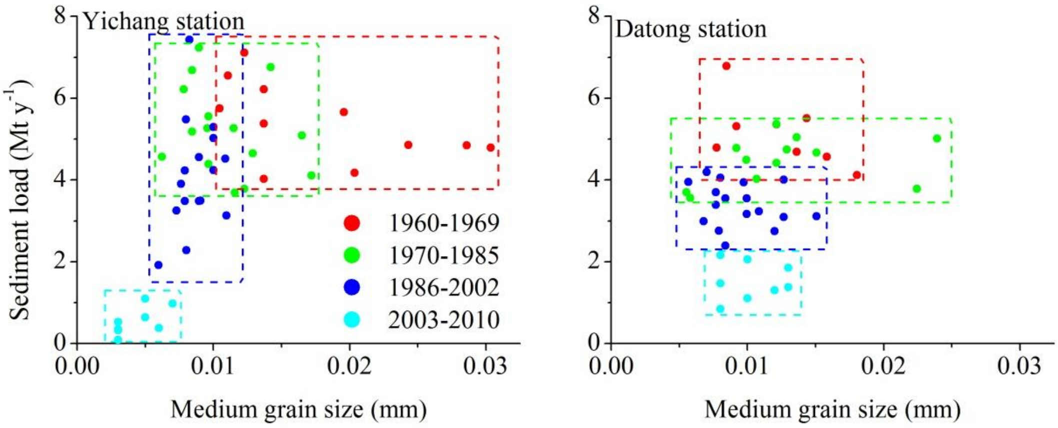


**Figure** 6. Relationship between the medium grain size of suspended sediments and the sediment load during different periods at the Yichang and Datong stations. Data are not available for the Datong station in 1968-1970, 1972-1973, and 1975.

In addition, the degree of inter-annual variation in the upstream sediment grain size continuously decreased during the four periods at the Yichang station, i.e., the range of $D_{50}$ variations is gradually narrowed (with a continuously reduced standard deviation), and the distribution range of the $D_{50}$ data and sediment load moves towards the side of finer grain sizes; however, such a change is not so significant at the Datong station (Fig. 6). The sediment grain size variations of the two stations also indicated that the average value of $D_{50}$ for the Yichang station was greater than that for the Datong station in 1960-1969, but the two stations had similar values in 1970-1985 and 1986-2002; after 2003, the average value of $D_{50}$ of the Yichang station was smaller than that of the Datong station. Furthermore, $D_{50}$ ranged from 0.003-0.007 mm for the Yichang station and 0.008-0.013 mm for the Datong station, in 2003-2010, suggesting that the $D_{50}$ variation range of the two stations did not overlap after 2003.

Compared with previous periods, after 2003, the clay and silt contents at the Yichang station greatly increased, and the sand fraction significantly decreased (Fig. 7). At the Datong station, however, although the sand fraction had no apparent variation trends, the clay content increased, and the silt content reduced. Furthermore, before 2003, the silt and clay contents did no differ much between the Yichang and Datong stations, and the sand content at the Yichang station was slightly greater than that at the Datong station; however, after 2003, the sand content at the Datong station became significantly greater than that at the Yichang station, and the clay content at the Datong station became lower than that at the Yichang station, implying that the sediment sources other than the seven tributaries supplied a sand fraction to the Yichang-Datong section of the Changjiang. This observation suggests that although the average value of the grain size of the sediment entering the sea during the different periods did not alter greatly, the inter-annual variation range, sediment components and the material sources changed considerably.

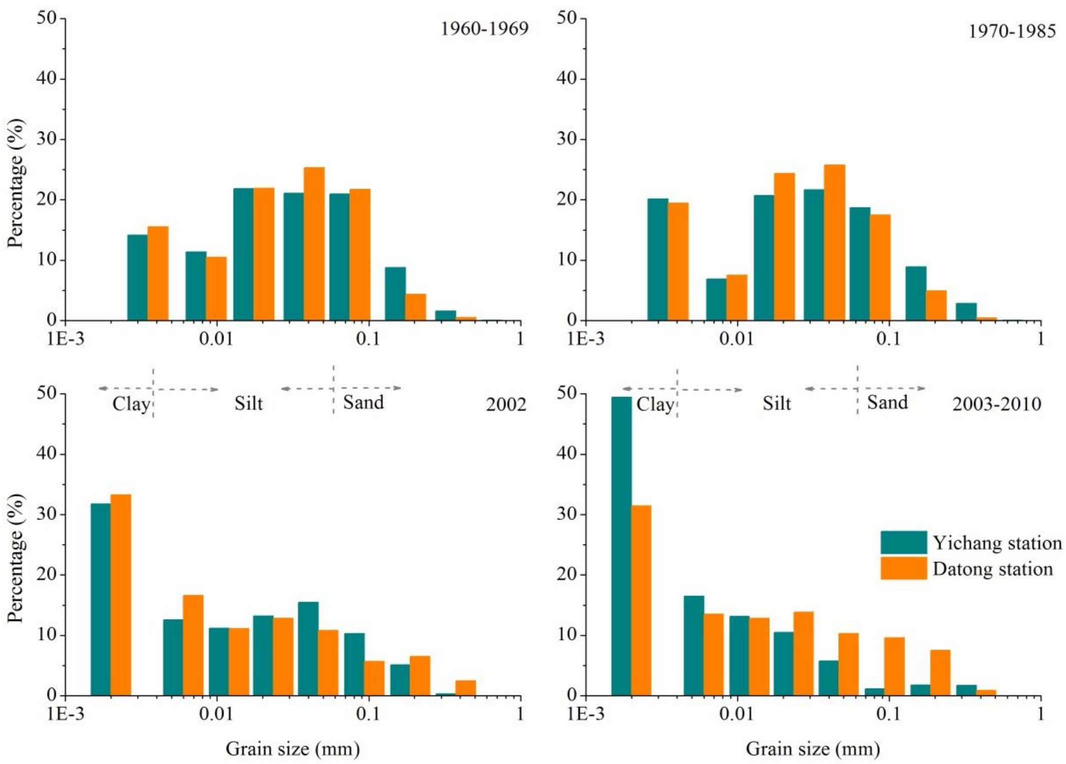

**Figure 7**. Distribution of the suspended sediment grain size of the Yichang and Datong stations in 1960-1969, 1970-1985, 2002, and 2003-2010.

# 5. Discussion

As outlined above, the Changjiang sediment load is influenced by mixing of weathering products supplied by the different sub-catchments. The spatial-temporal differences among the sub-catchments, in terms of sediment load variations, caused the sediment load reduction and changes in the sediment composition. According to the concept of sediment budget (Houben, 2012), the following equation may be used to calculate the sediment balance of the main stream Changjiang:

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

where $\sum S_{input}$ is the contribution of the tributaries to the main stream sediment load, $S_{output}$ is the sediment load entering the sea (measured at the Datong station), $\Delta S$ is the quantity of deposited (+) / eroded (-) sediment of the main stream Changjiang and the Dongting Lake. Thus, the contribution of the different tributaries to the overall sediment load can be expressed by:

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

The calculated results indicated that (Tab.2), in 1956-1969, the sediment load of the Datong station was mainly originated from the Jinsha, Jialing and Han Rivers, with their contributions being 35.0%, 24.3%, and 19.0%, respectively. As the sediment load of the Han River decreased, the Jinsha and Jialing Rivers accounted for 46.7% and 27.6%, respectively, in the sediment load at the Datong station during the 1970-1985 period; whereas the contribution from 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 at the Datong station further increased to 64.2% and that of the Jialing River decreased to 15.0%. The sediment composition changed considerably during the 2003-2010 period due to the TGD emplacement: the sediment proportion due to channel erosion of the main stream reached 48.3% and the proportion of the Jinsha River decreased dramatically to 24.1%. Furthermore, both the Jialing and Han Rivers only contributed 5.3% to the sediment load at the Datong station.

**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 indicates that as the sediment load at the Datong station decreased, although the average sediment grain size did not display clearly-defined variations, the sediment composition changed considerably. Before 2003, the four rivers of the upstream Changjiang were 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. In addition, during these periods, 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. However, after 2003, the sediment contribution of the upstream to the sediment load of the Datong station greatly decreased. The middle reach of the Changjiang became one of the major sinks of the upstream sediment (Yang et al., 2011); after 2003, channel erosion of the middle reach main stream became the most important source of sediment load at the Datong station.

Apart from the dam 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 at the Yichang station. The different grain sizes of the suspended sediment at the Yichang and Datong stations indicate that the clay, silt and sand fluxes at the Yichang station were greater than those at the Datong station during 1960-1969, 1970-1985 and 1986-2002 periods (Tab. 3), which implies that the sediment fractions of clay, silt and sand entering the sea were mainly originated from the upstream Changjiang, with weak sediment exchange between the water column 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 the Han River to the main stream Changjiang, we may still use the sediment budget concept, to calculate the balance for the different sediment fractions for the Yichang-Datong reach:

$$S_{Yichang} + S_{Han} + S_{Poyang} = \Delta S + S_{datong} \quad (7)$$

The calculations show that the eroded sediment of the main river channel (between Yichang and Datong) and the 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 at the Datong station in 2003-2010, which accounted for 27.1%, 55.8%

and 74.1% of the corresponding sediment components of the Datong station. Taking into account the eroded sediment supply within the estuarine areas (Li, 2007), the percentages of the silt and sand fractions discharging into the sea, due to the material supply by the eroding main river channel, may exceed 55.8% and 74.1%, respectively. These data imply that the clay fraction at the Datong station should be originated mainly from the upstream Changjiang, and the silt and sand fractions largely consisted of the eroded sediment of the middle reach 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 |

# 6. Conclusions

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

(2) The patterns of sediment delivery from the sub-catchments of the Changjiang River have been changed, with significant spatial-temporal differences in the sediment load variations of the main stream Changjiang: 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 Changjiang supplied around 48.3% of the sediment load into the sea.

(4) In response to 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 variations in terms of the size range, sediment components and source areas changed considerably.

(5) Before 2003, the clay, silt and sand fractions entering the sea were 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 middle-reach main channel of the Changjiang River.

## Acknowledgments

The study was supported by the National Basic Research Program of China (Grant No. 2013CB956503) and the Natural Science Foundation of China (Grant Nos. 41376068 and 41476052).

## References

BSWC (Bulletin of soil and water conservation in China): Press of Ministry of Water Resources of the People's Republic of China. (http://www.mwr.gov.cn/zwzc/hygb/zgstbcgb/), 2007

Chen, Z., Li, J., Shen, H., Wang, Z. H.: Yangtze River of China: historical analysis of discharge variability and sediment flux. Geomorphology, 41(2), 77-91, 2001.

Dai, S.B., Lu, X.X., Yang, S.L., Cai, A.M.: A preliminary estimate of human and natural contributions to the decline in sediment flux from the Yangtze River to the East China Sea. Quatern. Int., 186, 43-54, 2008.

Dai, Z., Liu, J. T.: Impacts of large dams on downstream fluvial sedimentation: An example of the Three Gorges Dam (TGD) on the Changjiang (Yangtze River). J. Hydrol., 480,10-18, 2013.

Dou, Y.G., Yang, S.Y., Liu, Z.X., Clift, P.D., Yu, H., Berne, S., Shi, X.F.: Clay mineral evolution in the central Okinawa Trough since 28 ka: Implications for sediment provenance and paleoenvironmental change. Palaeogeogr. Palaeoclimatol., 288, 108-117, 2010.

Driscoll, N., Nittrouer, C.: Source to Sink Studies . Margins Newsletter, 5, 1-24, 2002.

Gao, S., Wang, Y.P., Gao J.H.: Sediment retention at the Changjiang sub-aqueous delta over a 57 year period in response to catchment changes. Estuar. Coast. Shelf Sci., 95, 29-38, 2011.

Gao, S., Wang, Y.P.: Changes in material fluxes from the Changjiang River and their implications on the adjoining continental shelf ecosystem. Cont. Shelf Res., 28, 1490-1500, 2008.

Gao, S.: Catchment-coastal interaction in the Asia-Pacific region. in: Harvey, N. (Eds), Global change and integrated coastal management: the Asian-Pacific region. Springer, Dordrecht, pp. 67-92, 2006.

Gao, S.: Modeling the growth limit of the Changjiang Delta. Geomorphology, 85, 225-236, 2007.

Hamed, K.H., Rao, A.R.: A modified Mann-Kendall trend test for autocorrelated data. J. Hydrol., 204, 182-196, 1998.

Houben，P.: Sediment budget for five millennia of tillage in the Rockenberg catchment (Wetterau loess basin, Germany). Quatern. Sci. Rev., 52, 12-23, 2012.

Hu, B.Q., Wang, H.J., Yang, Z.S., Sun, X.X.: Temporal and spatial variations of sediment rating curves in the Changjiang (Yangtze River) basin and their implications. Quatern. Int., 230, 34-43, 2011

Kendall, M.G.: Rank Correlation Methods. Griffin, London, 1955.

Lei, X.Z., Cao, S.Y., Jiang, X.H.: Impacts of soil-water conservation in Jiangling River on sedimentation of the

Three Gorges Reservoir. Journal of Wuhan University. Natural sciences edition, 11(4), 922-928 (in Chinese, with English Abstr.), 2006

Lei, X.Z., Huang, L.L.: Discussion of soil erosion mechanism in some areas of the upper Yangtze River. Journal of Sichuan Forestry Science and Technology, 12(4), 9-16 (in Chinese, with English Abstr.) , 1991

Li, L.Y.: The characteristics of water and sediment discharge and river channel evolution of Datong-Xuliujing section of the Changjiang. Ph.D. Thesis, Hohai Univ. Nanjing, China (in Chinese, with English Abstr.) , 2007.

Liu, J.P.，Xu, K.H.，Li, A.C.，Milliman, J.D., Velozzi, D.M., Xiao, S.B., Yang, Z.S.: Flux and fate of Yangtze River sediment delivered to the East China Sea. Geomorphology, 85, 208-224, 2007.

Lu. X.X., Ashmore, P., Wang, J.: Sediment yield mapping in a large river basin: the Upper Yangtze, China. Environ. Modelling & Software, 18, 339-353, 2003.

Mann, H.B.: Nonparametric tests against trend. Econometrica, 13, 245-259, 1945.

Milliman, J.D., Farnsworth, K.L.: River Discharge to the Coastal Ocean: A Global Synthesis. Cambridge Univ. Press, Cambridge, 2011.

Milliman, J.D., Shen, H.T., Yang, Z.S., Meade, R.H.: Transport and deposition of river sediment in the Changjiang Estuary and adjacent continental-shelf. Cont. Shelf Res., 4(1-2), 37-45, 1985.

Milliman, J.D.: Blessed dams or damned dams? Nat., 388, 325-326, 1997.

Ministry of Water Conservancy and Electric Power, P. R. C.: Handbook for Hydrological Survey (Vol. 1-3). Water Conservancy and Electric Power Press, Beijing (in Chinese) , 1975.

Ministry of Water Conservancy and Electric Power, P. R. C.: National Standards for Hydrological Survey, (Vol. 1-3). China Industry Press, Beijing, 1962 (in Chinese).

MWRC (Ministry of Water Resources, China): The code for China Reservoir name, Chinese Water Conservancy and Hydroelectric Press, Beijing , 2001 (In Chinese).

Serrano, V.L., Mateos, V.L., Garcı´a, J.A.: Trend analysis of monthly precipitation over the Iberian Peninsula for the period 1921-1995. Phys. Chem. Earth B, 24(2), 85-90, 1999.

Shankman, D., Heim, B.D., Song, J.: Flood frequency in China's Poyang Lake region: trends and teleconnections. Int. J. Climatol., 26, 1255-1266, 2006.

Shi, C.X.: Scaling effects on sediment yield in the upper Yangtze River: Geogr. Res. 27(4), 800-811, 2008 (in Chinese, with English Abstr.).

Syvitski, J.P.M., Saito, Y.: Morphodynamics of deltas under the influence of humans. Global Planet. Change, 57 (3-4), 261-282, 2007.

Syvitski, J.P.M., Vörösmarty, C., Kettner, A.J., Green, P.: Impact of humans on the flux of terrestrial sediment to the global coastal ocean. Sci., 308, 376-380, 2005.

Syvitski, J.P.M.: Supply and flux of sediment along hydrological pathways: research for the 21st century. Global Planet. Change, 39, 1-11, 2003.

Vörösmarty, C.J., Meybeck, M., Fekete, B., Sharma, K., Green, P., Syvitski, J.P.M.: Anthropogenic sediment retention: Major global impact from registered river impoundments. Global Planet. Change, 39, 169-190, 2003.

Walling, D.E.: Human impact on land–ocean sediment transfer by the world's rivers. Geomorphology, 79, 192-216, 2006.

Wang, Z.Y., Li, Y.T., He, Y.P.: Sediment budget of the Yangtze River. Water Resour. Res., 43, W04401. doi:10.1029/2006WR005012, 2007.

Xu, J.X.: Variation in grain size of suspended load in upper Changjiang River and its tributaries by human activities. J. Sediment Res., 3, 8-16, 2005 (in Chinese, with English Abstr.).

Yang, S.L., Milliman, J.D., Li, P., Xu, K.: 50,000 dams later: Erosion of the Yangtze River and its delta. Global

Planet. Change, 75(1), 14-20, 2011.

Yang, S.L., Zhao, Q.Y., Belkin, I.M.: Temporal variation in the sediment load of the Yangtze River and the influences of human activities. J. Hydrol., 263(1-4), 56-71, 2002.

Yang, Z.S.: Soil erosion under different landuse types and zones of Jinsha River Basin in Yunnan Province, China. J. Moun. Sci., 1(1), 46-56 (in Chinese, with English Abstr.) , 2004.

Yin, H.F., Liu, G.R., Pi, J.G., Chen, G.J., Li, C.G.: On the river-lake relationship of the middle Yangtze reaches. Geomorphology, 85, 197-207, 2007.

Zhang, X., Wen, A.: Current changes of sediment yields in the upper Yangtze River and its two biggest tributaries, China. Global Planet. Change, 41(3), 221-227, 2004.