Dear referee who gave the comments,

My co-authors and I wish to thank the reviewers and editor for the comments and suggestions which we found very useful and relevant for improving the manuscript. According to your suggestion, the revised manuscript was thoroughly re-organized and re-written, and all these changes are explained in the following point-point response.

Referee 1

1. Source and reliability of the data (Section 3.1). While I have no issues per se with the data and its sources used here, the data does not appear to have been used in any previous work. There appears to be no references which is strange for a data set that covers a 55 year period. Is this the case? Further, given that the data does not appear to have been used, a much better description is needed. Information such as how the data was collected and how often, sample analysis methods and quality control, how missing data was managed together with methodological consistency described. Without this information the reader does not have confidence in the data.

Response:

All data concerning with water and sediment discharge in this paper is published by authorities of Chinese government. We supplement the source and reliability of the data in the revised manuscript (Section 3.1.1):

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 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/).

2. The paper is examining the role dam emplacement has had in altering suspended sediment flux. However, the site map (Figure 1) is near impossible to read given its size and complexity. The reader needs to be able to easily follow the flux downstream. Further, there are no dates in the text (that I could find) when individual dams were completed again so that fluxes could be followed. Maybe a flow diagram would help with this. It is really important to be able to

understand the connections and lags in the system.

Response:

Revised. The figure 1 was re-drawn. In the revised Fig. 1, some important reservoir sites (Fig. 1a), and all the reservoirs (Fig. 1b) we counted are shown. In addition, in the revised Fig.2 and Fig.3, when and how individual dams exerted impact on the sediment load, as well as their relationship is expressed.

3. The statistical treatment throughout the paper is very confusing. There is no problem with the description of the Analytical Methods (Section 3.2) but how and where this applied to the data throughout the text is not clear. This is compounded by the straight lines included in the individual plots in Figure 2 which suggest that they are part of the autocorrelation assessment or some other statistical treatment. Later on in Section 4 and 5 differences in sediment output are described and there is the suggestion that these are presented because of statistical similarity or difference but it is never made clear. Also, could any correlations be influenced by poor quality data or data that is poorly temporally consistent (see Comment 1)? This really lets the paper down.

Response:

Revised. The Section 4 and 5 were rewritten. In the revised manuscript: firstly, according to the M-K trends of sediment load, the time nodes, i.e. the beginning time of sediment load decreasing, and the statistical sediment load decreasing trends occurring qualitative change, are confirmed; subsequently, 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; thirdly, variations in quantity, composition and grain size of Changjiang sediment discharging into the sea during these four period in response to human activities are discussed.

In addition, the source and reliability of the data is supplemented (see response 1 or the Section 3.1.1 of the supplementary).

4. Results. I realize that there are a large number of sites and data which are examined in this paper. However, the way the data is presented in the text is near impossible to follow. There are too many sites, numbers and dates for any real understanding to be made by anyone not intimately familiar with the sites and data. The Results need a thorough reworking with (1) a minimum amount of numbers in the text with (2) the data places and summarised in a table or by some other means. Also, examining Figure 2, can something be said about the large variation in output? The variability of sediment transport is worthy of some comment in its own right.

Response:

Revised. The section of result and discussions was thoroughly re-organized and re-written, according to reviewer's suggestion. The following revision has been made in section of results: firstly, we compare the changes of the total RSCI with that of the sediment load of tributaries and the whole Changjiang catchment, the results indicate that the stepwise decrease of sediment load is highly related to the significant increase of the total RSCI, reflecting the impact dams have on sediment load; secondly, derived on the basis of the M-K method, of sediment load of the seven tributaries, the spatial-temporal sediment load variations within the catchment are acquired; thirdly, based on the M-K trends of sediment load variation at Datong station, four stepwise reduction stage periods of the sediment load discharging into the sea of the Changjiang were divided, and the factors leading to the sediment load into the sea between adjacent time periods gradually decreased were also analyzed; lastly, the variations in the grain size of the sediment entering the sea during different periods were explored.

In addition, the Fig.2 was redrawn and a new Fig.3 was supplemented in the revised manuscript. These two figures indicated, 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.

5. Other comments.

(a) Given the scale and pace of development in the region, what role have changes in hillslope management had in sediment transport? Could changes in vegetation type and cover influenced your finding? Were there hillslope/subcatchment practices that could have influenced sediment transport?

Response:

Supplemented.

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 late of 1980, 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 starting from 1989 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 watershed 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 River, 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 Watershed was not as obvious as that in Jialing River watershed (BSWC, 2011), reservoir interception is still the dominating factor leading to the sediment load reduction.

Jinsha River supplies most of the sediment to the upstream Changjiang. In addition, after 1989, the total reservoir storage capacity also greatly increased in the upstream of Changjiang. Thus, the soil conservation campaign accelerated the decreasing trend of the sediment grain size of Yichang station; but it is very difficult to quantitively evaluate the contribution of dam construction and land cover change.

(b) Page 9122, Section 4.2, line 11. How did you calculate the load of 503Mt/yr? This does not seem to connect with any other data. Line 26. Do you mean statistically significant?

Response:

503 Mt/yr is arithmetic mean value of sediment load of Datong station during 1956-1969. The annual sediment load of Datong staiton during 1956-2010 is shown in Fig.2.

In Fig. 4 of the revised manuscript, 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.

(c) Section 4.3, first para. Do you mean statistically significant? Also, the following work, is it yours or that of Xu (2005). This is unclear.

Response:

The study of Xu (2005) demonstrated that, in the past 40 years, grain size of suspended sediment load of major tributaries of the upper Changjiang River has a decreasing trend; and this decreasing trend can be explained by the effect of reservoir construction and implementation of soil-water conservation measures.

Our work is very different from his. We not only analyzed the variation trends in grain size of upstream sediment, but also the Changjiang sediment into the sea. But even more important, we pay more attention to the variation of sediment fraction of Changjiang entering the sea, for example, 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 and origin changed considerably.

(d) Section 5.1, page 9125, para starting line 17. This paragraph is impossible to follow. The issues surrounding data description as well over confusing data origins make this section difficult to rationalise. Similar comment can be made for Section 5.2

Response:

In the revised section of discussions, the content irrelevant to the sediment load, composition and grain size were deleted. We mainly systematically discussed the variations in sediment load and different sediment fraction originating from tributaries within the Changjiang catchment during different historical periods.

Referee 2

Paper summary:

In this paper, the authors present a study on the change in sediment load and sediment grain size over time in the Changjiang river basin. The study uses long-term datasets (1956-2010) of annual sediment load and grain size to determine when and where there were changes in sediment load at each sampling station along the tributary rivers and main stem. Changing sediment supply to coastal ecosystems is an important topic in an area where there are many anthropogenic pressures (i.e. dams) on watersheds. These impacts are felt throughout the watershed and near-shore environment, but timing of these changes can be different depending on the watershed and type of disturbance. Therefore, this paper addresses an important subject in global change.

General comments:

Overall, this paper is hard to understand and confusing. The introduction seems to introduce a paper that is different than what is presented in the methods and results, creating a narrative that does not fit their data. The introduction mentions a variety of sediment characteristics, but as far as I can tell the paper only includes information about load and grain size. The introduction also does not state any hypotheses or predicted trends, which makes it hard to understand the methods and their rationale.

1. The major issue with the methods is that they do not address much of the analysis that they report in the results and the discussion. For example, how was cumulative reservoir storage capacity determined? (see Specific Comments below for other examples).

Response:

Revised. In fact, the cumulative reservoir storage capacity can also be named as the total reservoir storage capacity. 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.

2. Perhaps most importantly, it is not at all clear how the authors attributed changes in sediment flux to the various tributaries. Was this based on mass flux data? How were the sediment grain sizes used to do this (as I assume that they were)?

Response:

We re-organize and re-wrote the section of result and discussion. Firstly, 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. The above two relationships reflected the impact dams have on sediment load. Secondly, the beginning time of sediment load decreasing of some tributaries is consistent with that of the main river, for example, 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.

In addition, in the revised manuscripts, the method based on sediment budget, concerning with calculating the sediment (sediment fraction) contribution proportion of different tributaries to the sediment load entering the sea of the Changjiang is also introduced (in the section of Discussions).

3. The methods fail to explain how they came to the numbers used in the analyses and tracing of sources of sediment in the river basin presented in the results and discussion (see Specific Comments below for examples).

Response:

Revised. See the response 2 and 4.

4. Finally, the results and discussion bring up topics not discussed or detailed earlier in the paper, making the narrative confusing. There needs to be a complete reworking of the narrative (in both the introduction and discussion) and the methods section of this paper in order to fully capitalize on the potential of the long term datasets used in this manuscript.

Response:

Revised. The section of introduction, method, result and discussion was re-written (see the revised manuscript in the supplementary). The topic of the revised manuscript is concentrated on variations in quantity, composition and grain size of Changjiang sediment discharging into the sea in response to human activities.

In addition, source and reliability of the data are also explained: 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 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. 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/).

Specific Comments:

Title – does not adequately portray what the paper is about. The authors are not really looking at the characteristics of the sediment, but the load and the grain size.

Response:

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

Page - 9115

Line 8: What are products of the coastal catchment system?

Response:

The products mainly refer to terrestrial sediment. So, in this paper, we mainly study the sediment load, sediment composition and grain size changes induced by human activities.

Line 14: How do alterations affect grain size and the proportion of sediment from different estuaries?

Response:

Estuary-coastal-continental shelf areas are the final destination of catchment sediments, and the catchment sediment supplied by different sub-catchments. Due to dams of tributaries intercept a lot of sediment, especially fine-grained sediment, so the sediment load and grain size of tributaries decreased. However, the intensity and occurrence time of human activities of these tributaries is also varied, which directly lead to different time node of variations in sediment load and grain size of the sediment of every tributary. Therefore, the catchment sediment composition and grain size entering the sea during different periods are also varied.

Line 21: "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." The authors do not address the mineralogy or geochemistry characteristics of the sediment contributions in the methods or results.

Response:

In the revised manuscript, these two features are the grain size and composition of sediment.

Line 24: "Sediment provenance tracing is a major method used to study the spatial-temporal 25 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)." - This sentence is misleading because the authors do not create end-members based on mineralogical and geochemical characteristics.

Response:

Deleted in the revised manuscript.

Page 9116

Line 1 – "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 five terrestrial sediment end members." – Again, the authors did not include this analysis in the methods or results. The introduction sets up the reader for a different paper than what the results actually report. I think that the analysis of grain size change and sediment supply is interesting on its own without this set up. The authors need to rewrite the narrative – there is a mismatch between the rationale and the analysis.

Response:

According to reviewer's suggestion, the topic of the revised manuscript is mainly concentrated on the variation in sediment load and grain size resulted by human activities, other irrelevant content was deleted.

Line 9 - Authors should support "one of the largest rivers in the world" with discharge info and the size of the delta

Response:

Supplemented.

Line 16 - Gao et al 2014 – is unpublished results. Authors report 90.10% reduction in sediment because of dam interception. They should considering putting in supplemental material to support this claim.

Response:

Revised.

Line 17-23 – What are the variations in sediment between the three reaches? How can the authors identify what sediment comes from each particular reach?

Response:

The upper reach is from the river source to Yichang station. The middle reach extend from Yichang station to Hukou station, and down-river from Hukou station to Datong station is defined as the lower reach of the river. No larger tributaries join the lower reaches, and downstream of Datong station is tidally influenced. Therefore, the sediment load of Yichang station is regarded as the quantity of sediment coming from upstream; and the Datong station is the last gauging station of the Changjiang basin, and its water and sediment discharge records are generally used to represent the terrestrial flux from the Changjiang to the East China Sea.

Line 23 – Again, the authors should identify how they expect the grain size and composition to change with decreases in sediment load. What are their hypotheses?

Response:

Revised. 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.

Section 2 – Regional Setting: This could be a good section to explain the differences in sediment in each region. I also think that this detailed description of the geography could be cut down with a better map in Figure 1.

Response:

Revised.

Page 9118

Lines 1-16: Again, I am not sure why the authors describe the rock types and mineralogy when this is not the data that they analyzed. I do not understand how they trace the origins of the sediment with just grain size based on their description of methods.

Response:

Deleted.

Line 23: How often were they sampled? Whole paragraph – It is hard to understand where the hydrological stations are and their names. The names should be intuitive to the reader – maybe based on the location?

Response:

Supplemented. Each hydrological station is named according its location by Chinese authorities, in addition, every hydrological station is shown in the revised Fi.1a. See the response 4.

Section 3.2: I could not tell how the authors analyzed grain size data. This is essential information and should be included here.

Response:

Supplemented. See the response 4.

Page 9120

Line 19 – Authors did not detail how they calculated cumulative storage capacity. The description should be in the methods.

Response:

Revised. In fact, the cumulative reservoir storage capacity can also be named as the total reservoir storage capacity. 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.

Page 9122

Line 14- 19 - This text should be in the discussion. Overall, the results section really needs some cleaning up. It lacks narrative and much of the results described in text could be concisely presented in a graph or table.

Response:

Revised. The section of result and discussions was thoroughly re-organized and re-written, according to reviewer's suggestion. The following revision has been made in section of results of the revised manuscript: firstly, we compare the changes of the total RSCI with that of the sediment load of tributaries and the whole Changjiang catchment, the results indicate that the stepwise decrease of sediment load is highly related to the significant increase of the total RSCI, reflecting the impact dams have on sediment load; secondly, derived on the basis of the M-K method, of sediment load of the seven tributaries, the spatial-temporal sediment load variations within the catchment are acquired; thirdly, based on the M-K trends of sediment load variation at Datong station, four stepwise reduction stage periods of the sediment load discharging into the sea of the Changjiang were divided, and the factors leading to the sediment load into the sea between adjacent time periods gradually decreased were also analyzed; lastly, the variations in the grain size of the sediment entering the sea during different periods were explored.

Page 9123

Line 6 – This is the first time the authors have talked about the analysis of grain size. The methods need to go in the methods section for this analysis. Methods also need to detail how many and which stations have grain size data.

Response:

Supplemented. See the response 4.

Page 9124

Lines 5- 8: “No clear variations” – This is a very broad statement and needs more clear cut support from data.

Page 9125

Line1: Methods for determining channel erosion should go in the methods section.

Response:

Revised.

Line 17: How did the authors determine the percentage of contribution of those rivers? How did they trace these numbers? It was not clear to me whether or how the authors account for erosion and deposition along the main stem before it goes out to sea. This was not detailed in the methods.

Response:

Revised and supplemented.

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

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

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:

$$\frac{S_{Jinsha}}{S_{output}} + \frac{S_{Min}}{S_{output}} + \frac{S_{Jialing}}{S_{output}} + \frac{S_{Wu}}{S_{output}} + \frac{S_{Han}}{S_{output}} + \frac{S_{Poyang}}{S_{output}} - \frac{\Delta S}{S_{output}} = 1 \quad (2)$$

Line 4 – 11: I do not understand how they traced sediment back to particular rivers. First, what methods were used for assessing sediment composition? Second, they have not traced the sediment composition back to particular rivers (because they are only using two stations for grain size analysis), so how did they come to the conclusion that certain rivers were driving the change in sediment composition. Methods should reflect results reported and discussion.

Response:

Revised. 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:

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

Line 13: Citations - Thiry 2000 – Shows that it is difficult to trace origin and climate based on clay materials; Garzanti and Ando 2007 – use heavy mineral concentration index to determine source environment. Neither of these studies use similar methods to those used, or at least described, in this manuscript.

Response:

Deleted.

Line 16: The authors should consider taking source samples from each of the rivers to analyze grain size and sediment composition. This could lead to better tracing results.

Actually, all the data we used, concerning with the grain size and sediment composition, is acquired *in situ* sampling. In the revised manuscript, the source of these data is introduced. See response 4.

Page 9127

Line 7: The manuscript states here that all of the sediment is derived from a homologous source. How do the authors trace it then? And what are "mineralogy characteristics"? These assertions seem inconsistent. Again, the methods should reflect all of the results reported in in the subsequent sections.

Response:

Revised. The method calculating the sediment contribution proportion of different tributaries to the sediment load entering the sea of the Changjiang, is supplemented in the revised manuscript (see response Page 9125 Line 17). In addition, according to the reviewer's suggestion, the content of mineralogy characteristics was deleted in the revised manuscript.

Line 14: In is unclear how the composition of the sediment at Dongting Lake was determined. This information should be in the methods section

Supplemented in the section of regional setting. Dongting Lake is the second largest freshwater lake in China, and joins the main Changjiang River from the south. Part of the main river flow enters Dongting Lake via five different routes. Four tributaries enter Lake Dongting from the south and southwest, and water from Dongting Lake flows into the Changjiang main river channel at Chenglingji station. Therefore, before 2003, Dongting Lake does not directly supply sediment to the Changjiang main river, and huge quantity of sediment originating from upstream Changjiang deposited in the Dongting Lake. After 2003, however, the Dongting Lake suffered from weak erosion, which is beneficial to slowing down the atrophy of Dongting Lake area , and this part of eroded sediment is included in the ΔS (the quantity of deposited (+) / erosive (-) sediment of the Changjiang main stream and Dongting Lake) (see the equation of response Page 9125 Line 17).

The sediment balance of Dongting Lake is as followed: $S_{\text{input of Changjiang}}=S_{\text{flowing from Dongting Lake}} + \Delta S$

Page 9128

Line 3: “Briefly” does not make sense at the beginning of this sentence.

Response:

Deleted.

Line 10: How did the authors come to this conclusion: “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?” - The end-members or phases were not discussed in the methods of the paper. The methods and results do not support this conclusion.

Response:

According to reviewer’s suggestion, the topic of the revised manuscript is mainly concentrated on the variation in sediment load and grain size resulted by human activities, other irrelevant content was deleted.

Line 14: There should be more detail about how change in grain size will affect these areas.

Response:

Revised. The section of Discussion was re-written.

Line 23: I would change to “and deserve further study”

Response:

Revised.

Conclusions: I think that the conclusions are a good outline for what this paper needs to look like. They concisely sum up your results and discussion and highlight the main points. I did not come to the same conclusions when I read the paper myself and was generally confused about the analysis. Bullet 4 in conclusions: Where in the paper did they look at the depositional area or estuarine-coastal deposits? This bullet does not reflect the text of the paper.

Response:

Revised.

Tables and Figures:

Table 1 – The information presented here is if it will be used to test for changes in the sediment, but the paper did not address this.

Response:

Deleted.

Table 2 – This following need to be addressed in the methods: how the quantities were measured and analyzed for each station, how frequently samples were taken, and how were annual numbers determined.

Response:

Supplemented in the method (see response 4)

Figure 1 – The map is hard to read with the font and the flowlines. This is a crucial part of the paper because they reference the different names of the reaches throughout the paper. The map needs to be clearly labelled so the reader can understand what areas are discussed.

Response:

Revised. See the Figure 1 of the revised manuscript of the supplementary.

Figure 2 – This figure is a really good illustration of what I think the main story should be - Understanding the sediment load changes through time. The reservoir storage capacity index calculations need to be addressed in the methods.

Response:

Revised.

Figure 5: How did they choose the time periods for breaking up the data? Was it random or based on some sort of analysis? These details need to go in methods.

Response:

Supplemented. 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.

Figure 6: What data did they use for this distribution? How often was it taken? Make y-axis the labels and scale the same across all of the graphs.

Response:

The data source is introduced in the section of method. Some revision has been made in this figure.

Figure 7: This figure is a bit confusing. Do the different colors signify the different tributaries? What is the label for the x-axis of the graphs (what do the numbers stand for)? What is y-axis label on the graphs (what do they mean by sediment load variations)?

Response:

This figure was replaced by Tab.2.

Figure 8: Hard to determine if there really is a relationship from four points. Is there yearly data for this graph (instead of the time periods used)? How did they come up with these time periods? Are the randomly selected? How did they calculate the data from the pie charts? Again, the methods do not reflect the results: I am confused about how they came up with the percentages from each river.

Response:

Deleted.

List of changes made in the manuscript

1. Title

- ✓ Revised as “Variations in quantity, composition and grain size of Changjiang sediment discharging into the sea in response to human activities”

2. Introduction

- ✓ Revised according to referee’s comments and suggestions.

3. Regional setting

- ✓ The content concerning with the impact of changes in vegetation type and cover on sediment load variation is supplemented.
- ✓ The figure 1 was re-drawn. In the revised Fig. 1, some important reservoir sites (Fig. 1a), and all the reservoirs (Fig. 1b) we counted are shown.

4. Material and method

- ✓ We supplement the source and reliability of the data in the revised manuscript.
- ✓ The cumulative reservoir storage capacity is defined.

5. Results

- ✓ This section was re-organized and rewritten. firstly, according to the M-K trends of sediment load, the time nodes, i.e. the beginning time of sediment load decreasing, and the statistical sediment load decreasing trends occurring qualitative change, are confirmed; subsequently, 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; thirdly, variations in quantity, composition and grain size of Changjiang sediment discharging into the sea during these four period in response to human activities are discussed.
- ✓ A new figure (Figure 3 Cumulative water discharge–sediment load relations of the seven tributaries of the Changjiang catchment) is used to explain the impact dams have on sediment load.
- ✓ More information is displayed in the revised Figure 2, 4 and 5.
- ✓ A new table (Table 1 The mean value of sediment load of the Changjiang main river during different period) is used to indicate the sediment load variation of different hydrological stations.

6. Discussion

- ✓ In the revised section of discussions, the content irrelevant to the sediment load, composition and grain size were deleted. We mainly systematically discussed the variations in sediment load and different sediment fraction originating from tributaries within the Changjiang catchment during different historical periods.
- ✓ A new table (Table 3) is used to indicate annual quantities of clay, silt, and sand at the Yichang and Datong stations during different periods.

Marked-up manuscript

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

批注 [微软用户1]: Revised according to reviewer's suggestion.

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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

批注 [微软用户2]: Revised according to reviewer's suggestion.

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 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 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

批注 [微软用户3]: Supplemented according to reviewer’s suggestion.

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.

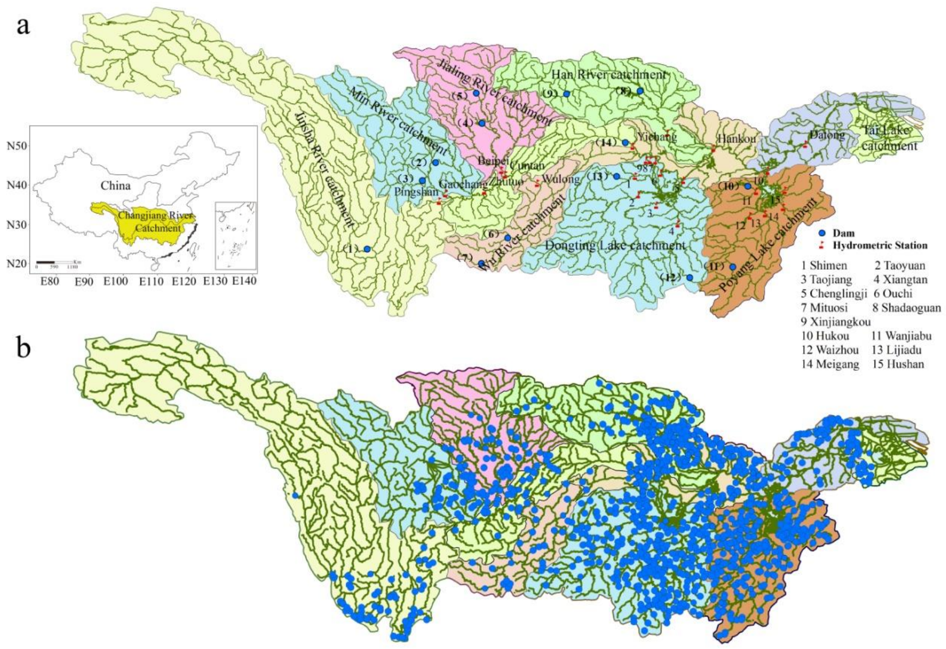

Figure 1. (a) Sketch of the Changjiang catchment and location of the hydrologic stations for the Changjiang catchment (the numeric symbols in the figure denote some important reservoir sites, including: (1) Er'tan; (2) Heilongtan; (3) Tongjiezi; (4) Shengzhong; (5) Baozhushi; (6) Wujiangdu; (7) Puding; (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.

批注 [微软用户4]: The figure 1 was re-drawn. In the revised Fig. 1, some important reservoir sites (Fig. 1a), and all the reservoirs (Fig. 1b) we counted are shown.

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/).

批注 [微软用户5]: We supplement the source and reliability of the data in the revised manuscript.

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: $X_t = (x_1, x_2, x_3 ....x_n)$, 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

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

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

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.

批注 [微软用户6]: This section were re-organized and rewritten. firstly, according to the M-K trends of sediment load, the time nodes, i.e. the beginning time of sediment load decreasing, and the statistical sediment load decreasing trends occurring qualitative change, are confirmed; subsequently, 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; thirdly, variations in quantity, composition and grain size of Changjiang sediment discharging into the sea during these four period in response to human activities are discussed.

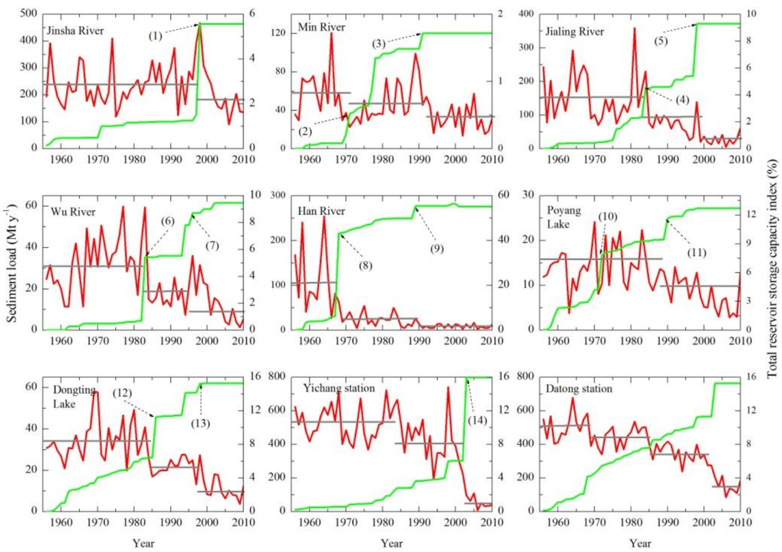

Figure 2. Relationship between the reduction in sediment load and the total reservoir storage capacity index in the tributaries and the main stream. Numeric symbols represent reservoirs listed in Figure 1a.

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.

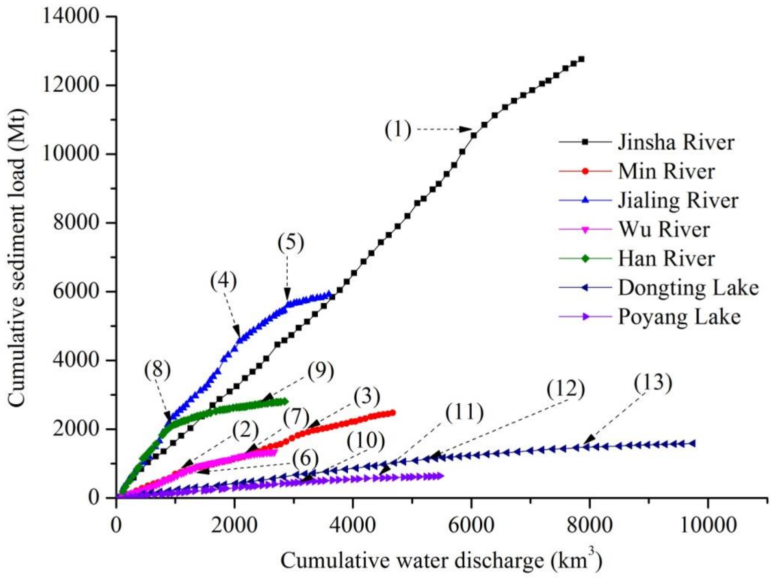

Figure 3. Cumulative water discharge–sediment load relations of the seven tributaries of the Changjiang catchment. Numeric symbols representing the reservoirs are the same as those in Figure 1a.

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.

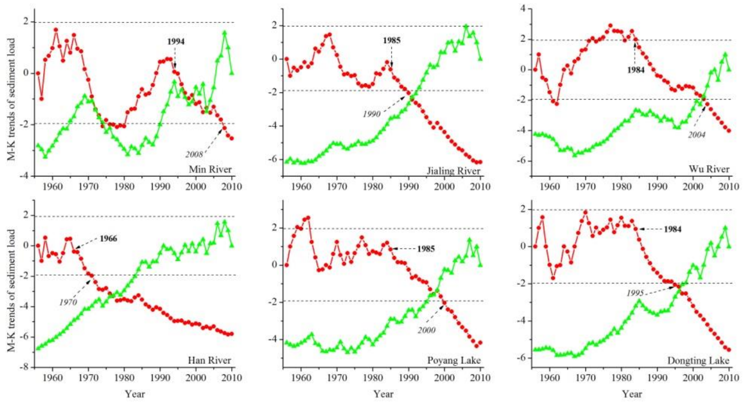

Figure 4. M-K trends of the sediment load for the Jinsha, Min, Jialing, Wu, and Han Rivers and the Poyang and Dongting Lake system. The symbol ● and ▲ denotes C_1 and C_2, respectively. The bold is the beginning time of sediment load decreasing; and the italics is the time when the M-K trends of the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

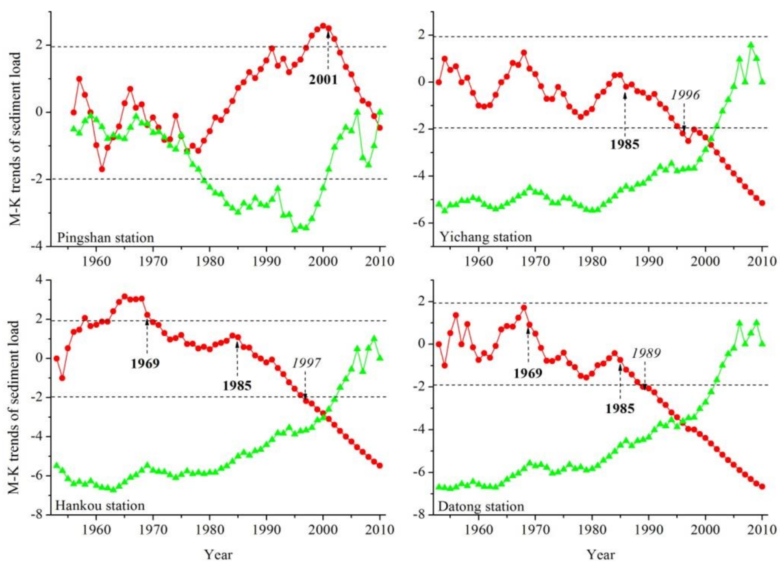

Figure 5. M-K trends of the sediment load for different gauging stations of the Changjiang main river. The symbol ● and ▲ denotes C_1 and C_2, respectively. The bold is the beginning time of sediment load decreasing;

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).

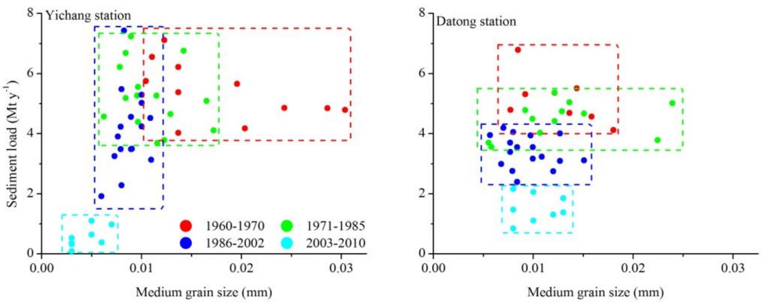

Figure 6. Relationship between the medium grain size of suspended sediments and the sediment load during different periods at the Yichang and Datong stations. Data are not available for the Datong station in 1968-1970, 1972-1973, and 1975.

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.

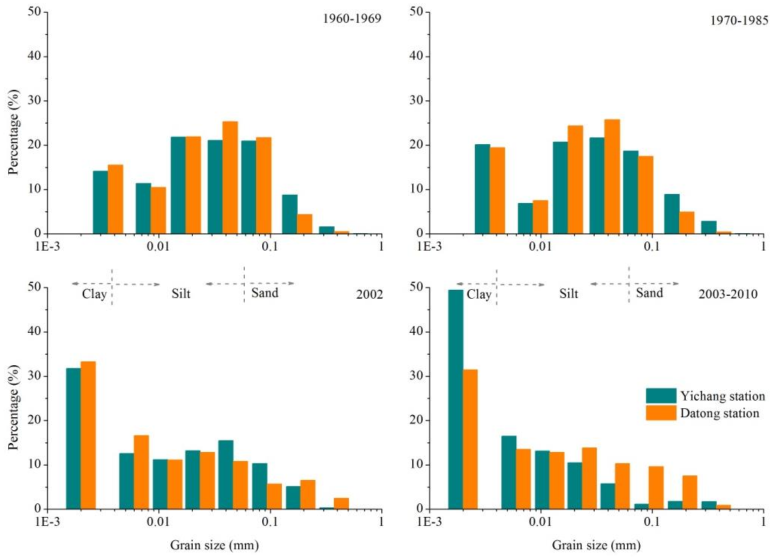

Figure 7. Distribution of the suspended sediment grain size of the Yichang and Datong stations in 1960-1969, 1970-1985, 2002, and 2003-2010.

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:

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

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

批注 [微软用户7]: The content irrelevant to the sediment load, composition and grain size were deleted. We mainly systematically discussed the variations in sediment load and different sediment fraction originating from tributaries within the Changjiang catchment during different historical periods.

sediment load entering the sea of the Changjiang can be expressed as:

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

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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