Reconstruction of sediment flux from the Changjiang (Yangtze River) to the sea since the 1860s

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Summary The Changjiang (Yangtze River) has been effectively gauged since the 1950s and demonstrates the transformation of a river system due to intensified human activities in its drainage basin over the past 50 yr. However, the 50-yr measurements of water and sediment are inadequate to show the long-term trend of sediment flux from the river to the sea or to capture the transition from natural to human dominance over the sediment flux. In this study we used the existing water discharge and sediment load records (1950s–2005) at the Hankou gauging station, together with water discharge recorded since 1865 at the same station, to reconstruct the changes of sediment flux to the sea since the 1860s. We established rating curves between stream discharge and suspended sediment concentration from the recent 50-yr data sets, which show that human disturbances have had a substantial impact on rating parameters. The commissioning of dams and undertaking of soil-conservation works have decreased sediment supply, leading to a decrease in the rating coefficient a of the rating curve equation \( C_s = aQ^b \). The decreases in suspended sediment concentration have increased the erosive power of the river, and hence increased the rating exponent b. In particular, the commissioning of the Three Gorges Reservoir in 2003 resulted in a further increase of b, and channel scour in the middle and lower reaches has increased sediment flux to the sea to a level higher than sediment supply from the upper reaches. Our results suggest that the rating curves derived from 1954 to 1968 data are appropriate for estimating sediment loads for the period from 1865 to 1953, since both were periods of minimal human disturbance. This approach provides a time series of...
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Introduction

The Changjiang (Yangtze River) is the largest river in China and the main source of terrigenous sediment delivered to the continental shelf of the East China Sea. Before human activities dominated the Changjiang, it carried sediment loads of ~480 million tons per year (Mt/yr) to the sea (Milliman and Meade, 1983; Milliman and Syvitski, 1992; Wang et al., 1997; Yang et al., 2006). The Changjiang, together with the Huanghe (Yellow River), is a major link between the world’s largest continent (Asia) and its largest ocean (the Pacific), and plays a critical role in delivering both particulate and dissolved terrestrial material from the Chinese mainland to the western Pacific Ocean (e.g., DeMaster et al., 1985; Milliman et al., 1985; Liu et al., 2004, 2006; Wang et al., 2007). Estimates from numerous boreholes and seismic profiles suggest that during the middle Holocene the Changjiang distributed 1,700,000 Mt of sediment to its huge delta plain and proximal subaqueous delta on the inner shelf of the East China Sea—on average of approximately 240 Mt/yr (Saito et al., 2001; Liu et al., 2006, 2007). Over the past several decades there has been growing interest in the Changjiang sediment flux to the sea (e.g., Chen et al., 2001; Shen, 2001; Yang et al., 2002, 2006). The reasons for this are numerous and diverse, and include interest in issues such as delta morphology, estuarine processes, and mud deposits on the continental shelf of the East China Sea, and the implications of sediment flux for engineering projects. The high water and sediment discharges of the Changjiang also account for a considerable amount of nutrients, particularly carbon, from the river basin to the coastal ocean (Martin and Meybeck, 1979; Ludwig et al., 1996; Smith et al., 2001). The materials delivered from this river play an important role in biogeochemical cycles in the East China Sea. Consequently, effective studies of the Changjiang sediment flux to the sea have been beyond the scope of individual disciplines such as marine sedimentology, hydrology, or marine geochemistry.

Many recent publications have documented the variations of sediment flux from the Changjiang to the East China Sea over the latter half of the twentieth century on the basis of continuous records at Datong gauging station since 1950 (e.g., Chen et al., 2001; Yang et al., 2002, 2006; Xu et al., 2006). Together, these studies present a detailed view of the rapid decrease of Changjiang sediment flux as a result of extensive human activities (e.g., dam construction, soil-conservation works), and provide excellent case studies on the transformation of world river systems by human activities over the past 50 yr (e.g., Syvitski, 2003; Meybeck and Vörösmarty, 2005; Nilsson et al., 2005; Syvitski et al., 2005). However, longer time series of sediment flux data, such as centennial-scale data sets, is unavailable but would be beneficial to geoscientists, since they would (1) illustrate the long-term variations and trends of Changjiang sediment flux to the East China Sea, and show the transition to the presently human-dominated period (1950–present); and (2) provide critically important data for the study of environmental changes since the Industrial Revolution. Furthermore, because the delivery of pollutants to the sea is mostly associated with sediment transport by rivers (Huh and Chen, 1999), a longer-term data set would allow more definitive assessment of basin-wide pollutants and contaminants released by human activities and delivered from rivers to the sea. Fortunately, there is a long time series of monthly water discharge records (since 1865) at Hankou gauging station in the middle reaches of the Changjiang (Fig. 1); however, the sediment load was not monitored there until the 1950s. Despite the absence of sediment load records, water discharge data from Hankou station are valuable and essential, not only for the estimation of long-term water discharge to the sea (e.g., Yang et al., 2005) but also for the reconstruction of time series of annual sediment flux from the Changjiang to the sea over the past century and a half.

Due to the absence of continuous measurements of suspended sediment concentration for rivers, hydrologists have made considerable efforts on the rating curves that can estimate or predict the suspended sediment concentration from the stream flow records (e.g., Campbell and Bauder, 1940; Gregory and Walling, 1973; Walling, 1977; Syvitski et al., 1987; Syvitski and Alcott, 1995; Phillips et al., 1999; Asselman, 2000). The rating curve generally takes the form of a power regression that relates suspended sediment concentration (or load) to stream discharge:

\[ C_s = aQ^b \]  

or, alternatively, a linearized equation based on natural logarithm transformation:

\[ \ln C_s = \ln a + b \ln Q \]
where $C_s$ is the suspended sediment concentration (kg/m$^3$), $Q$ is the stream discharge (m$^3$/s), and $a$ and $b$ are the rating coefficient and rating exponent, respectively. Since the suspended sediment of a river is essentially a non-capacity load (Walling and Moorehead, 1989), the rating curves usually demonstrate considerable scatter and consequently underestimate or overestimate the sediment concentrations (Horowitz, 2003). The errors are primarily ascribed to the fact that the suspended sediment delivery is impacted not only by the hydraulic properties of stream flow, but also by the sediment supply from the catchment and intensity and spatial distribution of rainfall. Despite these potential deficits, the rating curves, however, present a simple way that allows empirical conversion of stream discharge hydrographs into sediment load estimates, provided that the time series of stream discharge are known (Syvitski and Alcott, 1995). The rating curves have been widely used for a variety of scientific and engineering purposes, such as for prediction of the life span of a dam on a river, or for estimation of the sediment load of an ungauged river (Syvitski et al., 2000). However, it is important to note that the rating parameters can vary greatly both geographically and over time.

The extensive records since the 1950s from major gauging stations on the Changjiang provide a basis for detailed analysis of stream flow and suspended sediment load. For example, rating curves established from existing records can be used to quantitatively estimate sediment deficits during catastrophic flooding events (Xu et al., 2005). Yang et al. (2007) used data from the 1950s to the 1980s to calculate rating parameters and discussed their implications for hydrological processes and their relationship to the East Asian monsoon. However, their time-limited data set (1950s–1980s) made it difficult to reach a convincing conclusion on the relationships between channel morphology, hydrological processes, and the East Asian monsoon. Therefore, in this study we reconstructed the annual sediment load delivered from the Changjiang to the sea since 1865 by using the historical monthly stream-flow data from the Hankou station. Our first step in this approach was to approximate the rating parameters for the long-term estimation by using the records of stream discharges and suspended sediment concentrations at Hankou station from 1954 to 2005; we then used the derived rating parameters to estimate the annual sediment load during the period from 1865 to 1953; finally, we combined these two data sets to reconstruct the time series of sediment load for the period from 1865 to 2005, thus determining an estimated time series of sediment flux from the Changjiang to the sea over the past 140 yr. We believe that this estimate will provide an important centennial-scale reference for investigations into the evolution of the Changjiang estuary and deltaic depositional system, and also for studies of sedimentary processes on the inner shelf of the East China Sea.

Regional setting

The Changjiang rises on the Qinghai–Tibetan Plateau at an elevation of 6600 m and flows eastward into the eastern China for a total length of 6300 km and a drainage area of $1.94 \times 10^6$ km$^2$ before debouching into the East China Sea (Liu et al., 2007). It is divided into three segments: (1) the upper reaches extend 4500 km from the river source to Yichang, flowing through a mountainous region where a considerable number of tributaries join the main stream; (2) the middle reaches flow 950 km through the flat Jingjiang fluvial plain with very gentle slope from Yichang to

![Figure 1](image-url)
Hukou; and (3) the lower reaches flow from Hukou to the river mouth through a tidally influenced segment downstream from Datong gauging station (Fig. 1).

The annual water discharge from the upper reaches recorded at Yichang gauging station is approximately 463 km³/yr, and the annual sediment load amounts to 470 Mt/yr, which constitutes the main source of sediment delivered to the middle and lower reaches (Fig. 2a). Several major tributaries, including the Jinshajiang, Jialingjiang, Minjiang, and Wujiang contribute ~86% of the sediment load at Yichang station (Fig. 1, Yang et al., 2006). In the middle reaches, the river meanders across the almost flat Jingjiang fluvial plain, forming several large lowland lakes, including Dongting Lake and Poyang Lake. In addition, a major tributary, the Hanjiang, joins the Changjiang at Hankou station (Fig. 1). The Hanjiang annually contributed ~73 Mt/yr of sediment load to the Changjiang before construction of the Danjiangkou Reservoir in 1968 (Yang et al., 2006; Fig. 1). The middle reaches, particularly over the Jingjiang fluvial plain, act as an important flood-diversion area, accounting for at least 100 Mt of sediment loss due to overbank deposition (Yang et al., 2006) during years of catastrophic flooding (e.g., 1954 and 1998). As a result, the annual sediment load at Hankou averages 383 Mt/yr, accounting for ~80% of the sediment input from the upper reaches, whereas the mean annual water discharge at Hankou increases to 711 km³/yr (Fig. 2a). A large proportion of the lower reaches between Datong station and the river mouth (~600 km in length) is influenced by tides of the East China Sea. The mean annual sediment load from the Changjiang to the sea, as recorded at Datong station, is ~413 Mt/yr, slightly higher than that at Hankou station, whereas the mean annual water discharge at Datong is approximately twice that coming from the upper reaches (records at Yichang station) (Fig. 2a). The sediment loads at the three major gauging stations along the main stream indicate that the Changjiang sediment is predominately derived from the upper reaches, where severe soil erosion and frequent landslides have a significant effect, but the water from the upper reaches accounts for only ~50% of that discharging into the East China Sea.

The Changjiang river basin experiences a subtropical monsoon climate with monsoons initiated in the southeastern Pacific Ocean and Indian Ocean, which is closely related to the spatial and temporal variability of precipitation in the river basin. The summer monsoon normally starts to influence the river basin in April and retreats in October, accounting for more than 50% of annual total rainfall. The rainy season, when water discharge is high, is typically from July to September, whereas the dry season, when water discharge is low, is from December to March (Fig. 2b–d). The annual precipitation increases eastwards geographically from 300 mm/yr in the upper reaches to more than 1000 mm/yr in the middle and lower reaches. In the upper reaches, the total water discharge from July to September accounts for ~50% of annual discharge, whereas discharge in the middle and lower reaches during the same period contributes only ~40% to annual discharge. This indicates that water discharge from the upper reaches is dominantly influenced by monsoonal conditions, whereas water discharge from the middle and lower reaches is not. The seasonal distributions of sediment load at the three gauging stations show a strong association with the patterns of water discharge, as characterized by the coincidence of high

![Figure 2](image-url)

*Figure 2* Water discharge and sediment load at three major gauging stations (locations shown in Fig. 1). (a) Whisker-box plots of annual water discharge and sediment load at Yichang, Hankou, and Datong gauging stations. Monthly water discharge and sediment load at (b) Yichang station (1950–2005), (c) Hankou station (1954–2005), and (d) Datong station (1951–2005).
sediment load and high water discharge during the rainy season (Fig. 2b–d).

Since 1950, human activities have led to a notable reduction of sediment flux from the Changjiang to the sea, whereas water discharge to the sea has remained almost unchanged (Yang et al., 2002, 2006). The commissioning of several major reservoirs and soil-conservation works in the upper reaches has resulted in distinct stepwise decreases in sediment load delivered to the sea (Yang et al., 2006). For example, construction of the Danjiangkou Reservoir in 1968 produced the first downward step at Datong station, where the mean annual sediment load from 1969 to 1985 accounted for only ~90% of the reference level (the average from 1950 to 1968); the second downward step in the mid-1980s is ascribed to the construction of numerous hydropower stations and soil-conservation works in the upper reaches, which led to a further decrease of ~20% from the reference level during the period from 1986 to 2002; and in 2003, the Three Gorges Dam began trapping sediment and storing water from the upper reaches, resulting in the third downward step, with the mean annual sediment load to the sea during the period from 2003 to 2005 decreasing to 189 Mt/yr, accounting for only 39% of the reference level. The stepwise decreases of sediment load during a period when water discharge remained unchanged illustrates a significant loss of sediment from the river and reflects the extensive human impacts on this large river system. Therefore, it is noteworthy that the drastic decrease of sediment load will have a definite impact on the use of the rating curve method to examine the relationship between water discharge and suspended sediment concentration.

Data and methodology

The monthly records of water discharge at Hankou gauging station from 1865 to 1953 and those of both monthly and annual water discharge and sediment load from 1954 to 2005 were supplied by the Changjiang Water Conservancy Commission (CWCC). Records of the monthly and annual water discharge and sediment load from Datong station came mostly from the CWCC, but partly from Bulletins of Chinese River Sediment IRTCES (2001–2005) and a recent publication of the Ministry of Water Resources of China (E.J., 2006). The monthly suspended sediment concentrations (Cs) are of discharge-weighted values that are derived as the monthly suspended sediment loads divided by the monthly water discharges. We chose to use the data from Hankou station for our analysis for three reasons: (1) Hankou station, located at the mouth of the Hanjiang, records the water discharge and sediment load delivered from the upper and middle reaches of the Changjiang (Fig. 1); (2) Hankou station provides the longest records of water discharge (1865–2005) as well as recent records of both water discharge and sediment load (1954–2005); and (3) the water discharge and sediment load records at Hankou station approximate those at Datong station, because there is little additional input of water or sediment in the lower reaches (Fig. 1). River sediment load was measured according to the Chinese national standard criteria. Water samples were taken from a consistent gauging section across the full water column, and all flow discharge records were taken at the same time of day; the daily, monthly, and annual suspended sediment load and water discharge were derived from these data (Yang et al., 2006).

We used the uninterrupted records of monthly water discharge and suspended sediment concentration from Hankou gauging station from the 1950s to the present to determine the rating parameters for reconstruction of sediment load from 1865 to 1953. Because of the close similarity of sediment loads recorded at Hankou and Datong gauging stations, our analysis of data from Hankou station provides, for the first time, a data set that represents the sediment load delivered by the Changjiang to the sea during the past century and a half.

Results

Rating parameters and their implications

Given stream flows (Q) are known, the suspended sediment loads (Qs) can be approximated from the rating curve equation:

\[ Q_s = C_sQ = aQ^{b+1} \]  

where \( Q_s \) is the estimated suspended sediment load (kg/s) that can be converted to monthly or annual load at different time scales. Clearly, the determination of rating parameters (a and b) is critical to the estimation of sediment loads. The rating parameters are an index of erosion severity in the river channel (Morgan, 1995; Asselman, 2000). The coefficient a primarily reflects the grain size of sediment yielded from the basin and represents the erodibility of soil, or an index of sediment supply from the source region. High values of a generally indicate high sediment supply, such as in areas characterized by intensively weathered materials that can easily be eroded and transported. Although the coefficient a largely varies for different sizes of basins, the variations of a with time for a given basin are expected to have implications of human disturbances on the hydrological process. The exponent b represents the erosive power of the river and the influence on the sediment supply from the entire catchment surface; large values of b indicate an increase in sediment transport capacity of river stream (Asselman, 2000). And the values of b can also be affected by the grain-size distribution of the material available for transport in the river basin (Walling and Moorehead, 1989). A number of factors affect the suspended sediment transport in a river, including long-term climate, short-term weather events and discharge type (Syvitski et al., 2000), and these factors have characteristic impacts on the rating parameters. For example, rating coefficient a for rivers in areas of arid climate is high (100–80,000) and rating exponent b is low (0.2–0.7). Conversely, for rivers in areas of temperate and humid climates, a ranges from 0.004 to 40 and b from 1.4 to 2.5 (Reid and Frostick, 1987; Syvitski et al., 2000). The values of \( \ln(a) \) and b are generally inversely correlated and reflect the soil erodibility and stream erosivity, respectively (Thomas, 1988; Asselman, 2000). In addition to the above natural factors, human activities within the river basin (e.g., dam construction, soil-conservation works) create significant disturbances to the relationship between stream discharge and suspended sediment load. The marked
At Hankou station, the stream flow and suspended sediment concentration data from 1954 to 2005 (data unavailable in 2000) exhibit an approximately linear natural log–transformed relationship with a coefficient of determination \( r^2 = 0.61 \) (Fig. 3a). The corresponding rating parameters are \( \ln(a) = -10.14 \) and \( b = 0.92 \), which are similar to those of Yang et al. (2007). However, the relationship shows a distinct variation with time (Fig. 3a). For example, the data for 1954–1968 lie on the upper part of the plot, except for three anomalous data points in July–September of 1954, when there was catastrophic flooding in the middle and lower Changjiang (Fig. 3a). The mean stream flow during this period was 22,143 m³/s with a mean suspended sediment concentration of 0.52 kg/m³. The corresponding rating parameters are \( \ln(a) = -9.6 \) and \( b = 0.89 \), respectively (Table 1). For the period 1969–1985, the data points move downward in response to the construction and commissioning of the Danjiangkou Reservoir on the Hanjiang tributary (Fig. 1, Yang et al., 2006). The suspended sediment concentration decreased to 88% of the previous level, and the rating coefficient decreased to \( \ln(a) = -10.69 \), whereas the rating exponent \( b \) increased slightly (Table 1). After 1985, the commissioning of numerous hydropower stations and soil-conservation works in the upper reaches caused a significant decrease in sediment load of the Changjiang (Yang et al., 2006), and the data points shift distinctly downward to the middle part of the scatter plot (Fig. 3a). From 1986 to 2002, the suspended sediment concentration and rating coefficient decreased continuously while the rating exponent increased gradually (Table 1). After commencement of filling of the Three Gorges Dam in June 2003, the mean suspended sediment concentration over the next 3 yr decreased to only 33% of the reference level, leading to a low rating coefficient of \( \ln(a) = -12.45 \) and high rating exponent of \( b = 1.05 \) (Table 1). Consequently, the data points for the period 2003–2005 move further downward to the lowest part of the plot (Fig. 3a). All of the above changes in recorded suspended sediment concentrations at Hankou station, as well as the changes in rating parameters, are the effect of human disturbances on the relationship between stream flow and suspended sediment concentration. The results from Yang et al. (2007) also illustrate such trends; however, no reasonable explanation was presented.

The rating parameters obtained from annual rating curves also illustrate high variability at different stages during the total period from 1955 to 2005 (Fig. 3b). Data from the catastrophic flood year of 1954 was excluded. During the period 1955–1968, the values of \( \ln(a) \) ranged from

![Figure 3](image)

**Figure 3** (a) Rating curves derived from water discharge and suspended sediment concentration (SSC) data from Hankou station between 1954 and 2005. Both seasonal transitions along the regression lines and shifts of data perpendicular to the regression lines as a result of human disturbances are clearly demonstrated. (b) Rating parameters obtained from intra-annual data over different time periods.
7.6 to −12.3, and the values of \( b \) varied from 0.67 to 1.18. During the period 1969–1985, \( \ln(a) \) ranged from −8.0 to −13.8, suggesting a decreasing trend from past times, while the values of \( b \) increased slightly within the range 0.72–1.3. This pattern of variation of rating parameters was maintained during the period 1986–2002, before filling of the Three Gorges Dam commenced, and the values of \( \ln(a) \) decreased significantly to be within the range from −9.2 to −15.7, while \( b \) increased correspondingly to 0.8−1.5. During the period 2003–2005, this trend was no longer clearly evident, possibly because there was insufficient data to capture the long-term variation (Fig. 3b). The decreases in the values of rating coefficient \( a \) imply that the sediment available from the source regions (e.g., the upper reaches and the sub-basin of Hanjiang tributary) was progressively reduced as a result of human disturbances (e.g., the Danjiangkou Reservoir, numerous dams in the upper reaches, and the Three Gorges Dam) (see Yang et al., 2006). A decrease in sediment load during a period when water discharge is constant clearly produces a decrease in suspended sediment concentration, which increases the erosive power of the river, and therefore increases the value of \( b \) (Table 1). The variations of rating parameters we observed suggest that the influence of human activities on hydrological processes is substantial (Fig. 3) and must be considered when sediment loads are estimated from rating curves.

We estimated monthly sediment loads at Hankou station from 1954 to 2005 (Fig. 4a) from the annual rating parameters. These estimates agree well with the measured seasonal and interannual variations of monthly sediment load over the past 56 yr, apart from some underestimation during flood seasons. Thus, we were able to reproduce the long-term decreasing trend of sediment loads at Hankou station as a result of human activities within the drainage basin from 1954 to 2005 (Fig. 4a).

We assumed that the rating curves derived from the 1954–1968 data would be the most appropriate curves for estimating the unknown sediment loads from 1865 to 1953, since the effect of human disturbances on rating curves during 1954–1968 was much less than that of subsequent years. However, to select the best-fit annual rating parameters for the period since 1865 was proved to be difficult, because the annual rating parameters from 1954 to 2005, showed distinct annual variability (Fig. 3b). In order to rationally determine rating parameters for estimating sediment loads from 1865 to 1953, we established rating curves based on consideration of differences in stream flow during the period from 1954 to 1968, when the effects of human disturbance were nearly negligible. We grouped the data in three categories: \( Q < 6000 \text{ m}^3/\text{s} \) (3 pairs of data), \( 6000 \text{ m}^3/\text{s} \leq Q \leq 44,000 \text{ m}^3/\text{s} \) (164 pairs of data), and \( Q > 44,000 \text{ m}^3/\text{s} \) (13 pairs of data). We further divided the second category into 30 subcategories, 23 of which were

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*Figure 4* (a) Estimated monthly sediment load at Hankou station compared with observed sediment load (1954–2005, monthly data unavailable in 2000). The estimates were derived from the annual rating curves shown in Fig. 3b; (b) Measured monthly sediment load at Hankou station (1954–1968) compared with estimates from rating curves based on statistical analysis of different levels of stream discharges.
between 6000 and 30,000 m³/s at intervals of \( \Delta Q = 1000 \) m³/s, and 7 between 30,000 and 44,000 m³/s at intervals of \( \Delta Q = 2000 \) m³/s. We calculated rating curves for each of these categories and subcategories of stream discharge, and then used the least-squares method to determine the rating parameters. Comparison of the measured sediment load from 1954 to 1968 and the estimates from these rating curves showed that this approach is effective (Fig. 4b). There are a few large discrepancies between the measured and estimated loads during the catastrophic floods of 1954 owing to a large flood-derived sediment deficit in the middle reaches (Xu et al., 2005; Yang et al., 2006). The mean differences between the measured and estimated sediment loads from 1955 to 1968 are \( \sim 20\% \) for flood seasons (July–September) and \( \sim 16\% \) for non-flood seasons. The estimates from the rating curves explain approximately 83% of the data variance within the 95% confidence limits, with a residual mean squared error of 14.8 (Fig. 5). The estimates agree with more than 80% of the observed sediment loads during the period 1954–1968, despite some scatter around the regression line. It is worthwhile to note that clear relationships are hard to obtain for some categories of limited data sets, which may be an additional cause for the differences between the measured and estimated sediment loads.

Since there are only 180 pairs of monthly data of stream discharge and suspended sediment concentration (1954–1968), it is quite difficult to definitely conclude that these rating parameters derived from limited data are suitable for estimating the unknown suspended sediment concentration over the period of 1865–1953. However, the monthly stream discharges for both periods of 1865–1953 and 1954–1968 demonstrate very similar mode (Fig. 6), suggesting that the stream discharge varying from 6000 m³/s to 40,000 m³/s covers approximately 88% and 92% of the data sets of 1865–1953 and 1954–1968, respectively. Therefore, the rating parameters derived from the categorizing levels of stream discharge appear to be valid to estimate the unknown suspended sediment concentrations at Hankou station for the period 1865–1953.

Figure 5  Estimated monthly sediment load at Hankou station (1954–1968) compared with recorded data. The comparison indicates that the estimates explain 83% of the data variance with 95% confidence.

Figure 6  Occurrences of monthly stream discharges for the periods of 1865–1953 and 1954–1968, illustrating a very similar mode.

Time series of sediment load at Hankou station since 1865

Using the rating curves derived from the categorized stream discharges in the period from 1954 to 1968, together with the monthly records of stream discharge at Hankou station (1865–1953), we estimated the monthly sediment loads at Hankou station from 1865 to 1953 (Fig. 7a). These estimates and the records from 1954 to 2005 illustrate the long-term variations of monthly sediment load at Hankou station at centennial scale (Fig. 7a). They suggest that before construction of the Danjiangkou Reservoir on the Hanjiang tributary in 1968 (Fig. 1), the monthly sediment loads at Hankou station were relatively stable for a period of more than 100 yr, when there was little human disturbance on the river hydrological processes. Since 1968, the sediment loads at Hankou station have been strongly affected by human activities. The human influences are indicated by distinct step-wise decreases in sediment load that correspond to major events with hydrological implications; for example, the commissioning of the Danjiangkou Reservoir in 1968, numerous dams and soil-conservation works in the upper reaches since the mid-1980s, and the recent (2003) commencement of operations at the Three Gorges Dam (Fig. 7a; Yang et al., 2006).

Comparisons of the annual time series of sediment load with annual water discharge at Hankou station from 1865 to 2005 (Fig. 7b) shows that they fluctuated synchronously during the 100 yr preceding 1965 and have diverged only since the early 1990s, when the effects of human activities became more influential (Fig. 7b). We estimated the 100-yr mean annual sediment load from 1865 to 1968 to be 455 Mt/yr. After the divergence of the trends of annual sediment load and water discharge, the mean annual sediment load decreased to 286 Mt/yr, which is only 63% of the level before the effects of human disturbance took hold (Fig. 7b). These variations of sediment load clearly reflect the transition from a river system mostly dominated by nature to one strongly affected by human activities.

Time series of sediment load delivered to the sea since 1865

Datong gauging station, the last station on the mainstream of Changjiang, is located at the upstream limit of the tidally
influenced river segment (Fig. 1). Water discharge and sediment load recorded at Datong station are representative of the discharge from the Changjiang to the sea, even though the station is approximately 600 km away from the river mouth. Downstream from Hankou station, there is a little sediment input from channel erosion; therefore, the sediment load at Datong is only slightly higher than that at Hankou station. For example, the mean annual sediment load at Hankou (1950–2005) was \( 391 \text{ Mt/yr} \), while that at Datong station was \( 417 \text{ Mt/yr} \). A significant relationship between the annual sediment loads at Hankou \((Q_{SH})\) and Datong \((Q_{SD})\) station is obtained as follows:

\[
Q_{SD} = 1.07 \times Q_{SH} (r^2 = 0.84, n = 52)
\]

This relationship (see Fig. 8) allowed us to estimate sediment load at Datong (which represents sediment flux from the Changjiang to the sea) from the data recorded at Hankou station. Thus, we established the centennial-scale time series of annual sediment flux from the Changjiang to the sea (1865–2005), including estimates derived from rating curves for 1865–1950 and from gauging data for 1951–2005 (Fig. 9a). According to our calculations, over the 100 yr prior to the completion of Danjiangkou Reservoir in 1968, the annual sediment load at Datong station was \( \sim 488 \text{ Mt/yr} \) in average, which is comparable to the estimate presented by Milliman and Syvitski (1992).

Syvitski and Morehead (1999) proposed an equation to estimate sediment load from maximum basin relief and basin area according to the balance of gravity-driven sediment yield and potential energy, such that

\[
Q_s = a \rho g^{1/2} H^{3/2} A^{1/2} = 2 \times 10^{-8} H^{3/2} A^{1/2}
\]

where \( a \) is a constant of proportionality; \( \rho \) is grain density, usually taken as 2650 kg/m\(^3\); \( g \) is gravitational acceleration (9.8 m/s\(^2\)); \( H \) is maximum basin relief (m), and \( A \) is basin area (m\(^2\)). Eq. (5) was developed from data of 230 rivers worldwide (Syvitski et al., 2000). The maximum relief of the Changjiang basin \((H)\) is 6600 m, and its area \((A)\) is \( 1.94 \times 10^6 \text{ km}^2 \) (Liu et al., 2007); these values in Eq. (5) give an annual sediment load of approximately 470 Mt/yr (equivalent to a sediment transport rate of 14,936 kg/s), which is close to the estimate of Milliman and Syvitski (1992) and the present study \((\sim 488 \text{ Mt/yr})\). The estimate from Eq. (5) is valid for the period with little human disturbances on hydrological processes, and is therefore comparable to our estimate using the rating curve method.

The marked decrease in sediment flux from the Changjiang to the sea over the past 56 yr is well documented, demonstrating the transformation of the Changjiang river system under intensive human impacts (e.g., Yang et al., 2002, 2006). The reconstruction of annual sediment flux from the Changjiang to the sea over the past 140 yr is of great significance because it provides useful data for studies of climatic and human impacts on the river system, geomorphologic evolution of the Changjiang estuary and mega-delta, and related biogeochemical cycles in the East China Sea.

### Discussion

**Shifting dominance over the Changjiang sediment flux to the sea: 1865 to the present**

Yang et al. (2005) discussed the link between water discharge from the Changjiang to the sea and basin-wide
Figure 8  Relationship between annual sediment load at Hankou and Datong stations demonstrating a linear relationship that explains approximately 84% of the data variance.

Figure 9  (a) Time series of annual sediment flux from the Changjiang to the sea (1865–2005) derived from annual sediment load at Hankou (Fig. 6b) and Eq. (4); (b) anomalies of Indian Monsoon Rainfall since 1870 (data available at http://www.iges.org/india/allindia.html). The anomalies are defined as annual deviations from the mean annual rainfall between 1871 and 1994 (853 mm); (c) Index of East Asian Summer Monsoon, from IPCC (2007b). Solid lines in (a), (b), and (c) are 5-yr running averages.
precipitation. Basin-wide precipitation is closely associated with global climate episodes such as El Niño Southern Oscillation (ENSO) events and related flood-drought cycles (Jiang et al., 2006; Zhang et al., 2007). Global climate episodes through teleconnections have affected river hydrological processes and sediment fluxes to the sea. For example, ENSO events are usually accompanied by lower regional precipitation in the Huanghe (Yellow River, China) river basin, and account for a ~50% decrease in water discharge to the sea and ~30% of the total decrease of sediment load over the past 56 yr (Wang et al., 2006, 2007). Weather conditions and soil erodibility are critical factors that influence both sediment yield and sediment flux to the sea. Most of the sediment delivered by the Changjiang is derived from the upper reaches, from the Jinshajiang and Jialingjiang tributaries in particular (Fig. 1; Yang et al., 2006). Therefore, precipitation in the upper reaches has an important influence on sediment yield, but is itself substantially affected by climate change.

During the past 140 yr, there has been a decreasing trend in maximum annual stream flow in the upper reaches of the Changjiang but an increasing trend in the middle and lower reaches (Zhang et al., 2007). This is because different monsoons dominate precipitation in these segments of the river. For example, the Indian monsoon is dominant in the upper reaches, whereas the East Asian monsoon is dominant in the middle and lower reaches (Zhang et al., 2005). These two climatic systems are spatially and temporally asynchronous, and have different effects on trends and changes of stream flow. The Indian monsoon influences sediment yield in the upper reaches where most of the Changjiang sediment load is derived, and it is therefore of primary importance to the Changjiang sediment flux. Comparison of the time series of annual sediment flux to the sea with variations in Indian monsoon rainfall from the late 1860s to the present suggests that the Indian monsoon has an important influence on the Changjiang sediment flux to the sea (Fig. 9). It appears that during the period of little human disturbance (1865–1950s), the Changjiang sediment flux to the sea was dominantly influenced by the Indian monsoon, whereas the influence of the East Asian summer monsoon is unclear (Fig. 9).

Rainfall during the Indian monsoon wet season, which runs from June to September, accounts for about 70% of annual rainfall in the upper reaches of the Changjiang. Links between monsoon-related events (e.g., rainfall over East Asia) weakened between 1890 and 1930 but strengthened during the period from 1930 to 1970 (Kripalani and Kulkarni, 2001). A strong inverse relationship between Indian monsoon rainfalls and El Niño events has been recognized in several studies (Kumar et al., 1999; Krishnamurthy and Goswami, 2000; Sarkar et al., 2004) and implies that before the period of significant human disturbances, annual sediment flux from the Changjiang to the sea was closely associated with global climate change (Fig. 9). The East Asian monsoon has the dominant influence on precipitation in the middle and lower reaches of the Changjiang but has little impact in the upper reaches (the source region of Changjiang sediment). In addition, the long-term changes of the East Asian monsoon are consistent with a tendency for a southward shift of the summer rain belt over eastern China (Zhai et al., 2005). Therefore, the monsoons were the dominant influence on sediment flux to the sea during the period from the 1860s to the 1950s.

Since the 1950s, human activities have become the dominant influence on sediment flux to the sea, leading to stepwise decreases that correspond to major hydrologic events in the recent history of the river basin (Fig. 9a; Yang et al., 2006). Thus, the dominant influence on sediment flux to the sea has shifted from that of monsoons from the 1860s to the 1950s, to human activities from the 1950s to the present. Although global warming has increased the frequencies of heavy rainfall and severe droughts since the 1950s (IPCC, 2007a), leading to higher peaks of monthly sediment loads (see Fig. 7a and compare the 1860s and 1980s), human activities have been of primary importance to the sediment flux from the Changjiang to the sea since the 1950s, particularly since the 1980s. At present, the mechanisms by which the monsoons affect sediment flux to the sea are far from being totally understood. It is clear that since 1865 monsoons have initially been the dominant influence on sediment flux from the Changjiang to the sea, and that there is a transition to a period dominated by humans, but the boundary is not clearly identified. We have used data from the period of 1954–1968 to determine rating parameters and then applied those parameters to estimate sediment loads between 1865 and 1953. The period 1954–1968 may have been influenced by human activities to some extent. If so, it would then have an influence on the rating curves and on the sediment loads estimated from them. Impacts of human activities will likely continue into the foreseeable future. Although future global warming is expected to increase the frequency of heavy rainfall and severe drought (IPCC, 2007a), the effects of human activities on the Changjiang sediment flux will be more direct and serious than those of global warming.

### Human impacts on the rating curves

Few studies on the use of rating curves have considered the effect of human disturbances on the relationship between stream discharge and suspended sediment concentration.
Reconstruction of sediment flux from the Changjiang (Yangtze River) to the sea since the 1860s

Over thousands of years, human activities have modified the landscape of the Changjiang river basin (e.g., extensive agricultural reclamations). And the ancient Dujiangyan Irrigation System, constructed in the Minjiang tributary 2000 yr ago but still working well now, essentially changed the input of water and sediment from the Minjiang to the mainstream of the Changjiang (Li and Xu, 2006). Meanwhile, the constructions of flood diversions in the middle and lower reaches also impacted the river geomorphological features. By far, the levees and embankments have been well developed in the middle and lower reaches to control the floods and prevent from breaching. However, the early human activities had been of minor importance to the Changjiang sediment flux to the sea compared to the present situation. Observations at gauging stations on the Changjiang over the past 56 yr indicate that human activities, such as the operation of dams and undertaking of soil-conservation works, have decreased the sediment supply from the source region, and therefore decreased coefficient $a$ of the rating curves (Figs. 3 and 10, Table 1). Conversely, rating coefficient $b$ would be expected to increase as a result of human activities such as extensive deforestation or agricultural reclamation. Exponent $b$ of the rating curves increases when suspended sediment concentrations in streams decrease as a result of sediment retention within reservoirs, and the downstream channel becomes subject to scour (Table 1, Fig. 10). If the recorded stream discharges and estimated sediment concentrations for the period from 1865 to 1953 are used to establish rating curves, the derived rating parameters are: $\ln(a) = -9.1$ and $b = 0.84$. The value of $a$ is higher than that calculated for 1955–1968, and $b$ is lower than that calculated for the same period; this indicates that human disturbances had negligible effect during the first 100 yr of the study period (Fig. 10, Table 1). The Three Gorges Dam is designed to trap $\sim 70\%$ of the sediment supplied from the upper reaches by the time of its planned completion in 2009 (Yang et al., 2006). This will cause further decrease in coefficient $a$ and increase in exponent $b$, because as more sediment is trapped within the Three Gorges Reservoir, the erosive power of the river will increase substantially in the middle and lower reaches (Fig. 10).

It is noteworthy that this higher value of $b$ due to human activities will increase the erosive power of stream discharge such that the river channel will be scoured. When $b$ increased to a value of 1.05 after commissioning of the Three Gorges Dam in June 2003, a level much higher than that for the period 1955–1968 (Fig. 10, Table 1), the river channel in the middle and lower reaches became subject to riverbed scour. Annual sediment loads at Yichang station prior to 2002 were higher than those at Datong station (except for 4 abnormal years, see Fig. 11). We estimated that the mean annual sediment load at Yichang station (1950–2002) was approximately 491 Mt/yr, much higher than that at Datong (~426 Mt/yr). This suggests that deposition was then dominant in the middle and lower reaches (Fig. 11). The values of $b$ have gradually increased in parallel with the decrease of sediment load at Datong. However, this situation was reversed after commissioning of the Three Gorges Dam. The mean annual sediment flux to the sea at Datong (~189 Mt/yr, 2003–2005) then became higher than the mean annual sediment supply from the upper reaches (~125 Mt/yr at Yichang station), which indicates that there has been severe scouring in the middle and lower reaches. This is corroborated by the continuous increase in the calculated value of $b$ and the implied increase in erosive power of the river (Fig. 11).

Conclusions

The Changjiang is the major source of terrestrial materials to the East China Sea and to the western Pacific Ocean. It has been effectively gauged since the 1950s; however, a long-term time series of sediment flux to the sea (centennial scale) is essentially needed for the studies of geomorphology of the estuary and delta, sedimentology of the continental shelf, and biogeochemistry in the marginal seas.
In this study, we reconstructed the centennial-scale time series of annual sediment flux from the Changjiang to the East China Sea since 1865 based on the records of water discharge at Hankou gauging station. We established rating curves from the monthly records of water discharge and suspended sediment concentration at Hankou station during the period 1954–2005. Our results show that human activities in the river basin have substantially affected the rating curves and their parameters. The commissioning of reservoirs (e.g., the Danjiangkou Reservoir in 1968 and the Three Gorges Reservoir in 2003) together with soil-conservation works undertaken in the upper reaches substantially reduced sediment supply to the middle and lower reaches. This caused a decrease in the value of rating coefficient $a$. A marked decrease in suspended sediment concentration increased the erosive power of the river, as indicated by an increase in rating exponent $b$. Consequently, the river channel has been scoured in the middle and lower reaches in recent years when the annual sediment flux to the sea became higher than the sediment supply from the upper reaches.

We used data recorded at Hankou station from 1954 to 1968 to establish rating curves that allow the estimation of sediment load for the period of 1865–1953 when sediment loads were not monitored. Our estimates for this period combined with data recorded from 1954 to 2005 constitute a long-term time series of sediment loads at Hankou station and a centennial-scale time series of annual sediment flux to the sea that is derived based on linear regression analysis of sediment loads between Hankou and Datong. We estimated that the mean annual sediment flux to the sea during the period from 1865 to 1968, when the influence of human activities was negligible, was $\sim 488 \text{ Mt}/\text{yr}$, a result comparable to the estimate of Milliman and Syvitski (1992) and to that from an equation proposed by Syvitski and Morehead (1999). The annual sediment flux from the Changjiang to the sea from 1865 to the present can be considered in two periods: a monsoon-dominated period (1865–1950s) and a human-impacted period (1950s–present), although the mechanism of monsoon domination has not been well understood yet. During the human-impacted period, the rating curves changed markedly, leading to significant morphological responses in the middle and lower reaches and delta system of the Changjiang.

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