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Sediment budget of the Yangtze River

Zhao-Yin Wang,[1,2] Yitian Li,[3] and Yiping He[4]

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[1] The sediment budget is a method to study the distribution of sediment in different parts of a river basin. This paper studies the sediment budget of the Yangtze River by analyzing the data on soil erosion, size distributions of sediment deposits, sediment load, and fluvial process. A method to determine the sediment budget for the Yangtze River is proposed in which the total soil erosion from the upstream reaches and tributaries is divided into two parts: sediment load transported to the Yichang station and sediment storage in the tributaries and gullies. Furthermore, the sediment load is divided into three parts: bed material load deposited in the middle and lower reaches for the fluvial process, wash load transported to the estuary, and sediment deposition in Tongting Lake. The sediment transported into the estuary is further divided into two parts: very fine sediment drifting to the ocean and sediment deposition in the estuary for land creation. There is a large sediment demand for (1) the fluvial process to reach the minimum stream power in the middle and lower reaches; (2) sediment mining for building material; and (3) land creation in the estuary. The riverbed profile in the middle and lower reaches is developing toward the equilibrium profile defined by the minimum stream power, but the impoundment of the Three Gorges Reservoir interrupts and modifies this fluvial process. The annual sediment load in the Yangtze River has reduced due to various human activities by about 100 × 10^6 t in the past 15 years. Thus there is a sediment shortage for land creation in the river mouth.

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1. Introduction

[2] The sediment budget is a method to study the distribution of sediment in different parts of a river basin. The method deals with only the sediment amount without consideration of the transport mechanics. The International Association of Hydrological Sciences (IAHS) organized a symposium on the theme "sediment budget" in 1988. In selecting the theme, the organizers consciously chose a topic which draws on a wide range of research and which represents an important area of current interest [*Bordas and Walling*, 1988]. At this time the study of the sediment budget is in its infancy and more research is required to develop the necessary monitoring and modeling strategies and to improve understanding of the processes involved. In the past many studies have focused on the erosion processes operating within a basin and sedimentation at its outlet. Now there is an increasing awareness of the need to integrate the two and to establish sediment budgets, which attempt to qualify the relations among the various components of the overall drainage basin erosion/transportation/deposition system.

[3] *Wang et al.* [1997] proposed to study the sediment budget and also the sediment demand of rivers. There are various demands for sediment, for instance, sediment mining for building material, land creation using sediment, maintaining river regime equilibrium, and preventing the channel bed from eroding. The Rhine River was short of bed load because dams and barrages cut off the supply of bed load from the upper river basin. The riverbed had scoured by more than 2 m. The degradation caused many hydraulic works along the river to no longer function, and the groundwater table descended. To control the scour of the Rhine River and maintain navigation channel stability, German engineers feed 200,000 t of well-selected bed load into the river per year [*Nestmann*, 1992]. Both sediment yield and sediment demand need to be studied. Sediment budget studies balance between the yield and the demand and consider the disturbance to the balance by human activities.

[4] Figure 1 shows the 6300-km-long Yangtze River, which is the largest and longest river in China, with a drainage area of 1.80 × 10^6 km^2. Figure 1 also shows the locations of hydrological stations, meteorological stations, tributaries, riparian lakes, and debris flow areas. The Yangtze River basin has elevation varying from 5000 to 0 m with latitude from 25°N to 35°N. The river flows through the Qinghai-Tibet Plateau, Yunnan-Guizhou Plateau, Sichuan Basin, Three Gorges, Jiang-Han Plain,

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[1] State Key Laboratory of Hydroscience and Engineering, Tsinghua University, Beijing, China.

[2] Also at Key Laboratory of Mountain Hazards and Surface Process, Chengdu Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, China.

[3] Wuhan University, Wuhan, Hubei, China.

[4] Key Laboratory of Mountain Hazards and Surface Process, Chengdu Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, Sichuan, China.

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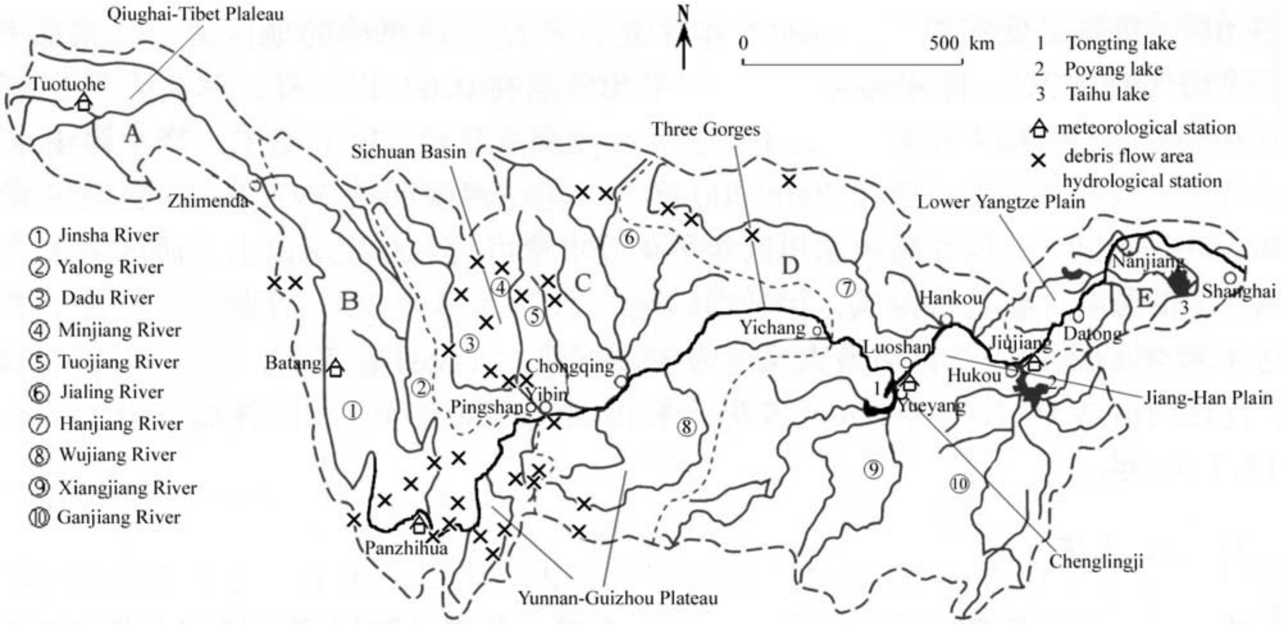


Figure 1. The Yangtze River basin, showing the locations of the hydrological stations, meteorological stations, tributaries, riparian lakes, and debris flow areas. Letters indicate A, Tongtian River basin; B, Jinsha River basin, including the Yalong and Xiaojiang River basins; C, Chuanjiang River basin, including the Minjang, Twojiang, Jialing, and Wujiang River basins; D, Jingjiang River basin, including the Hanjiang and Tongting Lake basins; and E, Yangtze River basin in its narrow sense, including the Taihu lake basin.

Lower Yangtze Plain, and pours into the East China Sea at Shanghai. From the source to Yichang (Three Gorges Dam site) is the upper reach, from Yichang to Hukou (Poyang Lake mouth) is the middle reach, from Hukou to Datong is the lower reach, and below Datong is the estuary. In China, the river is called Changjang (long river), with special names for different stretches: The lower reaches are called the Yangtze River, the middle reaches are called the Jingjiang River, the reach from Yichang to Yibin is called the Chuanjiang River, from Yibin to Zhimenda is called the Jinsha River, and from Zhimenda to the origin is called the Tongtian River (Heaven River).

[5] There have been quite a few studies on the sediment in the Yangtze River. *Lu and Higgitt* [1998] studied the sediment yield from the tributaries of the upper Yangtze River basin in the period 1956–1987 and indicated that 10 stations, located mainly on the Dadu River and Wujiang River, have shown increasing sediment yield, and six stations, located on the upper Jialing River and Tuojiang River, have experienced decreasing sediment yield. Most of the observed decreases in sediment yield are associated with large reservoirs on these rivers. *Zhang and Wen* [2004] also studied the sediment yield of the upper Yangtze River and illustrated a decrease in sediment yield in the Jialing River and an increase in the Jinsha River during the period from the 1950s to the 1990s. It was apparent that the decreasing sediment yield in the Jialing River was due to construction of reservoirs, reforestation, and soil and water conservation efforts. Land degradation, engineering, and channel activities were responsible for the increase in sediment yield of the Jinsha River. *Higgitt and Lu* [2001] examined sediment yield and its response to catchment disturbance and environmental variables in the upper Yangtze River basin and illustrated that a significant increase in sediment yield has occurred over about 8% of the catchment area while about 3% of the catchment has experienced decreasing sediment yields.

[6] *Yang et al.* [2006] analyzed the impact of dams on the sediment load in the middle and lower reaches of the Yangtze River and indicated that the river has experienced two sediment load reduction phases from 1969 to 2002. The first reduction phase was mainly the result of the closure of the Danjiangkou Reservoir on the Hanjiang River; and the second reduction phase was caused by construction of numerous dams and soil erosion control projects in the Jialing River basin after 1985. Recently, the impoundment of Three Gorges Reservoir in 2002 has been causing the third phase of sediment load reduction in the Middle and Lower Yangtze rivers. *Chen et al.* [2001] analyzed sediment transportation in the river and showed 80×10^6 t less annual sediment load in the middle reaches than that in the upper reaches, because the slope is gentler.

[7] Investigation of the temporal and spatial variability of sediment transport within the upper Yangtze River basin leads to the following paradox. There is evidence that the extent and magnitude of soil erosion across southwestern China has increased during the last 30–40 years [*Smil*, 1993; *Wen*, 1993; *Edmonds*, 1994; *Lu and Higgitt*, 1999]. However, there is evidence of sediment load reduction rather than increase. Moreover, many studies have indicated that the total soil erosion from the upper reaches of the Yangtze River is around 2.2×10^9 t yr^{-1} [*Tang*, 2004]. However, the sediment load measured at Yichang is only about 500×10^6 t yr^{-1}. A large volume of sediment is stored somewhere in the upper reaches.

[8] This paper studies the sediment amount in different reaches. A method of sediment budget for the Yangtze River is proposed in which the quantitative relations among

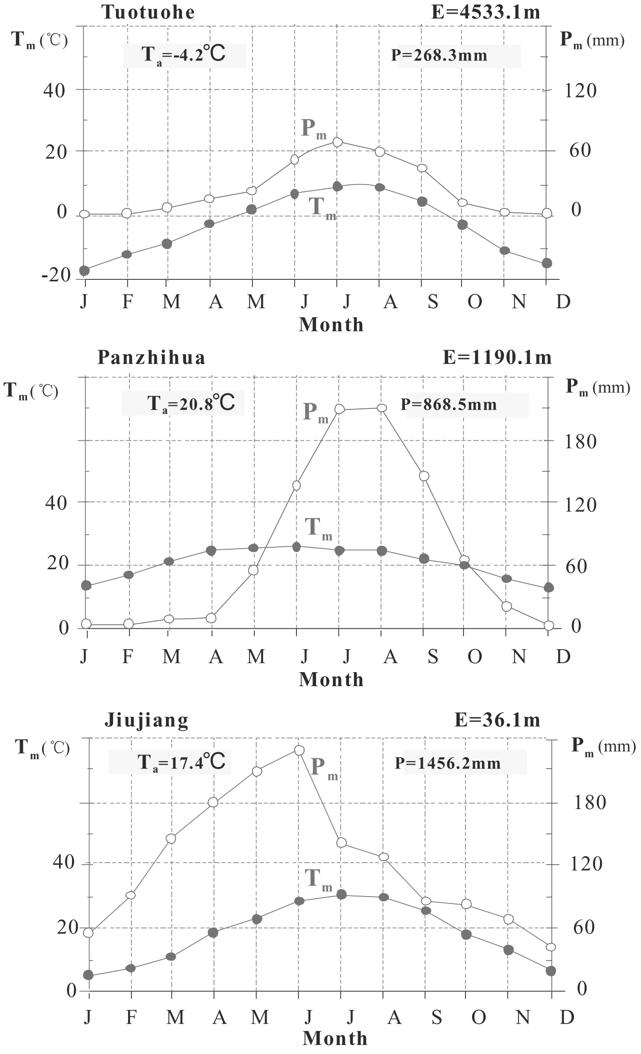


Figure 2. Climate diagrams showing monthly average temperature, T_m, and monthly average precipitation, P_m, for the three typical climate patterns in the Yangtze River basin (E is elevation of the station, T_a is annual average temperature, P_a is annual average precipitation). Data are averaged from 1950 to 2000; data source, *Climatic Data Center* [2004].

sediment yield, sediment transportation, and sediment demand are expressed in formulas. This method may be used for other rivers. This study will answer the questions of (1) what part of sediment is stored in the gullies and tributaries and how much of the sediment accumulating in the gullies and tributaries may become sources of sediment load in big events, (2) how much sediment load, and under what conditions, is deposited in the middle and lower reaches during fluvial processes, and (3) what is the sediment demand and does sediment reduction cause problems.

2. Soil Erosion in the Upper Yangtze River Basin

[9] There are three different climate patterns in the basin. Figure 2 shows typical climate diagrams for the three zones. The climate is cold in the source area, and the Tuotuohe Meteorological Station has a typical cold climate pattern. The climate is hot and dry in the Jinsha River reach from Batang to Yibin, for which the Panzhihua station is representative. In the middle and lower reaches, the climate is wet and warm. The Jiujiang station has a typical wet and warm climate pattern, as shown in Figure 2. The tributaries in the middle and lower reaches contribute little sediment but input 50% of discharge to the Yangtze River.

[10] At the Tuotuohe station the annual average temperature is only −4.2°C, which results in low evaporation. Vegetation may slowly develop but mainly is herbaceous. The Jinsha River basin (from Batang to Yibin) is called dry and hot valleys, with an annual average temperature of about 20°C, and monthly average rainfall from December to April is less than 10 mm, resulting in poor vegetation. In summer from June to September, the monthly rainfall is more than 120 mm, which causes high soil erosion. Splash erosion, sheet erosion, and rill erosion are moderate, but gully erosion is extremely intensive. The sediment eroded from the area is composed of clay, silt, sand, gravel, cobbles, and boulders. More than 50% of the sediment load to the middle and lower Yangtze River is from the Jinsha River basin.

[11] Soil erosion, sediment yield, and sediment transportation have been measured. There are many hydrological stations and numerous monitored cross sections and gauging stations on the river and its tributaries. Regular measurements are performed daily at the hydrological stations. The velocity and discharge are measured with propeller velocity meters, and the error for discharge measurement is less than 8%. The concentration and daily load of suspended sediment are measured by sampling with bottles. The error is less than 16%. The bed load is measured with Y78-1 (100 cm wide) and Y78-2 (300 cm wide) bed load samplers, which were designed by the Yangtze River Commission (YRC) in 1978. The two samplers were compared with the HS-1 and TR-2 bed load sampler designed by the U.S. Geological Survey (USGS) [*Helly and Smith*, 1971]. The results indicated that the Y78-1 and Y78-2 samplers and USGS samplers are comparable (see “Comparison of Chinese bed load samplers and American bed load samplers,” available at www.shuigong.com).

[12] In this study a double-box bed load sampler was designed and used by the authors. A plastic box, 600 cm long, 35 cm wide, and 35 cm high, with its upper side open, was put into the river bed with the upper edge at the bed surface. A second box was put into the first box and bed load particles moved into the inner box. The inner box was taken out after it filled with bed load sediment. This sampler can only be used in small streams, but the measurement efficiency is much higher than other samplers. Channel bed deformation is measured occasionally at all stations and at the monitored cross sections on the rivers, ravines, and gullies. The error in bed elevation measurement is less than 5 mm, and the error in horizontal positioning is less than 50 mm. The volume of sediment deposition on the riverbed and reservoirs is calculated with the measured cross sections.

[13] The traditional soil erosion measurement was done as follows: (1) The soil erosion areas are determined by field investigations; (2) for each soil erosion area, the rate of sediment load transportation is measured at the downstream end of the small watershed (generally several tens to a hundred square kilometers); (3) the rate of sediment erosion

Table 1. Rate of Soil Erosion From Different Drainage Areas of the Upper Yangtze River Basin[a]

Watershed	Area, km^2	Area of Soil Erosion, km^2	Soil Erosion, 10^6 t yr^{-1}	Percentage in Total Soil Loss, %	Rate of Soil Erosion per Area, t km^{-2} yr^{-1}
Jinsha River (upper Yangtze)	488,900	223,800	829	38.04	3,704
Jialing River	159,900	92,400	559	25.65	6,043
Tuojiang River	27,800	14,800	92	4.22	6,216
Minjiang River	135,400	5,800	253	11.61	4,362
Yangtze River Pingshan-Cuntan	45,700	24,400	107	4.97	4,385
Wujiang River	86,600	46,300	191	8.77	4,125
Three Gorges Reservoir (Cuntan-Yichang)	61,100	36,500	148	6.79	4,055
Total	1,005,400	496,300	2,179	100	4,390

[a] After *Yu* [2003].

is calculated as the total load per year over the area of the watershed; or (4) the rate of soil erosion is directly measured by collecting the sediment eroded from a 100-m^2 sample plot, which is isolated by using low steel plate walls during rainfall events; (5) the amount of soil erosion from all small watersheds is summed to obtain the total amount of soil erosion from the basin. Since 1985 the Ministry of Water Resources of China has been using satellite images (multispectral scanner and thematic mapping), GPS, and geographic information systems software, in combination with the traditional methods to estimate the soil erosion of the watersheds in China.

[14] The total amount of soil erosion from the upper Yangtze River basin is reported at 1.6–2.24 × 10^9 t yr^{-1}, depending on the statistics. *Yu et al.* [1991] evaluated statistics and reported the total soil erosion from the upper Yangtze River basin as 1.6 × 10^9 t yr^{-1}. *Tang* [2004] presented the value of 2.24 × 10^9 t yr^{-1}. *Yu* [2003] adopted the value at 2.179 × 10^9 t yr^{-1}. The Ministry of Water Resources reported the total soil erosion determined by remote sensing performed in 1990, which agrees with the value around 2.2 × 10^9 t [*Application Center of Remote Sensing Technology* (*ACRS*), 1990]. Table 1 lists the rates of soil erosion from different drainage areas of the upper Yangtze River basin presented by *Yu* [2003], in which the rate of soil erosion per area is the average value over the area of soil erosion but not over the whole river basin. The Jinsha and Jialing River basins are the main sediment sources for the Yangtze River.

[15] Various data have been collected and used in this study, including meteorological data, soil erosion, sediment yield, size distribution, sediment load, and sediment deposits. Table 2 lists the category, period, and sources of the data used in this paper. Most data are collected from literature and the Hydrological Year Books (known as Red Books) for the period from 1950 to 1989, which are printed hydrological data series and are available in the Ministry of Water Resources of China and affiliated research institutes. Some data were measured by the authors for this study.

3. Sediment Storage in the Upper Yangtze River Basin

[16] The total soil erosion from the upstream reaches of the Yangtze River is 2.179 × 10^9 t yr^{-1}, but the long-term average suspended load at Yichang before the impoundment of the Gezhouba Dam (the first dam on the river) in 1980 was 514 × 10^6 t, with an additional sum of bed load of 9.54 × 10^6 t (sand bed load 8.78 × 10^6 t plus gravel bed load 0.758 × 10^6 t) [*Three Gorges Project Water Survey*, 2005]. The difference between the volumes of the total soil erosion and sediment load at Yichang is 1.655 × 10^9 t. In other words, only 23.6% of the eroded sediment is transported to Yichang on the Yangtze River and 76.4% is still in the upper Yangtze River basin.

[17] The Jinsha River basin is the main sediment source of the Yangtze River, with a total soil erosion of more than 800 × 10^6 t yr^{-1}. There are many debris flow areas in the basin, as shown in Figure 1, and the slope in the basin is quite high. The sediment yield per area from the debris flow gullies is generally more than 40 times higher than the basin average. For example, the Xiaojiang River is a tributary of the Jinsha River, as shown in Figure 3, which is 138 km long and has a drainage area of 3043 km^2. The average sediment yield from the area is 130,000 t km^{-2} yr^{-1}, of which only a small part can be transported downstream by the Xiaojiang River. The Jiangjia Ravine is a tributary of the Xiaojiang River. Figure 4 shows the aggradation and degradation of the Jiangjia Ravine in the periods 1957–1985 and 1957–2002 [*He et al.*, 2003]. Gully erosion is the main type of erosion, which produces 75–83% of the total sediment yield from the ravine. The eroded sediment from the upstream reaches was transported by debris flows and deposited in the downstream reaches of the ravine. The gully bed aggraded by more than 40 m in the period of 1957–2002. A huge amount of sediment is stored in the downstream reaches and the mouth of the ravine. The same process occurred in numerous debris flow gullies. All the mouths of the debris flow gullies along the Xiaojiang River have been silted up by several tens of meters in the past 50 years.

[18] Bed load is a main type of sediment transportation in mountain streams, which consists of coarse sediment, including gravel, coarse sand, cobbles, and even boulders. The size distribution of bed load from the Diaoga River, a tributary of the Xiaojiang River, is shown in Figure 5. Measurement of the bed load and suspended load at the Diaoga River in the flood season from June to September 2006 demonstrated that the ratio of bed load to the sus-

Table 2. Types, Locations, Periods, and Sources of Data Used in This Paper

Category	Location, Period, Source
Temperature and precipitation	Tuotuohe 1956–2000, Yushu 1951–2000, Batang 1952–2000, Panzhihua 1988–2001, Yibin 1951–2000, Yueyang 1952–2000, Hankou 1907–2003, Jiujiang 1924–1990 [*Climatic Data Center*, 2004]
Debris flow gully bed profile	Jiangjia Ravine 1957–2002 [*He et al.*, 2003]
Soil erosion	Jinsha, Jialing, Tuojiang, Minjiang, Wujiang, and Yangtze (Pingshan-Cuntan and Three Gorges Reservoir) watersheds, long-term average before 1990 [*Yu*, 2003; *Application Center for Remote Sensing Technology*, 1990]
Size distribution	debris flows in the Tongchangqing Gully, Dade Gully, Little Haihe Gully, Jiangjia Ravine, and Daduo Gully [*Kang et al.*, 2004]; Sunshui River and Niuri River [*Xie et al.*, 2004]; bed load in the Diaoga River (this study); sediment deposits in the Xiaojiang River, Dabaini Gully, and Xiaobaini Gully (this study); suspended load at Yichang and Datong stations [*Wan et al.*, 2003]; sediment deposit at the river mouth (this study)
Sediment load and annul runoff	upper and lower reaches 1950–1989 (Hydrological Year Books, or Red Books); Zhimenda 1957–1999 [*Wu and Yu*, 2002]; Batang and Shigu 1954–1987 [*Pan*, 1999]; Panzhihua 1964–1996 [*Zhang and Wen*, 2002]; Qiaojia 1958–1992 [*Deng*, 1997]; Cuntan 1950–2000 [*Wang and Yi*, 2003]; Luoshan 1956–1995 [*Pan and Lu*, 1999]; Datong 1950–2002, Hankou 1950–2002, Yichang 1950–2002, Pingshan 1950–2002, Zhutuo 1950–2000, Beibei 1956–2002, Huangzhuang 1951–2002, Chenglingji 1951–2002, and Hukou 1954–2002 [*Ministry of Water Resources of China*, 2000, 2001, 2002]; Yichang 1950–1980 average [*Three Gorges Project Water Survey*, 2005]; Diaoga River 2006 (this study); Cuntan, Wanxian, Yichang, Shashi, Luoshan, Hankou, and Datong 2003 and 2004 [*Sediment Panel for the Three Gorges Project*, 2005]
Flow velocity and discharge	20 gauging stations in the middle and lower reaches 1950–1989 (Hydrological Year Books, or Red Books)
Depth, width, bed elevation, and cross section of channel	middle and lower reaches 1950–1989 (Hydrological Year Books, or Red Books)
Longitudinal bed profile	middle and lower reaches 1971 and 1982 [*Navigation Department of Navy of People's Liberation Army*, 1983; *Wuhan Management Department of Yangtze River Navigation Channels*, 1997]
Dam	dams and their capacity 1950–2003 [*Yangtze River Commission*, 2002, 2003, 2004]
Sediment mining	Yibin, Luzhou, and Chongqing 1990s [*Yi*, 2003]; middle and lower reaches 1980s and 1990s [*Chen*, 2004]
Sediment deposition	sediment deposition in the estuary 1951–2000 average [*Wu*, 2001]
Land creation	Shanghai 1950–1996 [*Jin et al.*, 1997]

pended load in the four months was 21% to 79%, much greater than the ratio in the Yangtze River (1.85% to 98.15%). In fact, bed load transportation reduces from mountain streams to tributaries and the stem channel of the Yangtze River following reduction in bed slope. In other words, coarse particles are transported from mountains for a distance and are stopped in streams with gentle slope.

[19] Figure 5 shows the size distributions of sediment deposits in debris flow gullies and tributaries in the upper Yangtze River basin in comparison with the size distributions of suspended load at the Yichang and Datong Hydrological Stations [*Kang et al.*, 2004; *Xu*, 2005; *Wang et al.*, 2001; *Xie et al.*, 2004; *Wan et al.*, 2003]. All the size distribution curves are averages of several tens of samples. Dividing the sediment into n-fractions with diameter in the ranges D_1–D_2, D_2–D_3, D_3–D_4,..., in which the subscripts 1, 2, 3,..., are the order numbers, let DP_i be the percentage of diameter within the range D_i–D_{i+1}. The amount of sediment depositing in the upper reaches, S_{di}, is given by

$$S_{di} = S_{\mathrm{up}}(DP_i)_{\mathrm{up}} - S_{\mathrm{down}}(DP_i)_{\mathrm{down}}, \tag{1}$$

in which the subscripts "up" and "down" represent the upper Yangtze River basin and the Yichang Station, S_{up} is the total sediment eroded from the watershed upstream from Yichang, and S_{down} is sediment load at the Yichang station.

[20] A representative size distribution of original sediment eroded from the upper Yangtze River basin can be roughly estimated in the following way: (1) Make an average for the 11 size distributions of sediment deposits from the river beds and gully beds in Figure 5, and denote it as Sa. (2) Because a part of fine sediment has been transported as suspended load into the Yangtze River, the representative size distribution of original eroded sediment, Sm, should be given by taking this part into account and may be given by

$$Sm = 76.4\% Sa + 23.6\% S12, \tag{2}$$

where the percentages are the ratios of sediment deposited and transported into the Yangtze River to the total eroded sediment, and $S12$ is the size distribution of suspended load at the Yichang station.

[21] Figure 5 shows the representative size distribution curve Sm. At the Yichang station, gravel bed load composes

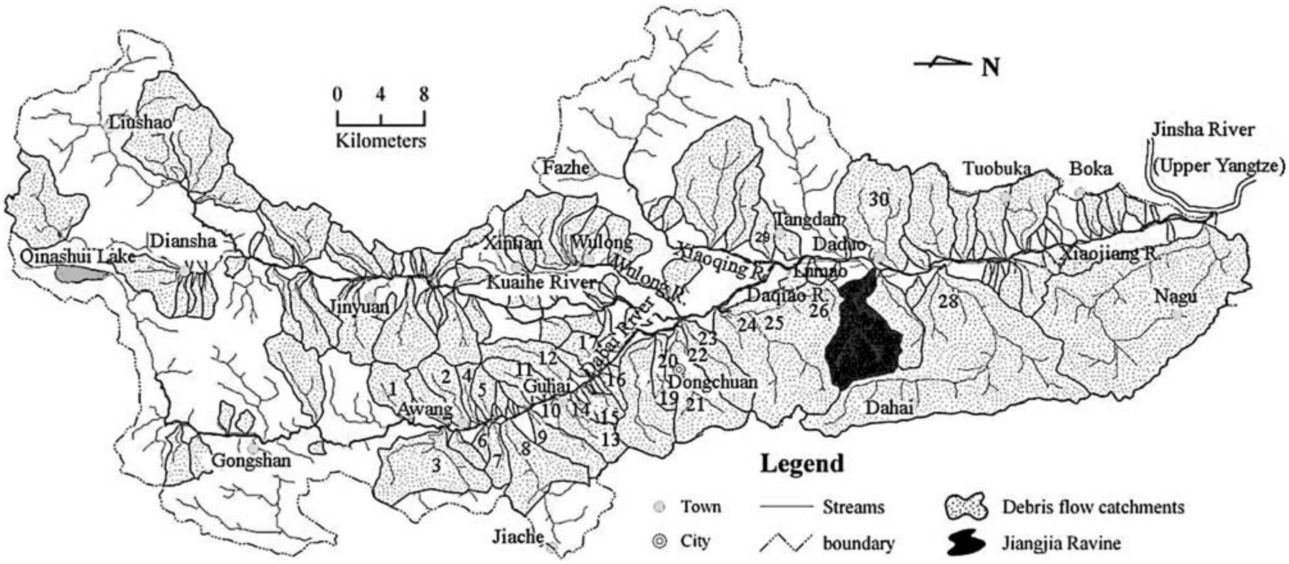


Figure 3. Xiaojiang River basin in the Jinsha River basin and debris flow gullies in the basin. Numerals indicate 1, Songshan Gully; 2, Tuota Gully; 3, Diaoga River; 4, Lilixiao River; 5, Luoge Gully; 6, Heisha Gully; 7, Xujiaxiao Ravine; 8, Tojiaxiao Ravine; 9, Hongsha Gully; 10, Xiaoshidong Gully; 11, Xiaobaini Ravine; 12, Dabaini Ravine; 13, Heishui River; 14, Dade Gully; 15, Laogan Gully; 16, Wangjiaqin Gully; 17, Tongchangqing Gully; 18, Xiaohai River; 19, Shiyang Gully; 20, Nilagu Gully; 21, Shengou Gully; 22, Zhuguosi Gully; 23, Tiankan Gully; 24, Reshuitang Gully; 25, Daqiao River; 26, Xiaoshui River; 27, Jiangjia Ravine; 28, Heishan Gully; 29, Shangchalu Gully; and 30, Lanniping Gully.

only 0.15% and sand bed load composes 1.7% of the total load, the size distribution curve of suspended load can be approximately regarded as the size distribution of the total load. The amount of sediment storage of different size fractions in the gullies and tributaries can be calculated by using equation (1) and taking figures for the upper watershed from *Sm* and for the downstream section from the size distribution at Yichang: For the fraction coarser than 0.5 mm, $S_d = (2179 \times 0.528) \times 10^6$ t $= 1151 \times 10^6$ t. For the fraction in the range 0.05 ~ 0.5 mm, $S_d = (2179 \times 0.226 - 514 \times 0.35) \times 10^6$ t $= 313 \times 10^6$ t. For the fraction finer than 0.05 mm, $S_d = (2179 \times 0.246 - 514 \times 0.65) \times 10^6$ t $= 202 \times 10^6$ t.

[22] In other words, almost all the sediment coarser than 0.5 mm eroded from the watershed deposits in the gullies and tributaries of the upper Yangtze River basin; 313×10^6 t of the 492×10^6 t of sediment of diameter in the range of 0.05–0.5 mm and 202×10^6 t of the 536×10^6 t of sediment finer than 0.05 mm deposit in the gullies and the tributaries of the upper Yangtze River basin.

[23] Figure 5 also shows the size distribution of bed load from the Diaoga River, which is an average of 18 samples weighted with the rate of bed load transportation. The rate of bed load transportation in the Diaoga River is as high as 100 kg m^{-1} min^{-1} in flood season, which is much higher than that in the Yangtze River. Nevertheless, most of the bed load cannot be transported to Yichang but deposits in the gullies and tributaries in the upper Yangtze River basin.

4. Sediment Transportation

[24] Figure 6 shows the annual runoff and sediment load in the Yangtze River along its course. The annual runoff increases from upstream to downstream but the annual sediment load increases from the source to Yichang (the Three Gorges Dam site), reaching its highest amount of 514×10^6 t yr^{-1}. Between Yichang and Luoshan the river flows out of the mountains and enters its alluvial reaches. The sediment load reduces from Yichang to Hankou due to deposition.

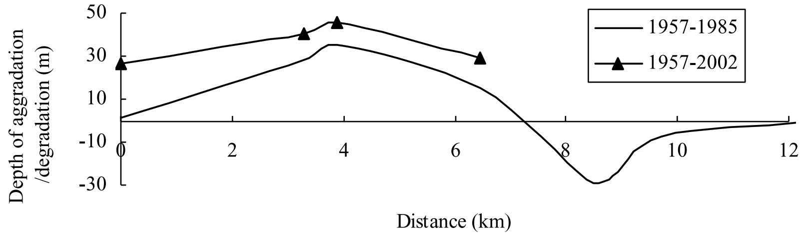


Figure 4. Aggradation and degradation of the Jiangjia Ravine in the periods 1957–1985 and 1957–2002 as a function of distance from the ravine mouth [after *He et al.*, 2003].

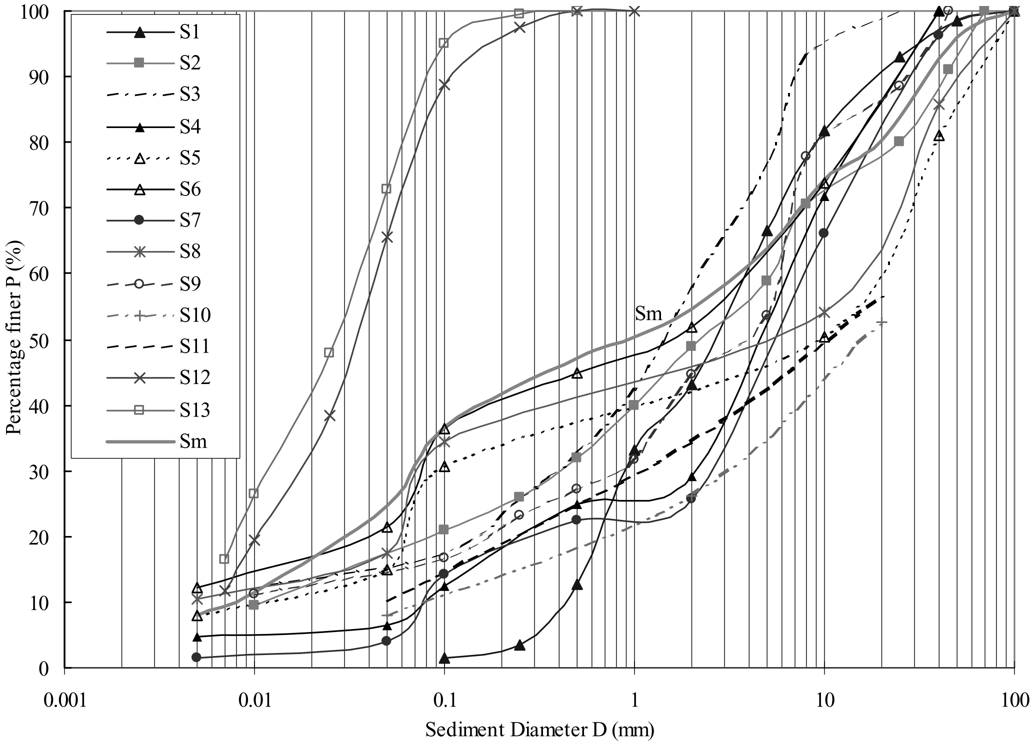


Figure 5. Comparison of the size distributions of sediment deposits in debris flow gullies and tributaries in the upper Yangtze River basin with those of suspended load at the Yichang and Datong stations. S1 is bed load in the Diaoga River; S2–S11 are sediment deposits in gullies and tributaries (S2, Xiaobaini Ravine; S3, Dabaini Ravine, S4, Tongchangqing Gully; S5, Dade Gully; S6, Xiaohai River; S7, Jiangjia Ravine; S8, Daduo Gully; S9, Xiaojiang River; S10, Sunshui River; S11, Niuri River); S12 is suspended load at Yichang; S13 is suspended load at Datong; and *Sm* is representative size distribution of eroded sediment from the upper Yangtze River basin.

[25] Figure 7 shows the water-sediment diagrams at four hydrological stations on the Yangtze River. In the diagrams the horizontal axis is the year of the statistics, the left vertical axis is the annual runoff volume, and the right vertical axis is the annual sediment load at the given hydrological station. The scales of the two vertical axes are set such that the long-term average runoff and the long-term average sediment load have the same position for the Datong Station, which is the most downstream station and the boundary between the lower reaches and the estuary. In the diagram the load and runoff are comparable and mutually convertible. A given runoff also represents the amount of sediment load the runoff can transport into the ocean. For the Pinshan (Yibin) and Yichang Stations,

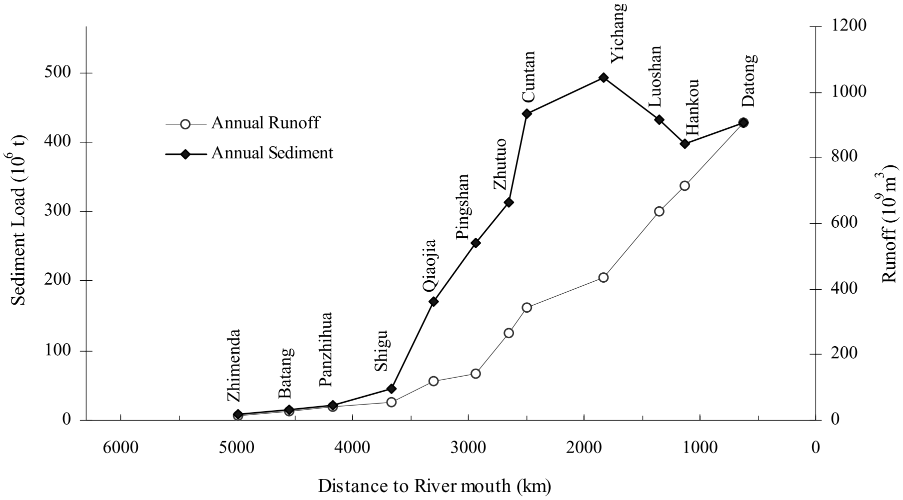


Figure 6. Distribution of annual runoff and sediment load along the course of the Yangtze River. The points are the average values for the period of 1950–2000 with data measured at the stations.

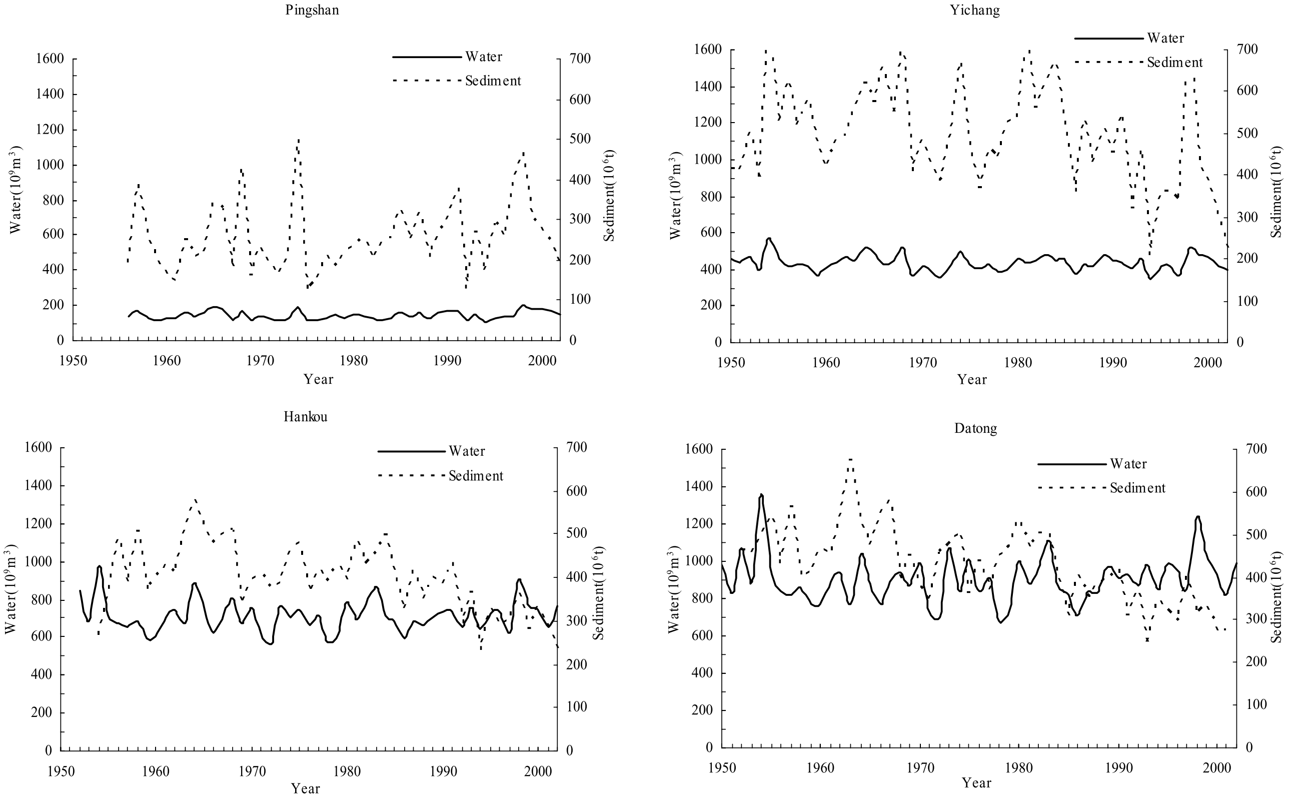


Figure 7. Water-sediment diagrams of the Pingshan (Yibin), Yichang, Hankou (Wuhan), and Datong Hydrological Stations on the Yangtze River. Water is annual runoff; sediment is annual sediment load.

the curve of sediment load is much higher than the curve of runoff, which implies that the load is more than the capacity of the flow and the difference between the two curves implies aggradation in a downstream reach. Both the runoff and load curves increase from Pinshan to Yichang, but the load curve increases more. From Yichang to Hankou (Wuhan), however, the runoff curve increases but the load curve reduces and the area between the two curves is much smaller, which implies a huge amount of sediment deposits in the reach between the two stations. At the Datong station the load curve is higher than the runoff curve in the period from 1955 to 1969. The sediment load has been continuously reducing since 1980, and the load curve is much lower than the runoff curve from 1990 to now.

[26] The middle and lower reaches of the Yangtze River are alluvial, and the sediment load varies in accordance with the sediment carrying capacity of the flow. Figure 8 shows the relations between the total sediment load and water discharge at the Yichang, Hankou, and Datong stations in different seasons. At Yichang (upper reaches), the sediment load is always proportional to the flow discharge because both sediment and water are from the upper reaches. At Hankou and Datong (middle and lower reaches), however, the sediment load is proportional to the flow discharge in the low-flow season from October to June, but the load is not related to the discharge in the flood season from July to September. In the middle and lower reaches, sediment consists mainly of bed material load in the low-flow season. The higher the flow discharge, the more sediment is eroded from the channel bed, and therefore the higher the sediment load. In the flood season, however, a lot of sediment is transported from upstream reaches but half of the water is from the middle and lower reaches. Sediment and water are from different reaches and a huge amount of sediment load is wash load, and therefore the sediment load is not strongly related to the flow discharge.

[27] *Wang and Dittrich* [1992] used the Rouse number, Z, to differentiate wash load and bed material load, in which the Rouse number is defined as

$$Z = \frac{w}{kU_*}, \tag{3}$$

where w is the fall velocity of the sediment particles, $k = 0.41$is the von Karman constant and $U^* = \sqrt{gs_f R}$ is the shear velocity, s_f is the energy slope, and R is the hydraulic radius of the flow. *Wang and Dittrich* [1992] found that some coarse sediment washed downstream for several hundred kilometers without exchange with the bed sediment at high flow intensities. Thence they proposed the following for identification of bed load, suspended bed material load, and wash load:

$$\text{bed load} > Z = 3 > \text{suspended bed material load} > Z = 0.06 > \text{wash load}. \tag{4}$$

[28] Figure 9 shows the calculated Rouse number at the Datong station in flood and low-flow seasons as a function of the flow depth. In the calculation the fall velocity is determined for the median diameter of the suspended sediment load. In the low-flow season the Rouse number is in the range of 0.1–0.25 and the suspended sediment is bed material load; in the flood season, however, the Rouse

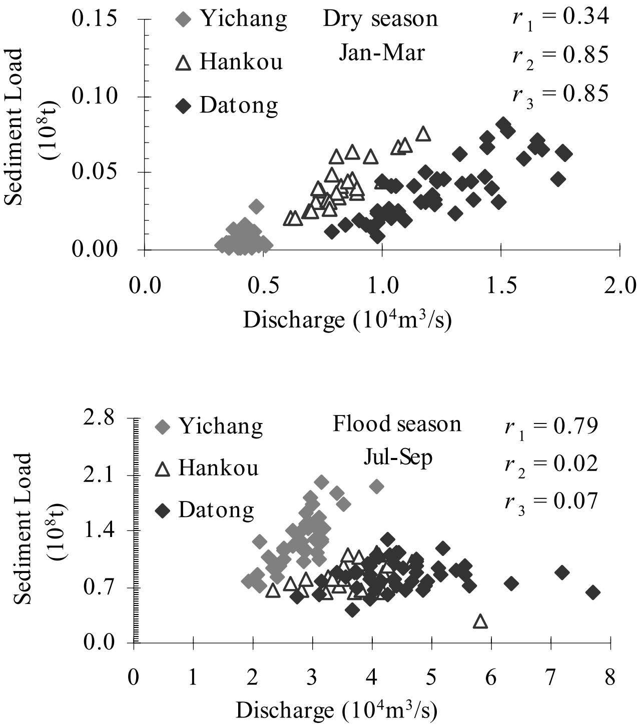


Figure 8. Relations between the monthly sediment load and monthly average flow discharge at Yichang (subscript 1, upper reaches), Hankou (subscript 2, middle reaches), and Datong (subscript 3, lower reaches) in low-flow season (January to March) and flood season (July to September) (r_n is the correlation coefficient of these relations). Data were measured in 1950–1989.

number is mostly smaller than 0.06 and thence the suspended sediment is wash load.

5. Sediment Demand

[29] The sediment demand in the Yangtze River consists of three parts: (1) sediment needed for fluvial processes; (2) sediment mining for building material; and (3) sediment utilized for land creation. The fluvial process and lateral movement of the channel is now constrained by the grand levees in the middle and lower reaches of the river. Sediment deposition and erosion mainly affect the longitudinal profile of the river. According to the minimum stream power theory, the morphology of fluvial rivers develops to reach the minimum stream power [*Yang*, 1996]. This can be described by the following equation:

$$\frac{dP}{dx} = \frac{d}{dx}(gsQ) = g\left(Q\frac{ds}{dx} + s\frac{dQ}{dx}\right) = 0, \tag{5}$$

where Q is the annual discharge, g is the specific weight of water, s is the bed slope, and x is the distance down the river. The equilibrium bed slope can then be calculated with the following formula:

$$s_{n+1} = \frac{s_n}{Q_n}\left[Q_n - \frac{DQ_n}{Dx_n}(x_{n+1} - x_{n-1})\right]. \tag{6}$$

[30] For the fluvial reaches of the Yangtze River (downstream from Yichang), the discharge increases along the course due to the inflow from tributaries; thus the equilibrium slope decreases along the course. The river exhibits a concave downward riverbed profile, as shown in the measured profiles in 1971 and 1982 in Figure 10. The fluvial process is developing toward the calculated profile (dashed curve). The inflow of water from the tributaries in the middle and lower reaches is reducing due to water diversion for economic development and agriculture. Assuming a reduction in the reach of about 10%, the equilibrium riverbed profile will be different as shown in Figure 10 (solid curve). It is clear that the measured bed profile is developing toward the equilibrium profile.

[31] The equilibrium bed profile is higher than the present profile and sedimentation dominates the fluvial process of the middle and lower reaches. Still a huge amount of sediment is needed for the riverbed to reach the equilibrium profile. Nevertheless, the volume of annual sedimentation in the middle and lower reaches depends on the incoming load. Figure 11 shows the relation between the net sedimentation (the volume of sedimentation minus erosion) and incoming sediment load from the upper reaches (measured at Yichang) and the Hanjiang River, in which the sedimentation in Tongting Lake is not included in the net sedimentation. The sediment load from Yichang and the Hanjiang River is more than 95% of the total sediment transported into the middle and lower reaches of the Yangtze River, to which the total incoming load refers in the following text. The net sedimentation in the middle and lower reaches increases linearly with the total incoming load. If the total incoming load is more than 280×10^6 t, sedimentation occurs in the river; if the total incoming load is around 500×10^6 t, 100×10^6 t of the sediment will deposit in the river. If there were no interruption by human activities, the fluvial process to reach the minimum stream power would continue for a long period of time because the present bed profile is still far from the equilibrium profile.

[32] Tongting Lake is between Yichang and Wuhan and is used as a flood diversion basin in the flood season. If the sediment load at Yichang is more than 100×10^6 t, a part of the load will be carried into Tongting Lake and deposit in the lake. The amount of sedimentation in the lake is proportional to the incoming sediment load from Yichang.

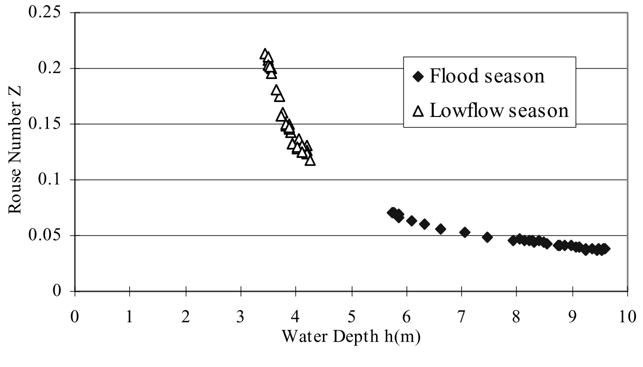


Figure 9. Calculated Rouse number at the Datong station in flood and low-flow seasons as a function of the flow depth (data from 1950–1980).

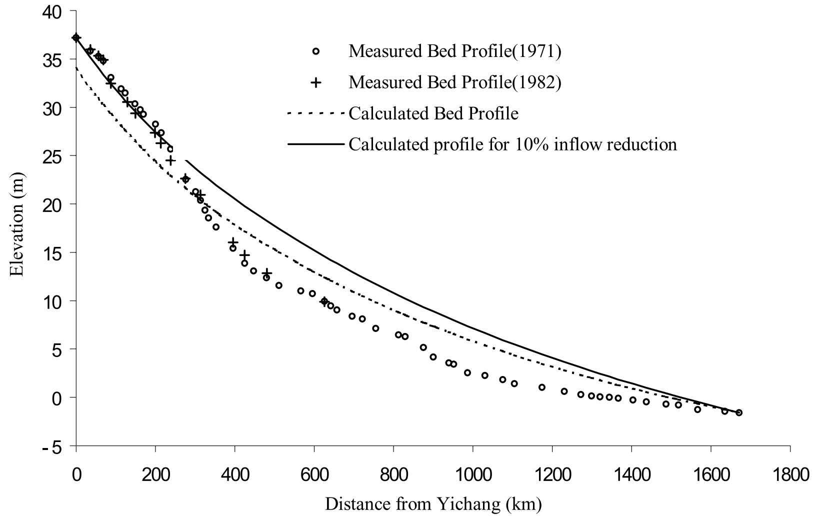


Figure 10. Longitudinal bed profiles of the middle and lower Yangtze River in comparison with the equilibrium bed profile required to reach the minimum stream power. Bed profile data are from *Navigation Department of Navy of People's Liberation Army* [1983] and *Wuhan Management Department of Yangtze River Navigation Channels* [1997].

The sediment budget for the middle and lower reaches can be summarized in the following formulas:

$$S_Y + S_H = S_F + S_T + S_E \tag{7}$$

$$S_F = k_1(S_Y + S_H - S_{c1}) \tag{8}$$

$$S_T = k_2(S_Y - S_{c2}), \tag{9}$$

where S_Y is the annual sediment load at Yichang; S_H is the annual sediment load from the Hanjiang River; S_F is the amount of sediment depositing in middle and lower reaches in the fluvial processes, which may be positive (sedimentation) or negative (erosion); S_T is the amount of sediment depositing in Tongting Lake; S_E is the annual sediment load at Datong, which represents the sediment load entering the estuary; S_{c1} and S_{c2} are the minimum incoming sediment load for sedimentation beginning to occur in the middle and lower Yangtze River and Tongting Lake, respectively; and k_1 and k_2 are dimensionless coefficients. Statistical analysis resulted in the value of k_1 and S_{c1}, as shown in Figure 11, and S_{c2} and k_2 as follows

$$k_1 = 0.4316; \qquad S_{c1} = 285 \times 10^6\text{t}$$
$$k_2 = 0.2905; \qquad S_{c2} = 105 \times 10^6\text{t}$$

From equations (7)–(9) and using the values of k_1, S_{c1}, k_2, and S_{c2} the following formula is obtained for the sediment load entering the estuary:

$$S_E = 0.2779 S_Y + 0.5684 S_H + 153.8 \times 10^6\text{t}. \tag{10}$$

If the sediment load from Yichang and Hanjiang reduce to 100 × 10^6 t and 20 × 10^6 t because of reservoirs, about 193 × 10^6 t of sediment may be transported into the estuary and most of the sediment is eroded from the middle and lower reaches.

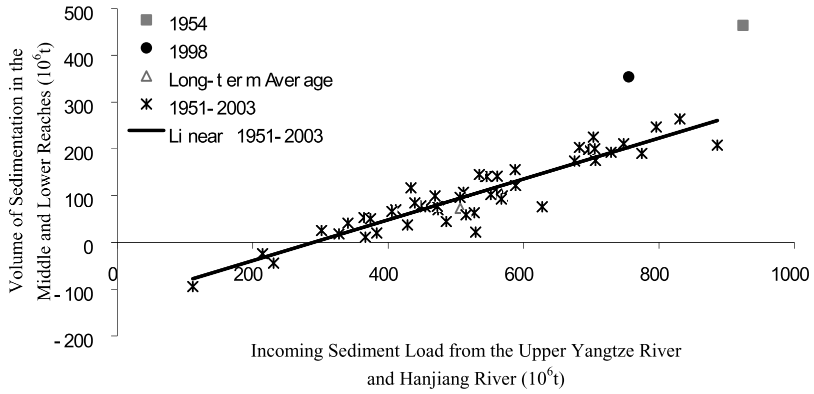


Figure 11. Relationship of the net sedimentation in the middle and lower Yangtze River to the incoming sediment load from the upper Yangtze River (measured at Yichang) and the Hanjiang River. Sedimentation in Tongting Lake is not included in the net sedimentation.

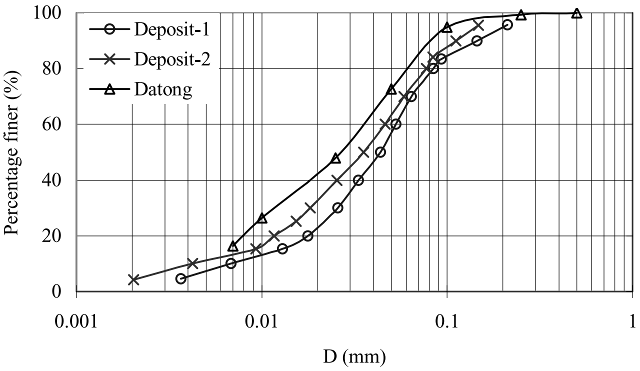


Figure 12. Size distributions of sediment deposits at the Yangtze River mouth and suspended load measured at the Datong hydrological station.

[33] Sediment mining has become an increasing sediment demand. In the 1990s, Yibin, Luzhou, and Chongqing (Wanxian City not included) mined 5.16×10^6 t of gravel and 10.14×10^6 t of sand from the Yangtze River for building material per year [*Yi*, 2003]. It is estimated that the other cities on the upper Yangtze River including Panzhihua, Wanxian, and Yichang mined roughly the same amount of sediment from the Yangtze River. The total sediment mining from the upper Yangtze River is around 30×10^6 t yr^{-1}. More sediment has been mined from the middle and lower reaches. In the early 1980s the annual mining from the middle and lower Yangtze River was about 40×10^6 t; this figure increased to 80×10^6 t in the late 1990s [*Chen*, 2004]. The Yangtze River Conservation Commission issued a regulation in 2003 that the total sediment mining from the middle and lower Yangtze River is limited to 34×10^6 t yr^{-1} [*Shen et al.*, 2003]. The amount of sediment mining has been not really reduced. The total capacity of sediment mining is about 6 times the limit. Illegal mining is active. The amount of sediment mining from the middle and lower reaches is not less than 80×10^6 t. At present the total sediment mining from the upper reaches and the middle and lower reaches is estimated at 110×10^6 t yr^{-1}.

[34] The third sediment demand is for land creation in the Yangtze River estuary. According to the data from 1951–2002, about 433×10^6 t of suspended load are transported into the Yangtze River estuary annually, of which about 45% deposit in the Yangtze River mouth for land creation, 45% are transported to the neighboring coastal areas and the Qiantang River mouth and deposit there, and only about 10% are transported into the ocean [*Wu*, 2001]. Figure 12 shows the size distributions of sediment deposits at the Yangtze River mouth and suspended load measured at Datong. The comparison between the size distributions shows that the percentage of sediment finer than 0.01 mm of the suspended load at the Datong Station is about 10% higher than those of deposits at the river mouth. In other words, about 10% of fine sediment in the suspended load transported to the estuary does not deposit in the river mouth but is transported away into the ocean by tidal currents.

[35] Land creation at the Yangtze River estuary is essential for development of Shanghai. In the past 50 years the Yangtze River has created 800 km^2 of new land in the river mouth [*Jin et al.*, 1997]. The natural land creation speed has slowed down and does not meet the increasing land demand. Various engineering measures have been and will be applied to accelerate land creation. The Shanghai government has an ambitious plan to create 1000 km^2 land at the Yangtze River mouth in 20 years by using the sediment load. It is estimated that 300×10^6 t of sediment is needed to maintain the equilibrium of the river mouth and for land creation.

6. Sediment Reduction Due to Human Activities and Sediment Shortage

[36] Numerous reservoirs have been built in the river basin in the past decades, and the sediment load has been reducing since the mid 1980s. There were 45,647 reservoirs of different sizes in the Yangtze River basin with a total storage capacity of 170.5×10^9 m^3 up to 2003, among which 143 reservoirs are large with storage capacities over 100×10^6 m^3. Figure 13 shows the reservoir capacity index, *RI*, of the Yangtze River varying with time from 1954 to 2003, in which

$$RI = \frac{\text{total reservoir capacity}}{\text{average annual runoff}}, \tag{11}$$

where the average annual runoff for the Yangtze River is 905.5×10^9 m^3.

[37] The Three Gorges Reservoir, which is still under construction and will have a storage capacity of 39×10^9 m^3, has recently started filling and trapping sediment. The capacity of the Three Gorges Reservoir is not included in the figure for 2003. Sediment trapping in the reservoirs causes sediment load reduction to the middle and lower reaches of the river. Figure 14 shows the 11-year moving average of water and sediment load in the Jialing and Hanjiang Rivers and at the Hankou and Datong Stations on the Yangtze River, in which the moving average is given as follows: The average from 1955 to 1965 is plotted at 1960, and the average from 1956 to 1966 is plotted at 1961, and so on. The moving average curve filters the random fluctuations and shows the varying trend. It is clear that the sediment load in the two main tributaries and the middle and lower Yangtze River have been continuously reducing since the 1980s.

[38] The Three Gorges Dam, located 37 km upstream of the Yichang Station, began to fill in June 2002. The pool level is now around 140 m and will rise to the normal pool level of 175 m in 2009. The filling of the reservoir has

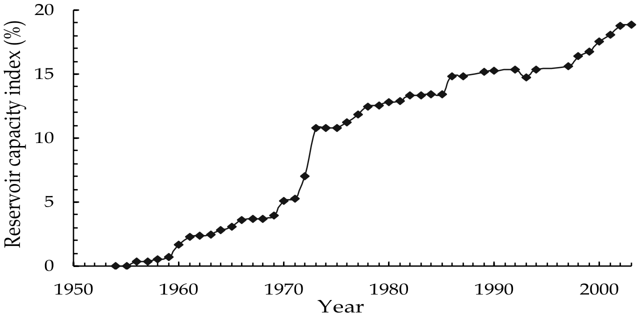
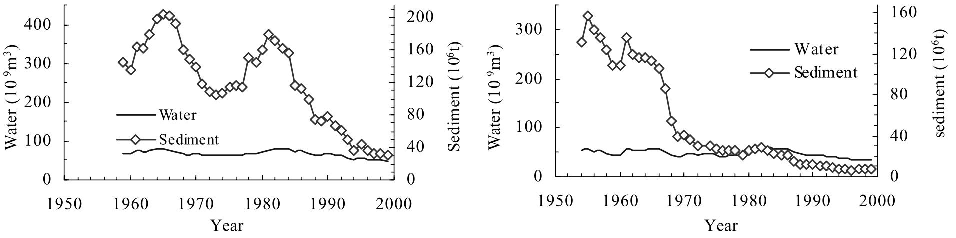
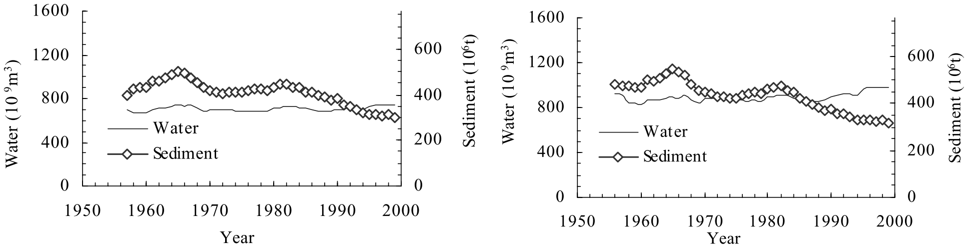


Figure 13. Reservoir capacity index of the Yangtze River during the period of 1954–2003.



Beibei Station on the Jialing River Huangzhuang Station on the Hanjiang River



Hankou Station Datong Station

Figure 14. Moving average (11-year) of sediment load and water at the Hankou and Datong stations on the Yangtze River, and the Beibei station on the Jialing River and the Huangzhuang station on the Hanjiang River.

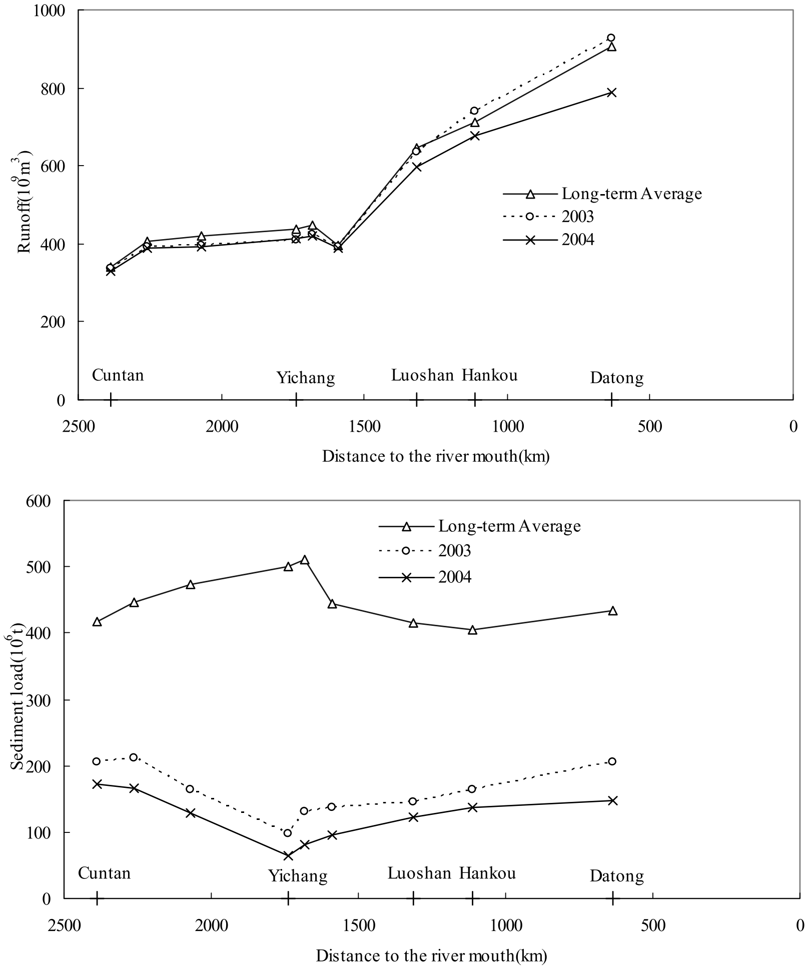


Figure 15. The annual runoff and sediment load after the impoundment of the Three Gorges Reservoir in comparison with the long-term (1951–2001) average values at the hydrological stations along the Yangtze River [after *Sediment Panel for the Three Gorges Project*, 2005].

caused further reduction in the sediment load. Figure 15 shows the distributions of runoff and sediment load along the course in 2003 and 2004, in which the long-term average distributions of runoff and sediment load in the period of 1950–2002 are shown for comparison [*Sediment Panel for the Three Gorges Project*, 2005]. The distributions of runoff in 2003 and 2004 are almost the same as the long-term average, but the distribution of sediment load changed greatly. The long-term average sediment load reduced from Yichang to Hankou due to sedimentation in the reach; but the sediment load in 2003 and 2004 increases from Yichang to Hankou because erosion occurred in the reach.

[39] Sediment transported to the lower reaches and the river mouth is remarkably reduced and cannot meet the sediment demands of the river. Sediment shortage has become a new challenge to the river engineers and sediment managers. The annual sediment load at Yichang has reduced from a long-term average of 514×10^6 t to 392×10^6 t since the mid 1980s and further reduced to about 100×10^6 t in 2003–2004, and sediment load at Datong has reduced from 427×10^6 t to 327×10^6 t since the mid 1980s and further reduced to less than 200×10^6 t in 2003–2004. On the other hand, the total sediment demand is more than 300×10^6 t for land creation and building materials. There is a sediment shortage of about 100×10^6 t.

[40] Because of the sediment shortage, the land creation projects in the river mouth will be performed using the sediment load from the river and also the sediment deposits in the neighboring areas, which may result in a change of estuarine processes.

7. Conclusions

[41] A method to determine the sediment budget is proposed for the Yangtze River. The total soil erosion from upper Yangtze River basin is about 2.2×10^9 t yr^{-1}, of which 76% is stored in the gullies and tributaries and 24% is transported to Yichang on the Yangtze River. The sediment stored in the gullies and tributaries is mainly the coarse part of the eroded sediment, including boulders, cobbles, gravel, and a part of the sand, silt, and clay. In the upper reaches of the Yangtze River, the sediment load is proportional to the flow discharge because both sediment and water are from the upper reaches. In the lower reaches, however, sediment comes from upstream reaches in flood season, but half of the water is from the middle and lower reaches. A huge amount of sediment load is wash load; thence sediment load exhibits a very poor relation with flow discharge. In low-flow season, not enough sediment is transported from the upper reaches, and much of the sediment load is from the riverbed. Therefore the sediment load in low-flow season consists mainly of bed material load and is proportional to the flow discharge.

[42] The sediment load transported into the middle and lower reaches is divided into three parts: One part deposits in the reaches to reach the equilibrium bed profile, which is proportional to the incoming sediment load from Yichang and the Hanjiang River; the second part deposits in Tongting Lake, which is proportional to the sediment load from Yichang; the third part is transported into the estuary, which also depends on the sediment load from Yichang and the Hanjiang River.

[43] There is a large amount of sediment demand for (1) the fluvial process to reach the equilibrium profile of the minimum stream power in the middle and lower reaches; (2) sediment mining for building material; and (3) land creation in the estuary. The riverbed profile in the middle and lower reaches is developing toward the equilibrium profile of the minimum stream power but the impoundment of the Three Gorges Reservoir interrupts this fluvial process. If reservoir trapped most sediment from the upper Yangtze River and Hanjiang River, less than 200×10^6 t of sediment may be transported into the estuary and most the sediment is eroded from the middle and lower reaches. There is a sediment shortage of about 100×10^6 t yr^{-1} to meet the sediment demand.

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Y. He, Key Laboratory of Mountain Hazards and Surface Process, Chengdu Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, Sichuan, China. (yiping_he@hotmail.com)

Y. Li, Wuhan University, Wuhan 430072, Hubei, China. (ytli@whu.edu.cn)

Z.-Y. Wang, State Key Laboratory of Hydroscience and Engineering, Tsinghua University, Beijing 100084, China. (zywang@tsinghua.edu.cn)