Dam impacts on the Changjiang (Yangtze) River sediment discharge to the sea: The past 55 years and after the Three Gorges Dam

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[1] In 5 recent years (2000–2004), the Changjiang (Yangtze) River has discharged past Datong (600 km from the river mouth) an average of ~250 million tons (mt) of sediment per year, a decrease of more than 40% since the 1950s and 1960s, whereas water discharge at Datong has increased slightly. Water and sediment discharge data from the upper, middle, and lower reaches of the river suggest that the reduction of the Changjiang sediment load has occurred in two phases between 1950 and 2002: following the closure of the Danjiangkou Reservoir on the Hanjiang tributary in 1968 and following the installation of numerous dams and water-soil conservation works in the Jialingjijang catchment after 1985. As the Three Gorges Dam (TGD) started operating in 2003, the Changjiang entered a third phase of sediment reduction with annual sediment loads at Datong less than 200 mt/yr. Upon completion of the Three Gorges Dam (TGD) in 2009, the sediment load at Datong will decrease to ~210 mt/yr for the first 20 years, then will recover to ~230 mt/yr during 2030–2060, and will reach ~310 mt/yr during 2060–2110. From the sediment budget and sediment erosion data for the Changjiang subaqueous delta, it can be assumed that the delta will be eroded extensively during the first five decades after TGD operation and then will approach a balance during the next five decades as sediment discharging from TGD again increases.

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1. Introduction

[2] The Changjiang (Yangtze) River is Asia's longest (6300 km) river and the fifth largest in the world in terms of water discharge (920 km^3/yr) and historically fourth largest in sediment discharge, 480 million tons per year (mt/yr) [*Milliman and Syvitski*, 1992]. However, over the past five decades the river's sediment discharge has decreased steadily [*International Research and Training Center on Erosion and Sedimentation* (*IRTCES*), 2000, 2001, 2002, 2003], whereas water discharge at Datong has increased slightly. According to data from the Changjiang Water Resources Commission (CWRC), the mean annual sediment load recorded at the Datong hydrographic station, 600 km landward of the East China Sea, has been 320 mt/yr between 1986 and 2004, which is only 65% of the 490 mt/yr (average of 1951–1968). Moreover, sediment load past Datong in 2004 was only 147 mt (Q. X. Xu, personal communication, 2005), or 30% of the 1951–1968 average.

[3] This decline in Changjiang sediment discharge has garnered increased attention and concern. Its catchment (1.8×10^6 km^2) is home to about 400 million people, 6.6% of the world's population [*United Nations Department of Economic and Social Affairs*, 2001], and as the Shanghai metropolitan region lies on the Changjiang delta, the total catchment provides 42% of China's GDP [*Chen et al.*, 2001]. The river's flood and droughts affect not only the lives of the people living in the catchment but also the nutrient content and salinity of ecosystems along the East China Sea and Sea of Japan. Since the late 1980s China has become the world largest consumer of chemical fertilizers, and huge quantities are eroded and transported downstream from the cultivated lands within the Changjiang watershed, causing eutrophication of coastal waters [*Zhang et al.*, 1995]. Therefore the decreasing Changjiang sediment load can have both regional and global significance.

[4] The situation is complicated by construction of the Three Gorges Dam (TGD). Although the project will not be completed until 2009, the 175 m high dam [*Li*, 1997] began to retain water and sediment in June 2003 as the dam rose to water level of 135m. According to its design plan, the TGD will trap 70% of the sediment discharge from the upper reaches of the river at the first two decades after 2009; over its first 100 years, the reservoir behind the dam is expected to retain more than 44% of the river's sediment from the upper reaches [*Yang et al.*, 2002]. Since the upper reaches of the river discharge ~500 mt/yr of sediment (as measured at Yichang; see Figure 1), a loss of 70% could reduce the

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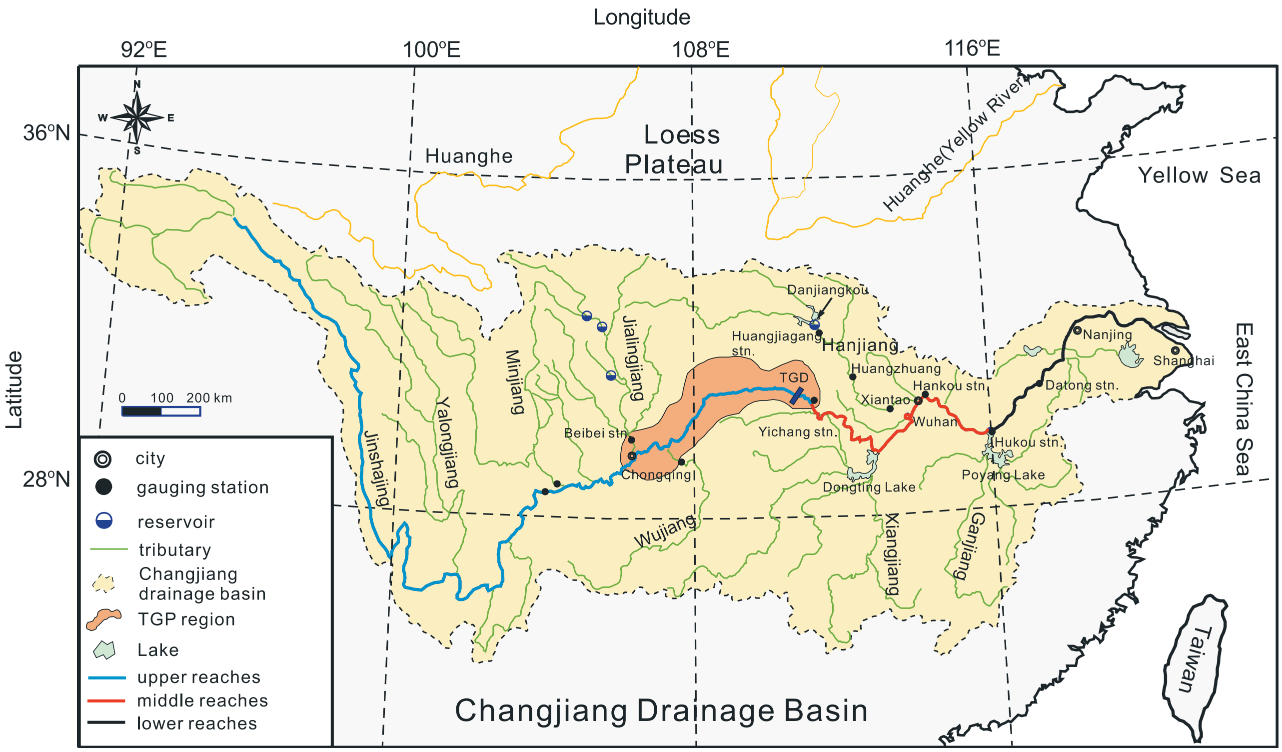

Figure 1. Map of the Changjiang (Yangtze) River: TGD, Three Gorges Dam; TGP, Three Gorges Project.

river's discharge to the East China Sea significantly. One possible consequence would be major coastal erosion to the Changjiang delta, the richest and most developed area in China. In addition, the South-to-North Water Transfer Project will remove ~5% of the Changjiang water, leading to ~3–5% sediment loss [*Yang et al.* 2002], which would finally impact the ecosystems of the Changjiang estuary and the adjacent sea [*Chen and Chen*, 2002].

[5] Previous studies, some of which are discussed in the following paragraphs, have concluded that the reduction of Changjiang sediment load has been the result of its 45,628 reservoirs (as of 1995), including 119 large ones [*Wen et al.*, 1999; *A. Xu*, 2000]. It was indicated that the retention of sediment by reservoirs in many impounded basins exceeds 90% [*Meybeck*, 2003]. The decrease of suspended solids due to the reservoir storage after damming has a stepwise character [*Meade and Parker*, 1985; *Meybeck and Vorosmarty*, 2005]. The Changjiang could be one of the best cases to illustrate how dams and reservoirs impact the river sediment flux to the oceans owing to large number of reservoirs constructed at different period during last 5 decades. Using water and sediment data from the major hydrological stations along the main stem and its main tributaries, we discuss the factors responsible for the declining sediment load. The impacts of the TGD on sediment discharge and delta erosion are then briefly considered.

2. Background

[6] In recent years many articles, particularly in the Chinese literature, have discussed variations in the Changjiang's water and sediment discharge, but most of them have dealt with the river's upper and middle reaches, which would affect directly the TGD project. Many of the papers dealing with downstream aspects, however, have been limited to data prior to 1990. On the basis of a data set of 250 stations in the river's upper reaches for the period up to 1988, *Higgitt and Lu* [2001] and *Lu and Higgitt* [2001] concluded that, despite evidence of increased sediment erosion within tributary drainage basins, the long-term sediment yield showed no increase because of the construction of numerous dams, a point also made by *J. Xu* [2000]. Using primarily historical data for main hydrologic stations up to 1980, for instance, *Chen et al.* [2001] found a decadal scale of decreasing sediment load in the upper and middle reaches of the river (Yichang and Hankou stations, respectively), caused by numerous dams in the upper drainage basin; but they concluded that sediment discharge at Datong was quite stable. *Shen* [2001], in contrast, showed that the annual Datong sediment load between 1951 and 2000 showed a distinct downward trend, perhaps the result of changing precipitation in the high sediment yield areas in the upper reaches of the drainage basin. The Changjiang Water Conservation Commission also showed a downward trend in sediment discharge at the upper, middle and lower reaches of the river (Yichang, Hankou and Datong, respectively), but offered no explanation as to its cause.

[7] Recently, *Yang et al.* [2002, 2003] described a decadal scale downward decrease in sediment load at the Yichang and Datong stations between the late 1960s and 2000, the result of the many dams in the catchment. Yang et al. calculated that dams on the upper reaches of the Changjiang basin captured 230 mt in 1990. The storage capacity is also seen by the Danjiangkou Reservoir, largest on the Hanjiang tributary, which alone has captured 50 mt of sediment since 1968. On the basis of the relationship between sediment

Table 1. Hydrological Settings of the Changjiang: Mainstream and Major Tributaries[a]

	Mainstream			Tributary				
				Upper				Middle/Lower
	Upper (Above Yichang)	Middle (Yichang-Hukou)	Lower (Hukou)	Jinshajiang	Minjiang	Jialingjiang	Wujing	Hanjing
Length, km	4,500	950	930	2,284	735	1,120	1,037	1,577
Basin area, km^2	1,000,000	680,000	120,000	344,000	133,000	160,000	87,920	159,000
Gauging station	Yichang	Hankou	Datong	Pinshan	Gaochang	Beibei	Wulong	Huangzhuang
Q, km^3/yr	440	710	910	150	90	65	50	50
Q_s, mt/yr	500	400	430	240	50	110	28	60

[a]Annual water discharge (Q) and sediment load (Q_s) are the averages between the 1950s and 2002 The figures for Huangzhuang are from *IRTCES* [2003].

reduction at Yichang and Datong, they calculated that the coastline Changjiang delta would be strongly eroded following completion of the TGD.

[8] However, a number of basic problems still remain unanswered.

[9] 1. It is difficult to calculate temporal and spatial variations of sediment discharge of the Changjiang, with its large number of tributaries, on the basis of data from only two gauging stations, Yichang and Datong.

[10] 2. Describing temporal variations of water discharge (Q) and sediment load (Q_s) on the basis of decadal time intervals may not adequately describe both shorter- and longer-term change.

[11] 3. Post-1980s data must be considered in evaluating long-term change.

[12] 4. Evaluating the effect of reservoirs on Q_s should be based on the contributions from the major tributaries, since, prior to the completion of the TGD in 2002, all Changjiang catchment dams save one (the Gezhouba low dam) were located on tributaries [*IRTCES*, 2001]. *Yang et al.* [2002], in contrast, considered only a single dam (Danjiangkou) on a single tributary (Hanjiang).

[13] 5. The effects of channel and floodplain deposition and scouring along the entire river path should be considered, particularly during large floods, such as in 1954 and 1998, when overbank flow has occurred.

[14] 6. Forecasting the effect of the TGD on Changjiang sediment discharge may not be valid unless the above factors are taken into account. All these problems, collectively, could result in misunderstanding the cause of sediment reduction and therefore promote errors in forecasting the impact of the TGD.

[15] In this paper we identify the key factors responsible for the change in Changjiang sediment discharge recorded by looking at hydrologic data from key gauging stations along the Changjiang and its main tributaries between 1950 and 2004. The data we used are from the CWRC and partly obtained from the River Sediment Bulletin of China [*IRTCES*, 2000, 2001, 2002, 2003] published by the Ministry of Hydrology of China.

3. Decreasing Changjiang Sediment Discharge From 1950 to 2004

3.1. Selecting Key Hydrologic Data and Stations to Describe Temporal and Spatial Variations in Changjiang Water and Sediment Discharge

[16] The Changjiang is generally considered in three sections. The upper reaches, from the river's source to Yichang, are more than 4500 km long; the middle reaches, from Yichang to Hukou, are 950 km long; and the lower reaches, from Hukou to the river mouth at about 930 km long (Figure 1 and Table 1). From this 6300-km long river we have chosen data from four gauging stations, Yichang, representing the upper reaches, Luoshan and Hankou, representing the middle reaches, and Datong, representing the lower reaches (Figure 2) to describe temporal and spatial changes along the river's course. Although the impact of dams can be demonstrated to a large extent from these four stations, we also use some data from several tributary stations. Data used in this paper were taken in large part from CWRC records, including data recently released in the River Sediment Bulletin of China [*IRTCES*, 2000, 2001, 2002, 2003].

[17] The measurement of the river sediment load was carried out according to the national standard criterion. At a

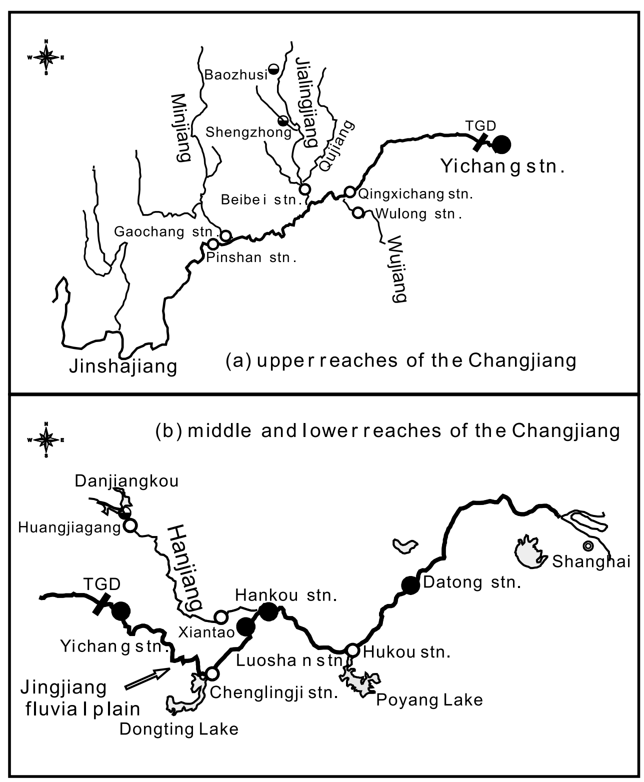

Figure 2. Location of key gauging stations and water reservoirs in the (a) upper and (b) middle and lower reaches of the Changjiang.

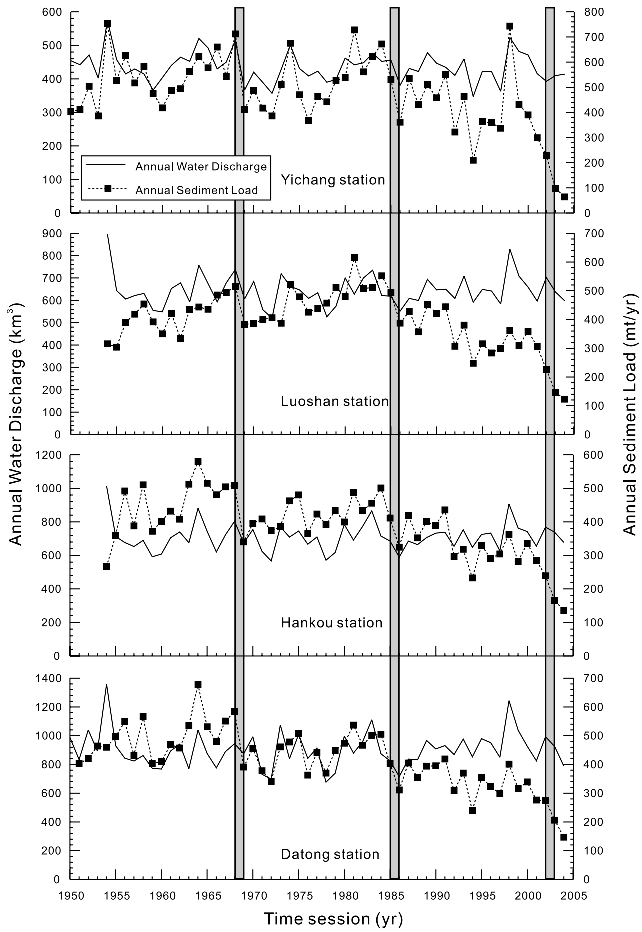

Figure 3. Annual water discharge and sediment loads at four key gauging stations, Yichang, Luoshan, Hankou, and Datong, 1950–2004. Initiations of the three phases of sediment reduction are designated by the vertical dashed lines.

fixed gauging section the water samples were taken across the water column as well as the flow discharge was recorded at certain time, from which the daily, monthly and annual suspended sediment loads passing the gauging section were derived.

[18] The mean water discharge (440 km^3/yr) and sediment load (500 mt/yr) recorded at Yichang from 1950 to 2002 represents water and sediment derived from Tibet and the Sichuan basin (Table 1). These are the main sources of sediment reaching the middle and lower reaches of the river. Above Yichang the river flows through narrow gorges hemmed in by mountains and is fed by four major tributaries, for example, Jinshajiang, Minjiang, Jialingjiang and Wujiang, totally contributing more that 86% of the annual sediment load at Yichang (Table 1). Below Yichang the river meanders across the gentle Jingjiang fluvial plain (Figure 1), forming numerous lowland lakes, bypasses and swamps in which overbank sediments are deposited. Dongting Lake, the second largest lake in China, is linked to the Changjiang channel by three outlets (Figure 1) through which there is extensive water and sediment exchange. Of the total 167 mt/yr of sediment entering the lake, 132 mt is from the Changjiang, and the rest is from the lake's tributaries. The sediment returned to the Changjiang, as recorded at the Chenglingji gauge (Figure 2) is 43 mt/yr, meaning that ~124 mt/yr is deposited in the lake [*IRTCES*, 2001]. The deposited sediment, however, can be resuspended and transported back into the river channel to compensate for any river channel scouring in the middle and lower reaches beyond Luoshan [*Shi et al.*, 2002].

[19] Sediment records at Luoshan, which is located on the Changjiang below the Chenglingji station, are important because the measured sediment load (410 mt/yr) and water discharge (645 km^3/yr) between 1954 and 2002 represents practically all the sediment from the upper reaches that remains in the river after it passes the Jingjiang fluvial plain and Dongting Lake (Figure 2). The ability of the upper middle reaches to trap sediment was particularly obvious during the 1954 and 1998 floods, when the high annual sediment loads noted at Yichang station (750 and 740 mt/yr, respectively) were not seen at the downstream stations; in fact, sediment loads at Luoshan, Hankou and Datong were slightly lower than normal during those flooding years (Figure 3). As the flood wave tops the Changjiang banks, it drives water onto the Jingjiang floodplain and into Dongting Lake (Figure 4). The ability of this area to trap sediment is reflected by the estimated 290 and 340 mt difference between annual sediment loads at Yichang and Datong during 1954 and 1998, compared to an average difference of 68 mt during ordinary years.

[20] The sediment load of 400 mt/yr and water discharge of 710 km^3/yr (1954–2002) measured at Hankou, just downstream from the Hanjiang (Figure 1 and Table 1), largest tributary to the Changjiang, reflects additional input from the Hanjiang.

[21] Hukou station, located at the outlet of Poyang Lake, largest freshwater lake in China, is at the upstream end of the Changjiang's lower reaches (Figure 2). The annual contribution of 10 mt of sediment and 150 km^3 of water to the Changjiang from Poyang Lake (minus the 1 mt/yr contributed from the Changjiang to Poyang Lake) represents only ~2% of the annual sediment load recorded at Datong. Because of its relatively minor role in the Changjiang sediment discharge, we do not discuss it further in this paper.

[22] Finally, the sediment load of 430 mt/yr and water discharge of 910 km^3/yr measured at Datong between 1950 and 2002 represents the sediment carried from the Changjiang to the upper edge of the tidal wedge (Table 1). Although ~10% of Datong's sediment load is deposited in the river channel before it reaches the East China Sea [*Shen*, 2001], the Datong sediment and water records are generally used to represent the Changjiang's mass flux to the sea. Therefore the sediment fluxes recorded at Yichang, Luoshan and Hankou basically control the Changjiang's sediment discharge at Datong and therefore to the sea, and variations at any one of these stations will affect a similar response at Datong.

3.2. Decreased Changjiang Sediment Flux as Recorded at Datong Station

[23] Sediment discharge between 1950 and 2002, as measured at Datong, decreased in two distinct phases. The first phase of reduction began in 1969 and the second in 1986, each represented by a distinct drop in the first year followed by a steady decline thereafter (Figure 3). If we take

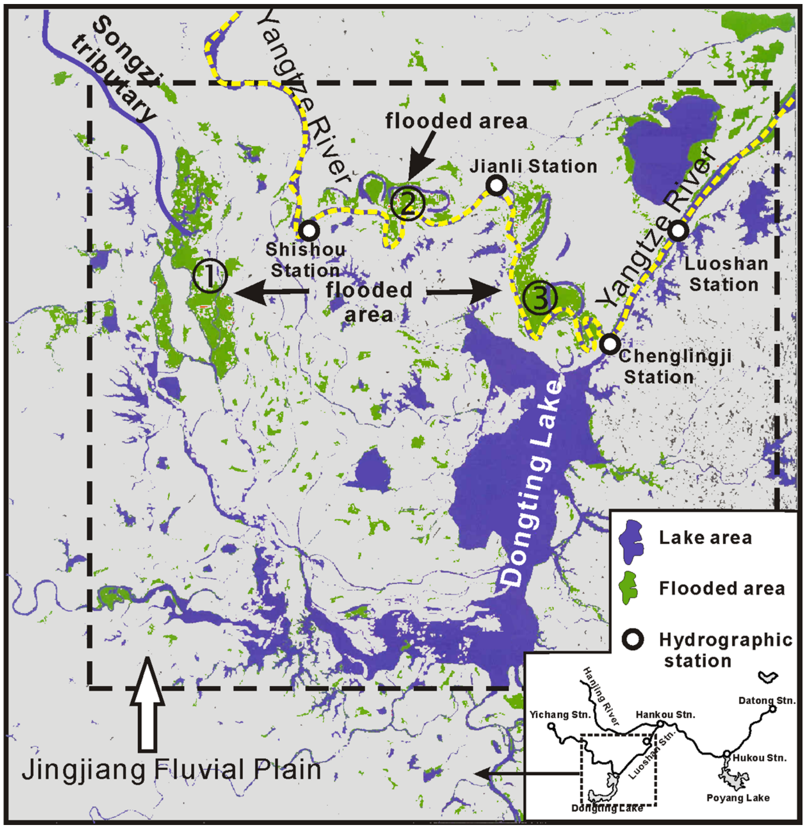

Figure 4. Flooded areas of the Jingjiang fluvial plain in 1998: flooded area downstream of the Songzi tributary, 340 km^2 (number 1); flooded area between Shishou and Jianli stations, 123 km^2 (number 2), and flooded area between Jianli and Chenglingji stations, 145 km^2 (number 3).

the mean annual sediment load of 490 mt/yr for the 18 years between 1951 and 1968 to represent 100% of the baseline, then during the first 17-year phase from 1969 to 1985, the sediment load decreased to about 440 mt/yr, or about 90% of the baseline. During the second phase, 1986 to 2002, it decreased to 340 mt/yr, or 70% of the 1951–1968 baseline. As the Three Gorges Dam (TGD) started operating in 2003, the Changjiang entered a third phase of sediment reduction as annual sediment loads decreased to 180 mt/yr, only 37% of the baseline (Table 2 and Figure 3).

3.2.1. First Phase of Sediment Reduction, 1969–1985

[24] Sediment discharge at Hankou has closely followed that at Datong (Figure 3). Between 1969 and 1985 the sediment load at Hankou decreased by 30 mt/yr, and during the second phase it declined a further 90 mt/yr (Table 2 and Figure 3). In contrast, discharge at Yichang showed no distinct downward trend between 1950 and 1985, and at Luoshan the sediment load increased by 60 mt/yr (Figure 3), indicating that the first phase of sediment reduction cannot be attributed to any decrease in the upper reaches of the river. The decline must have occurred between Luoshan and Hankou, almost certainly in the sediment load of Hanjiang.

[25] The longest tributary to the Changjiang, the Hanjiang annually contributed 65 mt/yr to the Changjiang, through the Xiantao gauging section, located in the lower reaches of the Hanjiang. More than 95% of the sediment is suspended

Table 2. Sediment Loads (Q_s) at Four Key Gauging Stations Along the Changjiang (Locations Shown in Figure 1) for Different Time Periods 1950–2004 and Major Events Responsible for the Sediment Reductions

	Sediment Discharge During Different Time Periods							
	1950–1968[a]		1969–1985[b]		1986–2002[c]		2003–2004[d]	
Stations	Q_s, mt/yr	Ratio, %	Q_s, mt/yr	Ratio, %	Q_s, mt/yr	Ratio, %	Q_s, mt/yr	Ratio, %
Yichang	540	100	520	96	410	76	80	15
Luoshan	410[e]	100	470	115	350	85	135	33
Hankou	450[e]	100	420	93	330	73	150	33
Datong	490[e]	100	440	90	340	69	180	37

[a]1950–1968 values are considered as reference levels of 100%.
[b]The Danjiangkou Reservoir was completed in 1969, trapping most of the sediment from Hanjiang.
[c]Numerous hydropower stations and the Water-Soil Conservation Project started in Jialingjiang basin.
[d]The Three Gorges Dam began trapping sediment from the upper Changjiang in June 2003.
[e]Averages are from 1954 to 1968 at Luoshan and Hankou and 1951 to 1968 for Datong.

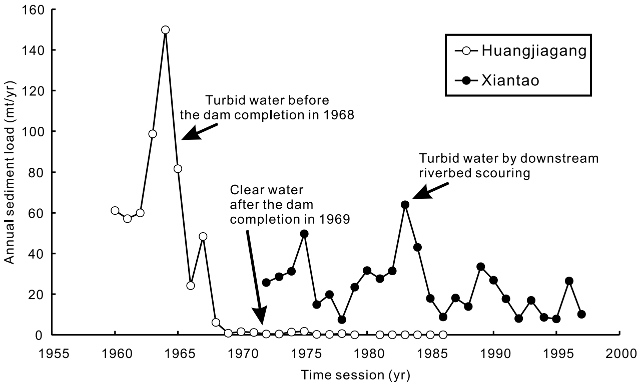

Figure 5. Annual sediment loads at Xiantao and Huangjiagang stations on the Hanjiang tributary.

[*Li et al.*, 2000], mostly derived from the Loess Plateau, which lies in the upper reaches of the river (Figure 1). In 1959 construction of the Danjiangkou Reservoir was begun, the largest ever built in China to that date, with a water storage capacity of 17 km^3. The reservoir continued to discharge turbid water until 1968, after which it began to trap sediment and the discharged water became sediment free. Although *Han and Yang* [2000] speculated on the role of the Danjiangkou Dam in reducing the post-1968 sediment load of the Changjiang, their analysis was more speculative than quantitative.

[26] Annual sediment load at the Huangjiagang gauge, located just below the Danjiangkou Reservoir (Figure 2), averaged 73 mt/yr before 1967 but decreased to 0.8 mt/yr after 1968 (Figure 5), indicating a 99% trapping efficiency. Nevertheless, an average of 24 mt/yr continued to be discharged through the Xiantao gauge after 1970, the result of scouring of the lower Hanjiang channel [*Li et al.*, 2000] (Figure 5), as evidenced by increased grain size of both bed load and suspended sediments [*Liu et al.*, 1998]. This gives a net reduction of sediment ~41 mt/yr from Hanjiang tributary to the Changjiang compared to the previous 65 mt/yr at Xiantao gauge prior to the construction of Danjiangkou reservoir. The reduction of sediment load at Hankou during the first phase has been 30 mt, slightly less than the sediment reduction of Xiantao gauge. If the flood year of 1954 were excluded from the baseline, the annual sediment load at Hankou during 1955–1968 would be 460 mt/yr, and the sediment reduction of the first phase would be 40 mt, almost equal to the decrease at Xiantao gauge. However, the increased grain size of sediment introduced by the Hanjiang presumably has resulted in greater deposition of sediment between Hankou and Datong, explaining the reduction in mean annual sediment load at Datong of 50 mt/yr (Table 2).

3.2.2. Second Phase of Sediment Reduction, 1986–2002

[27] After 1985, all four stations along the Changjiang exhibited a distinct downward trend in sediment load (with exception of the Yichang in 1998) (Figure 3). Whereas sediment loads at Yichang and Luoshan showed little change during the first phase of sediment reduction (sediment load actually increasing at Luoshan between 1969 and 1985), mean annual sediment loads at all four stations decreased by ~20% relative to their 1969–1985 values (except for Luoshan by ~30%) (Table 2). Because the upper reaches of the river contribute ~85–90% of the river's sediment supply, any change at Yichang was also experienced downstream.

[28] The mean annual sediment loads of four main contributors to upper Changjiang—the Jingshajiang (the upper part of the Changjiang), Minjiang, Jialingjiang and Wujiang (Figure 2 and Table 1)—total ~430 mt/yr, or 86% of the load measured at Yichang. Of the total of Yichang the Jinshajiang and Jialingjiang account for 47 and 24%, respectively (Table 3). Sediment loads on the Jialingjiang after 1986 dropped significantly, the Wujiang and Minjiang decreased by ~33% each, whereas the Jinshajiang's load increased slightly (Table 3 and Figure 6). The 100 mt/yr drop of the Jialingjiang (relative to 1954–1985 loads of 150 mt/yr) at Beibei Gauge accounts for nearly all of the decrease in sediment load measured at Yichang (120 mt) (compare Tables 2 and 3). About half of Jialingjiang load is derived from its upper reaches, which flows across the southern part of the Loess Plateau, and ~20% comes from the Qujiang tributary, which joins the middle reaches of the Jialingjiang (Figure 2).

[29] The decrease in Jialingjiang sediment load comes in part from the 4537 reservoirs (with a total water storage capacity of 5.6 km^3) built on the river before 1985. More important, however, has been construction of the Shengzhong Dam reservoir with storage capacity of 1.3 km^3 (Figure 2) completed in 1986 [*Mao and Pei*, 2002] as well as other smaller reservoirs with a cumulative water capacity of 4 km^3. In 1996 the large Baozhushi Reservoir (2.6 km^3) began operation (Figure 2). Collectively, these reservoirs accounted for a 68 mt/yr decrease in Jialingjiang sediment load [*Mao and Pei*, 2002]. In addition, beginning in 1988, the Changzhi Water and Soil Conservation Project (WSCP) began reducing sediment erosion by improving vegetation cover and construction of many small coffer dams; collectively these soil conservation measures have accounted for another 30 mt/yr of decreased sediment load along the Jialingjiang [*Shi et al.*, 2002]. Of the 100 mt/yr decrease in the Jialingjiang's sediment load during the

Table 3. Variation in Sediment Loads (Q_s) for Four Tributaries Entering the Upper Reaches of the Changjiang, 1954–2004

		1954–1968		1969–1985		1986–2002		2003–2004	
Tributary	Station	Q_s, mt/yr	Ratio, %	Q_s, mt/yr	Ratio, %	Q_s, mt/yr	Ratio, %	Q_s, mt/yr	Ratio, %
Jinshajiang	Pingshan	250	100	210	84	270	108	150	60
Minjiang	Gaochang	60	100	40	67	40	67	40	67
Jialingjiang	Beibei	160	100	140	88	50	31	24	15
Wujiang	Wulong	30	100	40	133	20	67	13	43
Total		500	100	430	86	380	76	230	46

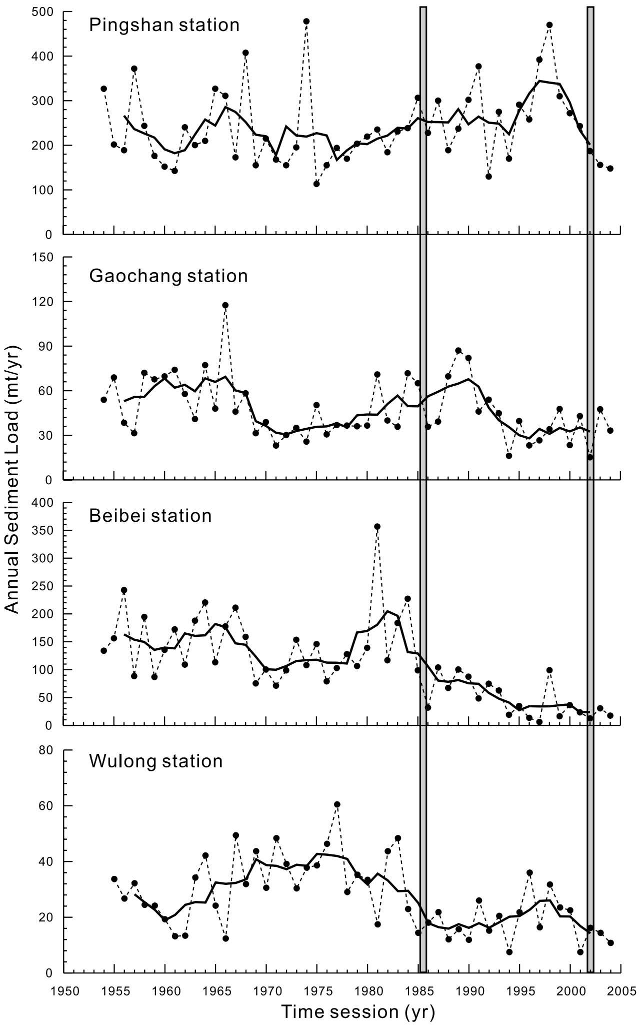

Figure 6. Annual sediment loads at four stations in the upper reaches of the Chanjiang: Jinshajiang (at Pingshan station), Minjiang (at Gaochang station), Jialingjiang (at Beibei station), and Wujiang (at Wulong station). The solid lines are 5-year running averages.

second phase of sediment reduction; therefore about 2/3 was due to dam construction and 1/3 to increased soil conservation.

3.2.3. Third Phase of Sediment Reduction

[30] The TGD has started retaining Changjiang water and sediment as its reservoir reached water level of 135 m in June, 2003, then to 139 m in November, 2003. While the mean sediment load at Qingxichang located in the upper reaches of TGD's reservoir (Figure 2) was 190 mt/yr between 2003 and 2004, the mean sediment load at Yichang located at the lower edge of the reservoir was only 80 mt/yr. This represents a decrease of 330 mt/yr (~60%) relative to 1986–2002 sediment loads at Yichang, or of 460 mt/yr (~85%) relative to 1951–1968 values (Table 2). That means ~60% of sediment that entered into the reservoir was trapped by TGD, which caused a sharp sediment reduction at all the four stations along the Changjiang. The mean annual sediment load at Datong between 2003 and 2004 was 180 mt/yr, which decreased dramatically by 160 mt/yr (~30%) relative to 1986–2002 values, or by 310 mt/yr (~60%) relative to 1951–1968 values. (Figure 3 and Table 2). As sediment loads at Yichang after 2002 sharply reduced much earlier than that was expected, the river channel erosion in the middle and lower reaches seems to happen first in the Changjiang history.

[31] Meanwhile, the annual sediment loads of four main contributors to upper Changjiang—the Jingshajiang (the upper mainstream of the Changjiang), Jialingjiang, Wujiang and Minjiang in 2003–2004 have decreased to 230 mt/yr, or 60% to their 1986–2002 values and to less than 50% to their values in 1954–1968 (Figure 6 and Table 3), resulting in sediment reduction of the Changjiang upper reaches at Yichang and for the remainder of the Changjiang as well. The sharp reduction of sediment load from the upper reaches has caused the drastic sediment decrease at Yichang even earlier than the TGD operation. The annual sediment loads of four main contributors to upper Changjiang in 2001–2004 has been reduced to 270 mt/yr, or to ~50% of their 1954–1968 values (Figure 6). This situation accelerated the sediment reduction along the Changjiang in recent years, resulting in phase change of sediment reduction happening earlier in the upper reaches than that in lower reaches. After the TGD's completion in 2009 as the water level elevation reaches to 175 m [*Li*, 1997] it is estimated that ~70% of sediment will be retained within the reservoir for the first 2 decades, and more intensive sediment reduction is expected.

3.3. Relations of Sediment Loads Between the Yichang and Datong Stations

[32] The correlation of sediment load between Yichang and Datong from 1951 to 2002 is $R^2 = 0.69$, however, varying largely from phase to phase. For the baseline period of 1951–1968, before the construction of Danjiangkou Reservoir, the Hanjiang was the largest sediment supplier to the Changjiang below Yichang; therefore, for that period, the correlation between sediment discharge at Yichang and that at Datong was low ($R^2 = 0.52$). It became higher, however, during the first phase ($R^2 = 0.69$), and then reaching 0.89 remarkably during the second phase, as the sediment input from the Hanjiang had practically stopped (Figure 7).

[33] On the basis of the sediment data at Yichang and Datong from 1986 to 2002, the linear regression equation, calculated after excluding the flooding effect of 1998, is as follows.

$$\mathrm{QsD} = 0.489\ \mathrm{QsY} + 144 \qquad (1)$$

where QsD and QsY are annual sediment loads at Datong station and Yichang station, respectively.

[34] The recently released sediment records of 2003 and 2004 at Yichang and Datong were used to verify the validity of this equation. The annual sediment loads at Yichang were 98 mt and 64 mt in 2003 and 2004, consequently, the predicted sediment loads at Datong are 190 mt in 2003 and 175 mt in 2004, while the measured sediment loads at Datong were 210 mt and 150 mt, respectively. It is reasonable to assume that this equation is adequate for estimating the Changjiang sediment load at Datong after TGD completion since it takes into account for the whole present water and sediment situation of the Changjiang.

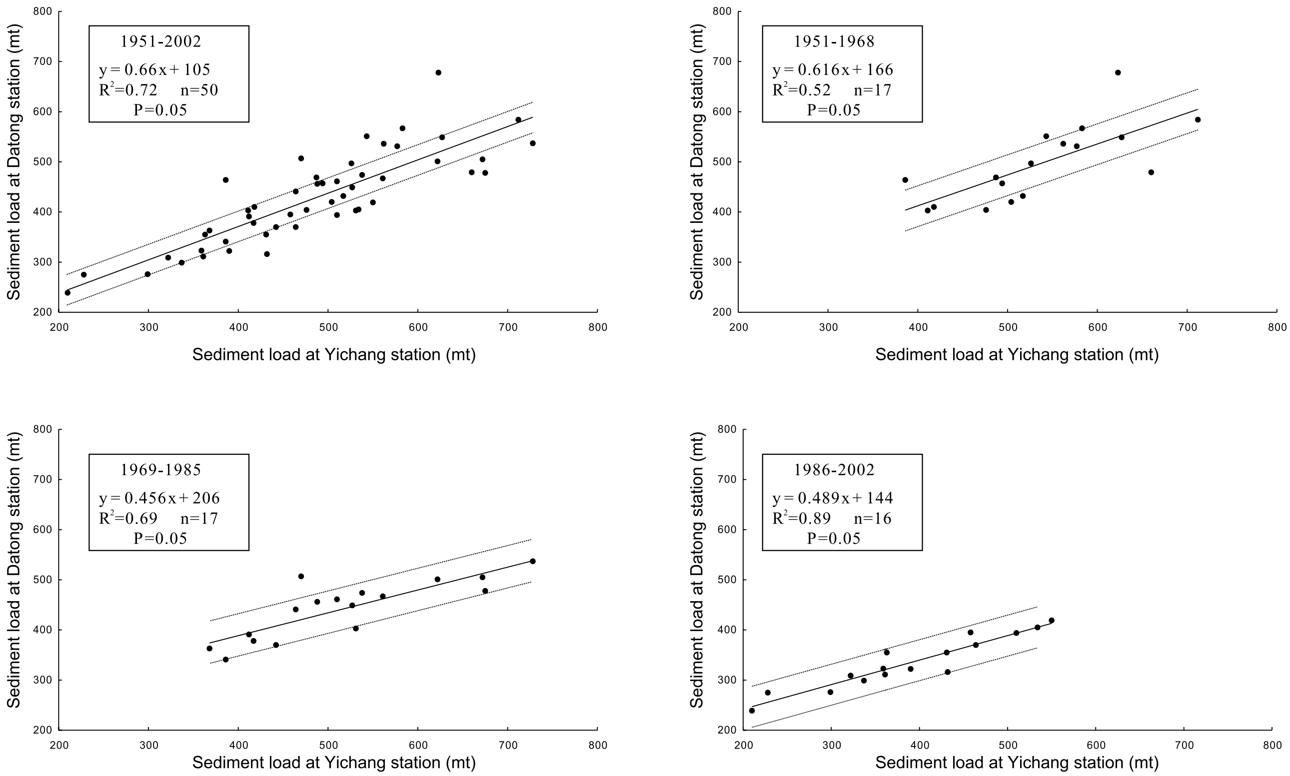

Figure 7. Correlations between annual sediment loads at Yichang and Datong gauging stations at different time periods.

[35] During the flood years of 1954 and 1998, a large amount of sediment was lost in the middle reaches through the river breaches and overbank flows, especially in the Jingjiang fluvial plain (Figure 4), as indicated by the high sediment loads at Yichang and low sediment loads at Luoshan, Hankou and Datong (Figure 3). The amount of overbank deposition in the middle and lower reaches can be estimated by equation (1). For the flood year of 1954, during which the measured sediment load at Yichang was 750 mt, the equation predicts a sediment load at Datong of 510 mt. The measured sediment load at Datong in 1954 was 460 mt. If the additional sediment input of 65 mt (records at Xiantao gauge) from the Hanjiang were taken into account, the sediment lost in the middle reaches would be 115 mt. In 1998 the Hanjiang input almost stopped, and the predicted sediment load at Datong is 510 mt, nearly 110 mt higher than the actual record of 400 mt. During the flood of 1998 the flooded area in the Jingjiang fluvial plain was more than 600 km^2 (Figure 4), and the overbank deposition in Hubei Province was more than 60 mt [*Xu*, 2000]. Therefore the predictions suggested that $\sim$100 mt were lost to overbank deposition between the two hydrologic stations during the flood years.

4. Estimated Impact of the Three Gorges Dam on Changjiang Sediment Discharge to the East China Sea

4.1. Impact of TGD Sediment Trapping

[36] The reservoir behind TGD, which began filling in 2003 and initiated a third phase of sediment reduction for the Changjiang, will have a water storage capacity of 39 km^3 and a dead storage capacity of 17 km^3. Of the sediment entering the reservoir during the first 20 years after the TGD's completion in 2009, it is estimated that only 30% will be discharged from the dam, the remaining 70% being retained within the reservoir. This means that sediment discharge at Yichang will be reduced to 30% of its input value. From 2030 to 2060, about 56% of the sediment will be retained, and by 2060–2110 the proportion of sediment trapped within the reservoir will be reduced to 19% (Table 4) [*Yang et al.*, 2002].

[37] Assuming the amount of sediment entering the reservoir of TGD is similar to the measured sediment load at Yichang during Phase 2 (1986–2002: 410 mt/yr; see Table 2), the amount of sediment passing Yichang would be 130 mt/yr during the first 20 years after completion of the dam, 180 mt/yr for the next 30 years, and 330 mt/yr between 2060 and 2110 (Table 4). The amount of riverbed erosion below Yichang should decrease with time as a new equilibrium is reached, and sediment should begin accumulating as sediment discharge from the TGD increases.

[38] *Yang et al.* [2003] also have predicted the Changjiang sediment discharge to the East China Sea for the ten decades after TGD completion on the basis of the observed decrease in sediment loads from Yichang to Datong (their R^2 = 0.64). However using the above approach, our predictions are greater than those of Yang et al. by about 25% (50 mt/yr) on average (Table 4). In part this is based on a better correlation between Yichang and Datong, since we have excluded the anomalous flood years of 1954 and 1998, increasing the R^2 to 0.89 as the TGD is designed to prevent

Table 4. Estimated Sediment Discharge at Datong Station and Sediment Contributing to the Changjiang Estuary and its Subaqueous Delta After Completion of the Three Gorges Dam

	Time Periods After TGD Completion									
	2010–2020	2020–2030	2030–2040	2040–2050	2050–2060	2060–2070	2070–2080	2080–2090	2090–2100	2100–2110
Export ratio of sediment discharge from the TGR, %	29.9	31	36.6	43.3	52.7	67.4	77.4	84.5	87.6	89.7
Average export ratio of sediment discharge from the TGR, %	30.5	30.5	44.2	44.2	44.2	81.3	81.3	81.3	81.3	81.3
Sediment discharge from Yichang, mt/yr	130	130	180	180	180	330	330	330	330	330
River bed erosion/ accumulation, 10^6 m^3/yr[a]	83	83	44	44	44	−14	−14	−14	−14	−14
Sediment discharge at Datong, mt/yr, Approach 1[b]	210	210	230	230	230	310	310	310	310	310
Sediment discharge at Datong, mt/yr, Approach 2[c]	240	240	240	240	240	310	310	310	310	310
Sediment contribution to Changjiang estuary and its subaqueous delta, mt/yr[d]	90	90	94	94	94	124	124	124	124	124

[a]Values are proposed by the Academy of Changjiang Research; positive numbers represent erosion, and negative numbers represent accumulation.
[b]Estimation is based on the correlation between sediment discharge at Yichang and at Datong: QsD = 0.489 QsY + 144 (equation (1)). QsY is the annual sediment load at Yichang and QsD is the annual sediment load at Datong.
[c]Estimation based on the river channel erosion/accumulation from Yichang to Datong The bulk density of river sediment is taken as 1.35 t/m^3.
[d]According to *Milliman et al.* [1985], the sediment contributing to the Changjiang estuary and its subaqueous delta comprise 40% of the sediment discharges from Datong. The sediment at Datong was the average of the prediction results from two approaches.

the effects of such extreme flooding, they can be discounted, as we have done in our calculations. Further more, the sediment input from Hanjiang has been almost stopped. On the basis of the relations between sediment loads at Yichang and Datong, we estimated that during the first 20 years after the TGD's completion (2010–2030) the annual sediment loads at Datong would be 210 mt/yr, then increase slightly to 230 mt/yr during the next 30 years (2030–2060) and finally approach 310 mt/yr (Table 4), near quantity of the second phase (Table 2).

4.2. Impact of Riverbed Scouring

[39] Because of the 70% reduction in sediment reaching the Changjiang downstream of the TGD (Table 4), increased riverbed scouring is expected. Using one-dimensional models, the Changjiang Academy of Science and the Changjiang Institute of Water Conservancy and Hydroelectric Science calculated that there would be extensive scouring for about 230 km downstream of the dam for the first decade, whereas accumulation would occur further downstream. Scouring would gradually extend downstream after the first 50 years, reaching its maximum extent after about 60 years, after which net accumulation would begin to exceed net erosion [*Li et al.*, 1997]. Using these erosion accumulation predictions in decadal intervals for the first 80 years after TGD completion, we calculated additional Changjiang sediment supply from riverbed scouring. If the bulk density of the river sediment was taken as 1.35 t/m^3 [*Shi et al.*, 2002], the estimated sediment load at Datong during different time periods after the TGD's completion were quite close to the results from equation (1) (Table 4).

4.3. Possible Deltaic Erosion Resulting From Reduction in Changjiang Sediment Discharge

[40] According to a preliminary sediment budget proposed by *Milliman et al.* [1985], more than 40% of the sediment passing Datong station is deposited in the Changjiang estuary. Of the 60% escaping to the East China Sea, *DeMaster et al.* [1983] estimated that about 40% is deposited on the inner shelf north of 30°N, but that much of that is resuspended and transported southward during winter storms. The stratigraphical study of the Changjiang delta also proposed that ~47% of the Changjiang sediment deposited in the delta area [*Liu et al.*, 2006], including ~10% depositing in the segment between Datong and the Changjiang estuary [*Shen*, 2001]. Natural deltaic erosion, according to *Yang et al.* [2002], is about 100 to 150 mt/yr. The average annual erosion of the Changjiang estuary and its subaqueous delta can be estimated as 125 mt/yr that consisted ~40% of the sediment load at Datong. Therefore the critical sediment load at Datong for keeping balance of the Changjiang estuary and its delta would be 310 mt/yr.

[41] During the first 20 years after TGD's completion, the annual sediment load passing Datong is estimated as 210 mt/yr (Table 4), much less than the critical value. Thus the Changjiang estuary would be deepened and its subaqueous delta would be eroded during this period. As the sediment discharge ratio from the TGR increased, the annual sediment load at Datong would increase correspondingly, to 230 mt/yr during the next three decades (2030–2060) and to 310 mt/yr during the five decades of

2060–2110 (Table 4), implying that the Changjiang delta would gradually approach an approximate equilibrium.

5. Conclusions

[42] Between 1969 and 2002 sediment discharge from the Changjiang decreased by ~25% in two reduction phases, although water discharge actually increased slightly. From a baseline sediment load of 490 mt/yr recorded at Datong between 1950 and 1968, over the following 17 years (1969–1985) the mean annual load decreased to 440 mt/yr, followed by a 17 year interval (1986–2002) during which the mean annual load was 340 mt/yr, and dramatically decreased to 180 mt/yr in the recent years of 2003 and 2004. The first reduction phase was mainly the result of the activation of the Danjiangkou Reservoir on the Hangjiang tributary; the second one caused mainly by construction of numerous dams and reservoirs as well as a water-soil conservation plan on the Jialingjiang tributary in the upper reaches; the last one was resulted from the TGD's impact as well as the sediment decrease in the tributaries of the upper Changjiang that continued from the second phase.

[43] On the basis of a relationship between sediment discharge at Yichang and Datong gauging stations, we calculate that sediment discharge from the Changjiang to the East China Sea will decrease to 210 mt/yr for the first 20 years following completion of the Three Gorges Dam (TGD), 2010–2030, and then recover to 230 mt/yr between 2030 and 2060, and to 310 mt/yr for the next 50 years (2060–2110).

[44] Assuming the critical discharge of sediment past Datong to maintain the Changjiang delta to be 310 mt/yr, for the first two decades after TGD completion, there should be extensive erosion, but the erosion accumulation should gradually balance out by 2060. However, for the first 50 years after TGD completion, we hypothesize that the Changjiang deltaic area should undergo significant morphologic and environmental change because of local and regional erosion.

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