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Yangtze River of China: historical analysis of discharge variability and sediment flux

Zhongyuan Chen [a,*], Jiufa Li [a], Huanting Shen [a], Wang Zhanghua [b]

[a] *State Key Laboratory for Estuarine and Coastal Research, East China Normal University, Shanghai, 200062, China*
[b] *Department of Geography, East China Normal University, Shanghai, 200062, China*

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Abstract

Hydrological records (covering a 100-year period) from the upper, middle and lower Yangtze River were collected to examine the temporal and spatial distribution of discharge and sediment load in the drainage basin. The Yangtze discharge, as expected, increases from the upper drainage basin downstream. Only an estimated 50% of the discharge is derived from the upper Yangtze, with the rest being derived from the numerous tributaries of the middle and lower course. However, the distribution of sediment load along the Yangtze is the reverse of that observed for discharge, with most of the sediment being derived from the upper basin. A dramatic reduction in sediment load (by $\sim 0.8 \times 10^8$ tons/year) occurs in the middle Yangtze because of a marked decrease in slope and the change to a meandering pattern from the upper Yangtze rock sections. Considerable siltation also occurs in the middle Yangtze drainage basin as the river cuts through a large interior Dongting Lake system. Sediment load in the lower Yangtze, while significantly less than that of the upper river, is somewhat higher than the middle Yangtze because of additional load contributed by adjacent tributaries. A strong correlation exists between the discharge and sediment load along the Yangtze drainage basin during the dry season as lower flows carry lower sediment concentration. During the wet season, a strong correlation is also present in the upper Yangtze owing to the high flow velocity that suspends sand on the bed. However, a negative to poor correlation occurs in the middle and lower Yangtze because the flow velocity in these reaches is unable to keep sand in suspension, transporting only fine-grained particles downstream.

Hydrological data are treated for 30 years (1950–1980), when numerous dams were constructed in the upper Yangtze drainage basin. At Yichang and Hankou hydrological stations, records revealed a decreasing trend in annual sediment load, along with slightly reduced annual discharge at the same stations. This can be interpreted as the result of water diversion primarily for agriculture. Sediment load at Datong further downstream is quite stable, and not influenced by slightly reduced discharge. Furthermore, sediment concentration at the three hydrological stations increased, which can be attributed to sediment loss in association with intensifying human activity, especially in the upper drainage basin, such as deforestation and construction of numerous dams. Mean monthly sediment load of these 30 years pulses about 2 months behind discharge, implying dam-released sediment transport along the entire river basin during the high water stage.

Keywords: Human impact; Discharge; Seasonal fluctuation; Sediment load; Yangtze drainage basin

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[*] Corresponding author. Department of Geography, Yangtze Delta Program, East China Normal University, Shanghai, 200062, China. Tel.: +86-21-62232706; fax: +86-21-62232416.

E-mail address: Z.Chen@gislab.ecnu.edu.cn (Z. Chen).

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1. Introduction

Runoff and sediment load play an important role in modifying river morphology and patterns through time and space, and supporting riverine ecosystems along adjoining fluvial surfaces (Hupp and Osterkamp, 1996; Gupta et al., 1999; Lu and Higgitt, 1998, 1999; Miller and Gupta, 1999). The physical processes driving these two important components result from the interplay among the source of water and sediment, sediment flux, fluvial geomorphology and atmospheric circulation (Milliman and Syvitski, 1992; Gupta and Asher, 1998).

Over its geological history, China's Yangtze River, which flows from west to east to debouch into the East China Sea, has served as a link between nature and people. Its abundant fluvial resources, operating under the eastern Asian monsoon were vital for early Chinese Neolithic civilization $>$ 10,000 years B.P. (Chang, 1986). The huge Yangtze drainage basin, which is more than 6300 km in length and has a catchment area of 1.94×10^6 km^2, can be divided into the upper, middle and lower Yangtze reaches, primarily on the basis of geology and climate, and secondarily on the basis of the resulting geomorphology of the river.

The upper Yangtze is more than 4300 km long from the source to Yichang, and has a total drainage area of about 100×10^4 km^2 (Tong and Han, 1982). The mainstem (the Jingshajiang) is jointed by four major tributaries in this river section: the Yalongjiang, Mingjiang, Jialingjiang and Wujiang (Fig. 1,①–⑤). These rivers originate on the Tibetan plateau where the elevation is generally over 4000 m, and the rivers are deeply incised into rocky canyons with >1000 m in elevation difference between the riverbeds and mountain peaks (Fig. 2a). The channels are about 0.5–1.5 km wide, 5–20 m deep, and vary in slope from $10\text{–}40 \times 10^{-5}$, reaching a maximum of 450×10^{-5} (Fig. 3).

The middle Yangtze is 950 km in length, and has a total drainage area of about 68×10^4 km^2 (Tong and Han, 1982). Three large inputs join the main stream in this section: the Dongting Lake drainage basin, Hanjiang River and Poyang Lake drainage basin (Fig. 1; ⑥–⑧). This section of the river starts from Yichang, at the end of the Three-Gorges reach, to Hukuo, an outlet of the Yangtze on Poyang Lake (Fig. 1). In the middle Yangtze, the slope decreases dramatically to $2\text{–}3 \times 10^{-5}$, but at some locations slope can be as high as $6\text{–}8 \times 10^{-5}$. Locally negative bed slope occurs in the middle Yangtze where the two interior Dongting and Poyang Lakes are located (Figs. 1 and 3). The channel of middle Yangtze is wider and deeper than the upper course, with the width between 1 and 2 km and the depth between 6 and 15 m. A typical meandering river pattern with many cutoffs prevails in this river reach, where the river exits from the upper rock-confined valley into the Jingjiang fluvial plain (Fig. 2b). The well-known Jingjiang dike has been constructed along the river and elevated over time to 12–16 m in different places above the ground surface (Fig. 2c). This is the most vulnerable region for flood hazards (Changjiang Hydrological Committee of Hydrology Ministry, 1997; Li et al., 1999). The Three-Gorges Dam will be completed in 2009 in the Yichang reach to serve as the flood control (Fig. 2d). Several major meander cutoffs on the Jingjiang plain occurred during the early to mid-20th century. In the 1960s and the 1970s, a set of cutoff projects were used to manage the fluvial environment (You, 1987). This stabilized the migration of the river channel although the course of the river was shortened by approximately 78 km. This straightening of Jingjiang has resulted in tremendous siltation downstream in the river channel, bypasses, and interior lakes (You, 1987). Consequently, river and lake beds were raised to increase flood hazard potentials (Yin and Li, this volume).

Below the Hukuo, the final 930 km constitutes the lower Yangtze River with a total drainage area of 12×10^4 km^2. Several large interior lakes, such as the Chaohu and Taihu (Fig. 1; ⑨ and ⑩) in association with many tributaries, drain into the lower Yangtze. This segment of the river wanders among plains and hills, on which a high-stage water level about 8 m above mean water level, is clearly marked (Fig. 2e). The slope of riverbed decreases to $0.5\text{–}1.0 \times 10^{-5}$, and the channel widens to 2–4 km and deepens to 10–20 m. The river channel can however, be wider than >15 km and as shallow as ~ 6 m in its estuarine region (Fig. 2f). The lower Yangtze drainage basin, including its large estuarine system, benefits largely from upstream discharge and sediment accumulation (Chen et al., 1988). These are

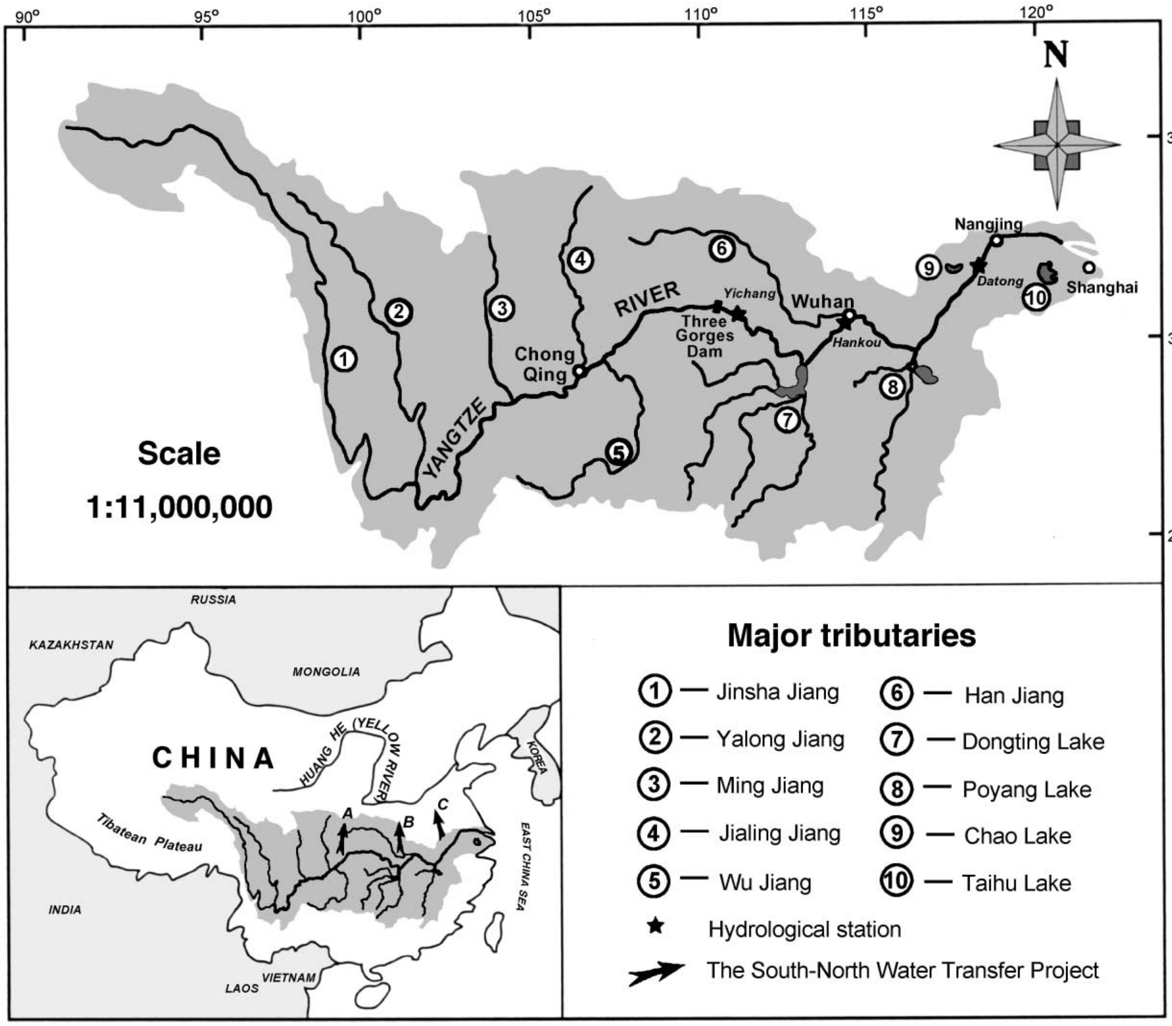
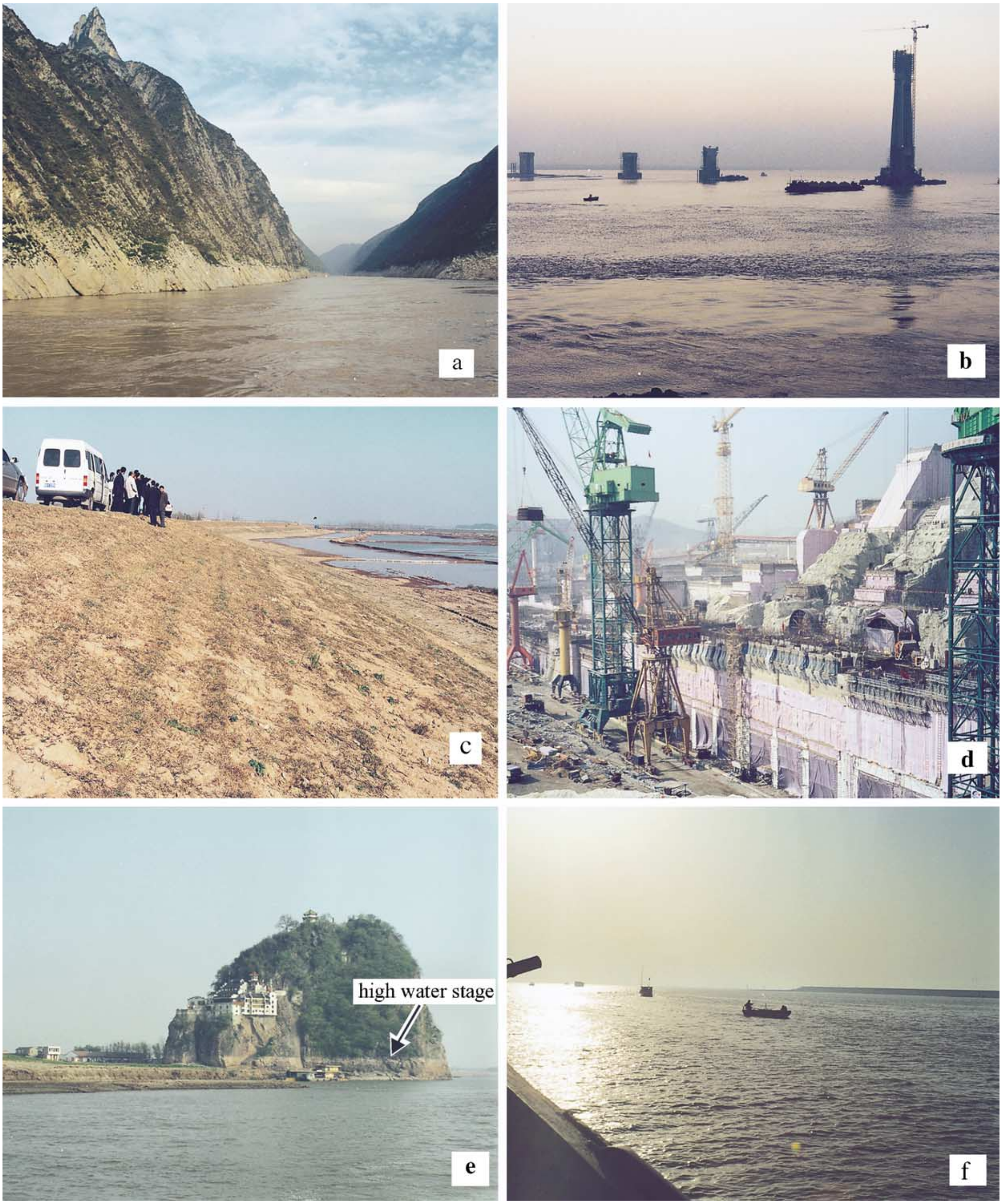


Fig. 1. The location of the Yangtze drainage basin, the major tributaries and interior lakes are indicated. Arrows (A, B, C) show the plan of the South-North Transfer Water Project.

vital natural resources for the intensive agriculture, fisheries, waterfowl production, vegetable irrigation and domestic consumption in the lower basin. Large estuarine islands (up to 40 km wide and 100 km long) and vast coastal wetlands, primarily due to rapid sediment progradation seaward during the last 2000 years B.P. (Chen et al., 2000) have been used for agriculture, housing and industry. On average, Southwest Pacific typhoons effect the lower Yangtze basin directly or indirectly one to three times each summer. On some occasions, typhoon-generated storms have met the annual Yangtze flood, raising sea level along the estuary by 2–3 m (Shao et al., 1991).

2. Methods and observations

In the study reported here, records of discharge and suspended sediment concentration in the Yangtze drainage basin were collected to examine their spatial and temporal distributions. Suspended sediment


a
b
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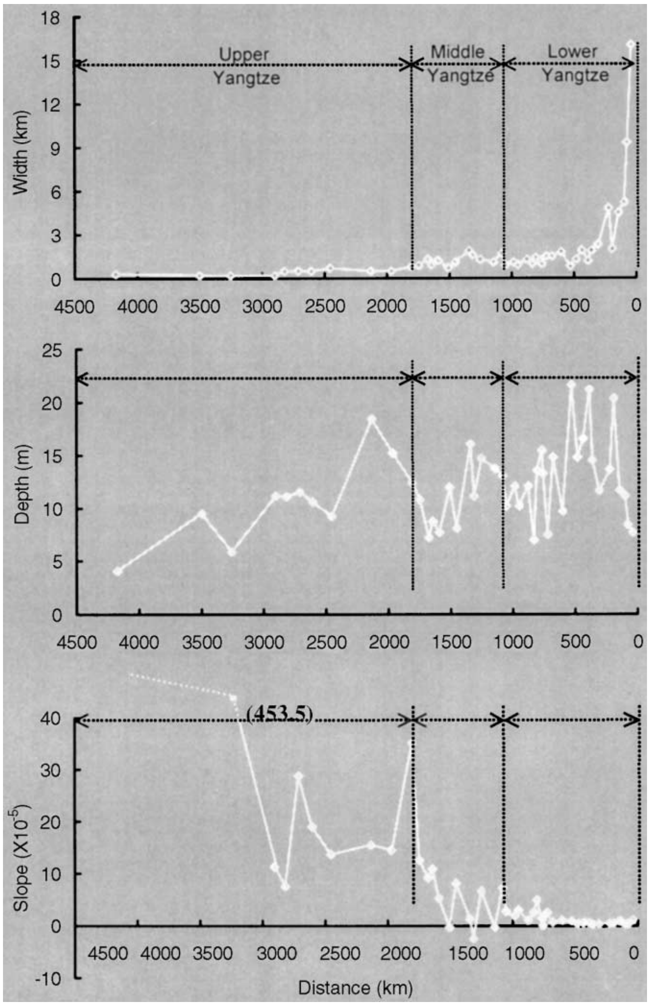

Fig. 3. The Yangtze fluvial variables, represented by slope, width and depth, along the entire river basin.

concentration was measured two or three times per month and averaged from four to six different water depths. Suspended sediment load is the product of discharge and concentration. Measurements were carried out along transects at hydrological stations located along the Yangtze River (Yangtze Water Conservancy Committee, 1875–1985). Three major hydrological stations were chosen for this study at Yichang, Hankou and Datong, representing the upper, middle and lower Yangtze River, respectively, (Fig. 1). Data from Loushan station positioned near Chengliji, east of the Dongting Lake in the middle

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Fig. 2. Fluvial landscape of the Yangtze drainage basin. (a) Upper Yangtze topography showing high relief between the water level and the mountain peaks (> 1000 m); (b) meandering river pattern and wide river channel (> 1000 m) of the middle Yangtze; (c) Jingjiang dike along the middle Yangtze River, which is now > 12 m above the adjacent ground surface, this dike was inundated during the big flood in 1998, and later was raised to another 1.0 m; (d) Three Gorges dam under construction, to be ready in 2009; (e) lower Yangtze plain reaches with local rock outcrops with about 8 m high flood marker that is almost 1.0 m higher than adjacent fluvial plain; (f) Yangtze estuary, > 10 km wide.

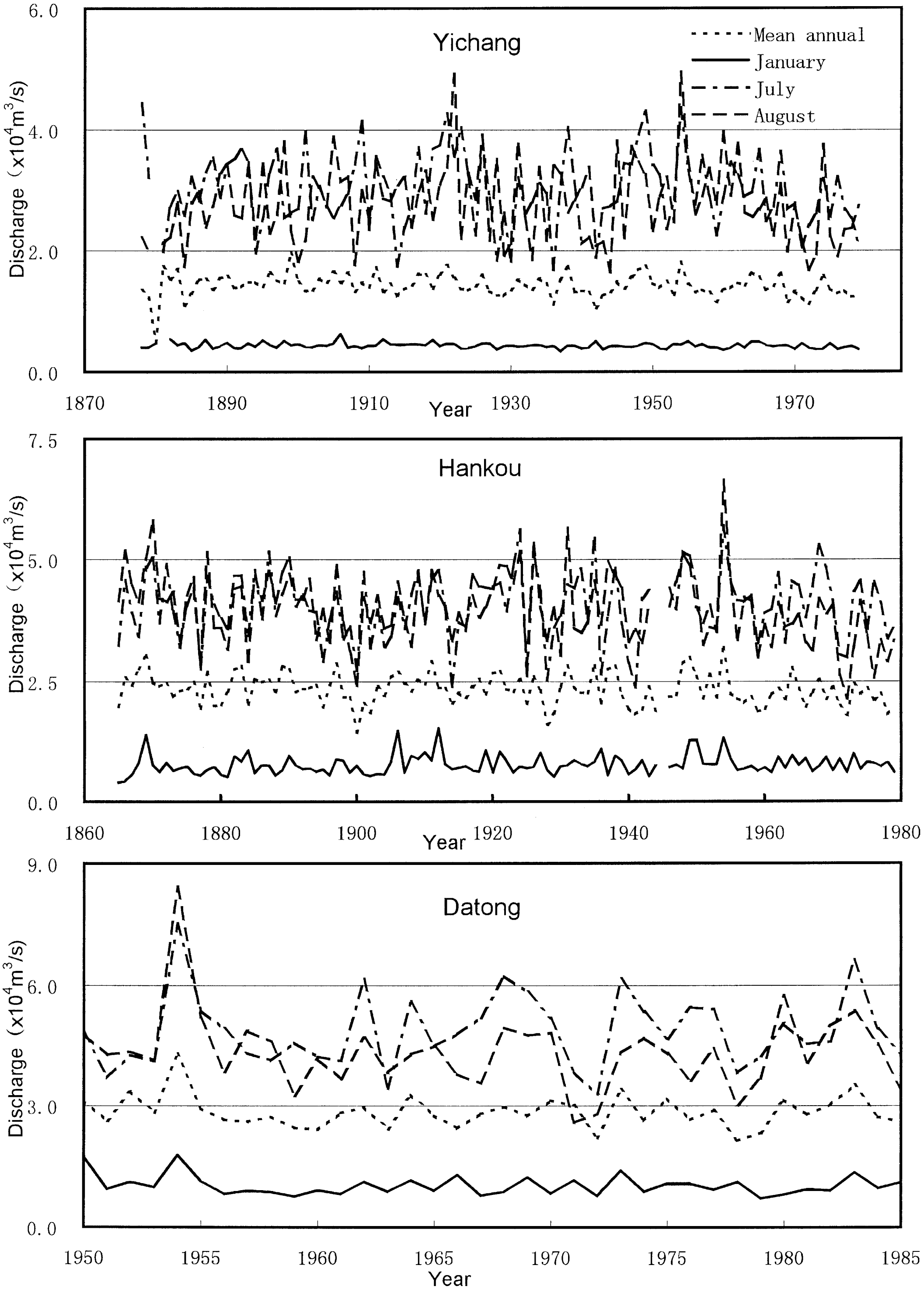

Fig. 4. Relation between discharge and time.

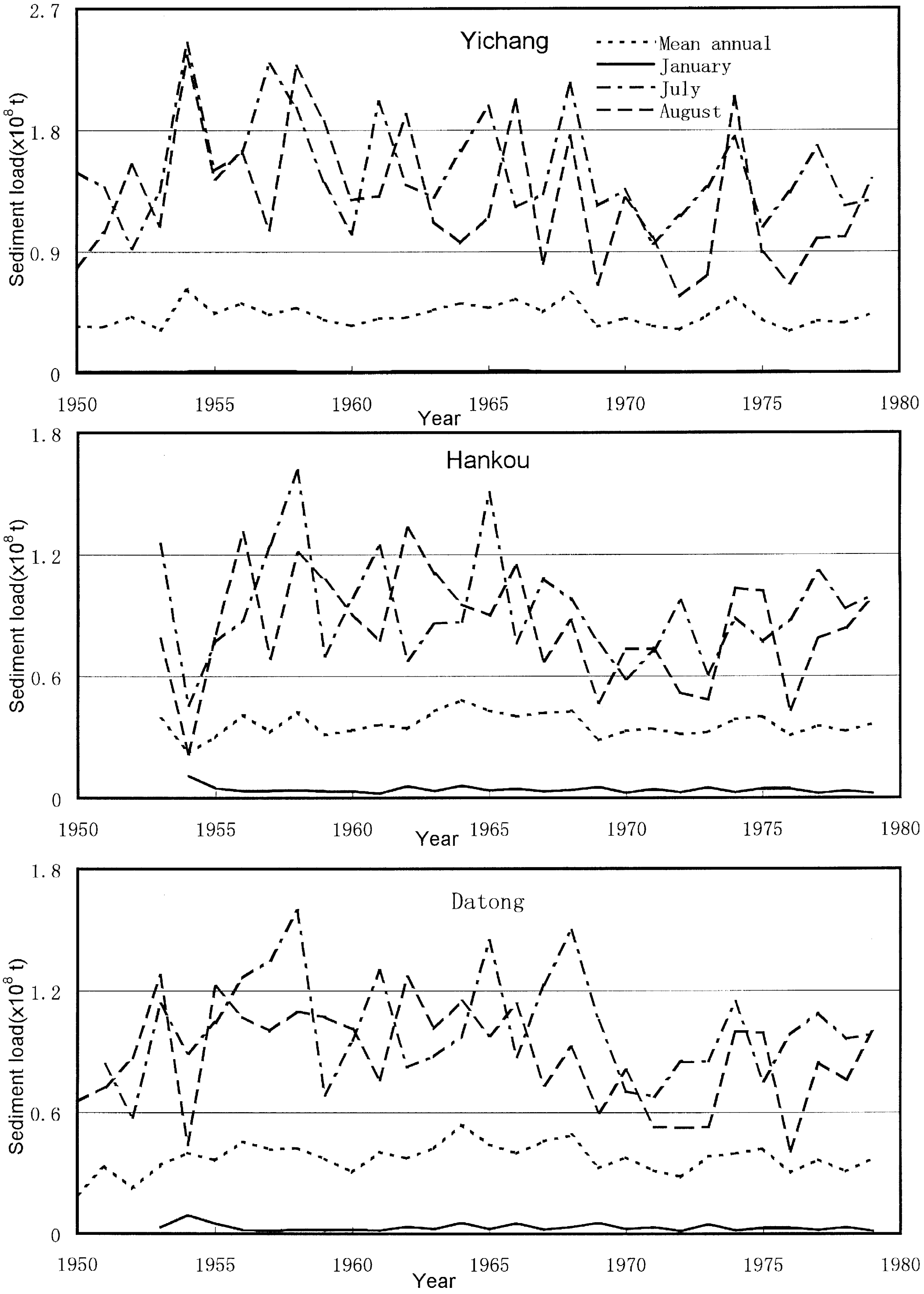

Fig. 5. Relation between sediment load and time.

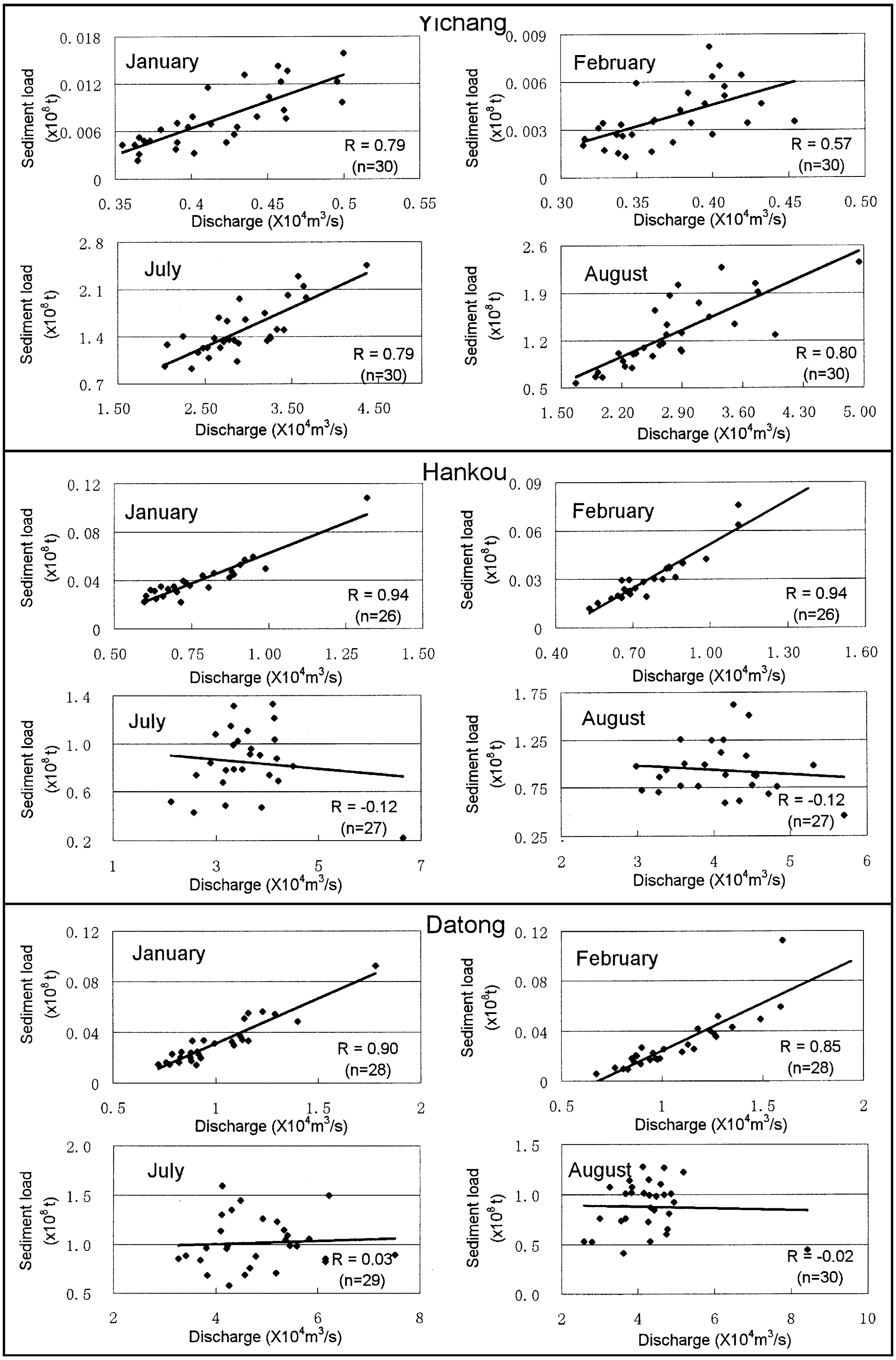

Fig. 6. Correlation of sediment load to discharge.

Yangtze (Fig. 1) were also used. The period record of these three stations did not start simultaneously. Hankou station has the longest record (1875–1980 for discharge and 1950–1980 for sediment load), Yichang has the second longest (1875–1980 for discharge and 1953–1980 for sediment load), and Datong has the shortest (1950–1985 for both discharge and sediment load). All the data are documented in an internal report "Annual Report on Yangtze Water and Sediment" (Yangtze Water Conservancy Committee, 1875–1985). Data for discharge and sediment load after 1980 (Yichang and Hankou) and 1985 (Datong), respectively, have not been released to the public and thus have not incorporated into the present study.

Discharge and sediment load were plotted against time to help understand the variations in water and sediment flux and their impact on the fluvial morphology in the Yangtze drainage basin over the last century (Figs. 4 and 5). Mean monthly data were calculated for July, August and January for the three sites to represent wet and dry seasons in the study area. Mean annual discharge and sediment load (sum of monthly values divided by 12) for the same period are also indicated on Figs. 4 and 5.

There is a marked difference in discharge between the wet and dry seasons (Fig. 4). At Yichang, discharge ranges approximately from 2.0 to 4.0×10^4 m^3/s in the wet season, in contrast to 0.4×10^4 m^3/s during the dry season. Downstream at Hankou (about 1000 km east of Yichang) discharge increases to $\sim 3.0–5.0 \times 10^4$ m^3/s in the wet season and about $0.6–1.1 \times 10^4$ m^3/s during the dry season. Further downstream, at Datong (about 700 km east Hankou) discharge ranges from about $3.3–6.0 \times 10^4$ m^3/s during the wet season to $0.9–1.2 \times 10^4$ m^3/s in the dry season (Fig. 4).

It is also obvious that the frequency of major discharge peaks along the Yangtze drainage basin increases downstream. There was almost no single major discharge peak exceeding 5.5×10^4 m^3/s in the upper Yangtze drainage basin in the 20th century (Fig. 4). In contrast, five major peaks of this size occurred in the middle Yangtze drainage basin within the same time period, and even more peaks (at least nine times from 1950 to 1985) occurred in the lower Yangtze drainage basin (Fig. 4).

The spatial variations in sediment load along the Yangtze show a trend opposite to that displayed by discharge (Fig. 5). Sediment load in the upper Yangtze, as recorded by Yichang hydrological station, varies during the wet season from 1.0 to 2.0×10^8 tons/month (about 0.5×10^8 tons mean annual). The sediment load is considerably lower in the dry season and is too low to be shown in Fig. 5. Downstream at Hankou, sediment load during the wet season decreases to about $0.6–1.2 \times 10^8$ tons/month (about 0.35×10^8 tons mean annual), while the dry season load is again very low, being only about 0.1×10^8 tons/month. In the lower Yangtze, sediment load during the wet season, as recorded by the Datong hydrological station ranges from about $0.7–1.4 \times 10^8$ tons/month, less than the upper Yangtze, but nearly the same as that from the middle Yangtze. Mean annual sediment load in the lower Yangtze (about 0.45×10^8 tons) is slightly higher than the middle Yangtze (Fig. 5). The dry season sediment load in the lower Yangtze is also similar to that in the middle reach (of the order of $\sim 0.1 \times 10^8$ tons/m), but still higher than that in the upper Yangtze.

We analyzed the correlation between discharge and sediment load for the past decades. The results demonstrate that along the upper, middle and lower

Table 1
Variables of suspended sediment (Yangtze Water Conservancy Committee, 1875–1985)

Station	Annual sediment concentration (kg/m^3)	Maximum		Annual sediment load ($\times 10^6$ tons)	Maximum		Minimum	
		Concentration (kg/m^3)	Date		Annual load ($\times 10^6$ tons)	Year	Annual load ($\times 10^6$ tons)	Year
Yichang	1.175	10.5	1959.7.26	516	754	1954	321	1992
Luoshan	0.677	5.66	1975.8.12	435	615	1981	307	1992
Hankou	0.594	4.42	1975.8.14	421	579	1964	267	1954
Datong	0.504	3.24	1959.8.06	451	678	1964	309	1992

Table 2

Average monthly precipitation along the upper, middle and lower Yangtze drainage basin (modified after You, 1987). Shaded box represents the wet season

Area	Jan (%)	Feb (%)	Mar (%)	Apr (%)	May (%)	June (%)	July (%)	Aug (%)	Sep (%)	Oct (%)	Nov (%)	Dec (%)	Annual total precip. (mm)	Month of the maxi. precip.	Max. precip. of that month (mm)
Upper Yangtze (%)	0.9	1.3	2.5	5.5	9.6	15.4	20.6	18.9	14.6	7.2	2.5	1.0	435	July	349
Middle Yangtze (%)	3.4	5.1	8.3	13.1	16.6	13.6	9.7	9.6	5.6	6.6	5.1	3.3	1396	May	369
Lower Yangtze (%)	3.7	6.4	9.8	13.7	17.4	15.9	7.9	8.1	5.4	4.3	4.0	3.4	1644	May	473

Yangtze drainage basin a strong positive correlation (significant level $\alpha = 0.001$) exists between discharge and sediment load during the dry season (Fig. 6). The middle Yangtze has the highest correlation coefficient ($R = 0.94$ for January and February), which is followed by the lower Yangtze ($R = 0.90$ for January, $R = 0.85$ for February) and then followed by the upper Yangtze ($R = 0.79$ for January, $R = 0.57$ for February). In contrast, our analysis reveals generally no significant correlation between discharge and sediment load in the middle ($R = -0.12$ for July and August) and lower Yangtze ($R = 0.03$ for July, $R = -0.02$ for August; Fig. 6) during the wet season. However, a strong correlation ($R = 0.79$ for July, $R = 0.80$ for August, significant level $\alpha = 0.001$) still exists during the wet season in the upper Yangtze.

Also, calculated are the variables of suspended sediment (Table 1), average monthly and annual precipitation (Table 2), and average monthly distribution of suspended sediment concentration (Table 3) of the Yangtze River (data after Yangtze Water Conservancy Committee, 1875–1985; You, 1987). These data all indicate: (1) decreased sediment con-

Table 3

Average monthly distribution of the suspended sediment concentration (kg/m^3) along the upper, mid and lower Yangtze drainage basin (Yangtze Water Conservancy Committee 1875–1985). Shaded box represents the wet season

Station	**Monthly average sediment concentration**											
	May	**June**	**July**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**	**Jan.**	**Feb.**	**March**	**April**
Yichang	0.928	1.130	1.910	1.770	1.380	0.740	0.470	0.200	0.073	0.045	0.122	0.318
Average	**1.310**						**0.205**					
Hankou	0.432	0.544	0.851	0.853	0.927	0.600	0.388	0.250	0.174	0.159	0.212	0.336
Average	**0.701**						**0.253**					
Datong	0.469	0.510	0.810	0.780	0.740	0.570	0.370	0.230	0.125	0.117	0.164	0.318
Average	**0.647**						**0.221**					

centration and sediment load downstream (Tables 1 and 3); and (2) concentrated precipitation from March to September, which increases from the upper drainage basin downstream (Table 2).

Mean annual sediment load and concentration, and mean annual discharge over the past 30 years (1950–1980) for Yichang, Hankou and Datong hydrological stations are shown on Fig. 7, respectively. Three 7–8-year cycles of sediment and discharge fluctuations are recognizable during that time period. Regression analysis indicates decreasing trends in sediment load and discharge at the Yichang and Hankou stations (Fig. 7a,c), except for Datong's sediment load, which increases slightly with time (Fig. 7a). Sediment concentration at the three stations also increases slightly (Fig. 7b) over that time period. The distribution of average monthly discharge and sediment load over the past 30 years (1950–1980) is also depicted to show the non-coeval fluctuations between the discharge and sediment load pattern at the three hydrological stations (Fig. 8).

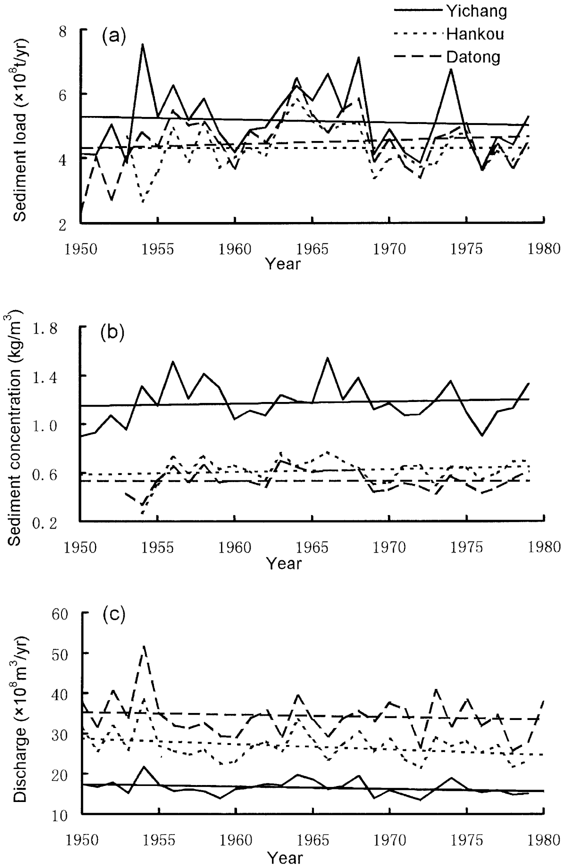

Fig. 7. Fluctuations of sediment distribution and discharge with time (1950–1980); (a) sediment load, (b) sediment concentration, (c) discharge.

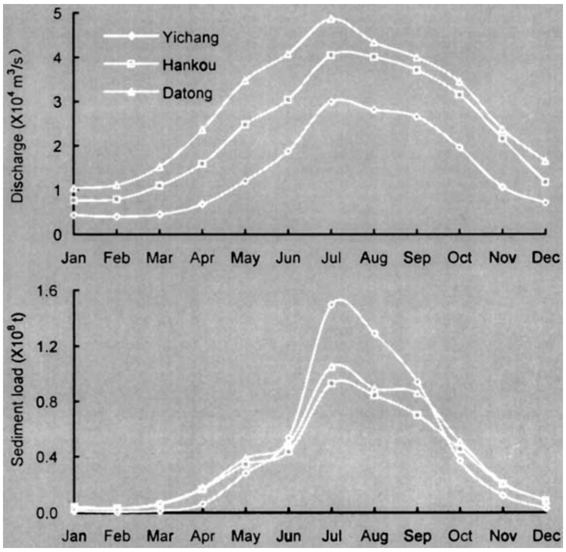

Fig. 8. Monthly runoff discharge and sediment load averaged for 30 years (1950–1980).

3. Discussion

3.1. Discharge

The annual Yangtze discharge (Fig. 4) increases as the drainage basin area increases downstream. The recorded data indicate increases in mean discharge, 1.4×10^4 m^3/s at Yichang to 2.3×10^4 m^3/s at Hankou and then to 2.8×10^4 m^3/s at Datong (Yangtze Water Conservancy Committee, 1875–1985). On the basis of these data, it seems that only about 50% of the annual runoff discharge in the lower Yangtze drainage basin is derived from the upper basin. This is due probably to both increased drainage basin area and higher precipitation downstream (China Academy Science and Ministry of Electrohydrology, 1963). Precipitation increases gradually from 400 to 1600 mm/year from the upper to lower Yangtze (Table 2). The network of tributaries that are located along the mid and lower Yangtze drainage basin also deliver a high regional runoff volume into the Yangtze (Fig. 1).

Although the annual runoff that discharges to the Yangtze estuary can be as high as 8.94×10^{11} m^3, this is however, much less than the volume of tidal water incoming from the sea. The annual tidal prism into the river mouth has a total volume of 83.98×10^{11} m^3, which is an order of magnitude greater than that of the annual Yangtze runoff discharge to the sea (Chen et al., 1988). The water chemistry in the estuary therefore will be sensitive to the impacts of "South to North Water Transfer Project", which has been planned upstream (Fig. 1). Saltwater will intrude further into the estuary, especially in the winter season. This could affect irrigation, and domestic and industrial water supplies in the estuarine region, where the metropolitan city Shanghai, with >12 million people located.

The ecosystem of the large Yangtze estuary is nursed by the upper stream discharge regarding the growth of large estuarine islands, freshwater watertable maintenance and aquaculture. The role of high-river stage, in associated with tidal oscillations along the river mouth area, has been long deliberated for various industrial and agricultural purposes. Examples include maintaining a smooth channel, particularly through the estuarine turbidity maximum zone where the water depth is only 7 m, and the reclamation of tidal flats which has enlarged the Yangtze coastal land by nearly 50% during the last century (Chen et al., 1988). Any significant change of the Yangtze discharge from upper stream will alter the ecological balance in such an important habitat base.

3.2. Sediment load

Suspended sediment load dominates over the bedload in the Yangtze River, representing about 95% of the total Yangtze sediment flux (Yangtze Water Conservancy Committee, 1875–1985; Chen et al., 1988). The decrease in sediment load downstream from the upper Yangtze is directly responsible for siltation within several large-scale interior lakes connected with the mid and lower Yangtze basin. Data collected by the Yangtze Water Conservancy Committee (1875–1985) reveal that nearly 27% of the sediment load (5.16×10^8 tons/year measured totally) at Yichang station is deposited in Dongting Lake, before the flow leaves the lake. About 0.59×10^8 tons/year suspended sediment load are carried out of the lake through the Chenglinji outlet to the east (Fig. 1) to merge with the remaining sediment in the Yangtze trunk stream. The total volume measured at the hydrological station of Loushan is 4.35×10^8 tons/year (Table 1).

The Hanjiang is a major tributary that meets the middle Yangtze at Hankou (Fig. 1). The Danjiangkou dam constructed in the upper Hanjiang basin in the late 1960s has been responsible for a 70% reduction in the suspended sediment load for the Hangjiang from a pre-dam level of 0.85×10^8 tons/year to a present level of 0.25×10^8 tons/year (Tong and Han, 1982). Ordinarily, the sediment load in the Hankou station would be expected to increase due to the input from the Hangjiang, but the suspended sediment load measured at Hankou actually decreases to 4.21×10^8 tons/year when compared with upstream Loushan (Table 1). This indicates that siltation occurs obviously along the middle Yangtze River between Chenglinji and Hankou section.

Below Hankou station, the Poyang Lake drainage system (Fig. 1) carries a low suspended sediment load (0.1×10^8 tons/year; Yangtze Water Conservancy Committee, 1875–1985) to the main Yangtze River. However, data measured at Datong station, located downstream, demonstrate that suspended sediment in the Yangtze increases to 4.51×10^8 tons/year (Table 1). We propose that this increase results from both net erosion and/or re-mobilization of numerous longitudinal bars and the carving of soft riverbanks along the lower Yangtze, together with significant inputs of sediment from the regional tributaries (Fig. 1), especially during the wet season.

3.3. The correlation between discharge and sediment load

The relationship between discharge and sediment load along the Yangtze is affected by a number of river channel variables, including slope, flow velocity, nature of sediment and river pattern (Higgitt and Lu, 1996), plus the fact that discharge is used to calculate sediment load. The strong correlation between discharge and sediment load observed during the dry season along the entire Yangtze arises partially because the low discharges during this season are matched by very low sediment loads (Fig. 6). The same high level of correlation in the upper Yangtze during the flood season can be interpreted as reflecting the fact that high flow velocities and stream power during high stages are able to mobilize and transport commensurately high sediment loads.

The poor correlation that occurs in the middle Yangtze during the flood season results from the abruptly diminished slope (Fig. 3) and lower velocities which are unable to transport as much sand as the upper reach. Concentrations of fine sediment are related to supply and not to flow. Sediment load is largely reduced in the Yichang area, where the river undergoes a transition from the upper Yangtze rock-cut channel to the middle Yangtze meandering course (Fig. 2). A large amount of sediment settles out in Dongting Lake, where the slope changes to $1–2 \times 10^{-5}$ or even becomes negative (Fig. 3). These river variables in the middle Yangtze greatly alter the balance between discharge and sediment concentration. The Danjiangkou Dam along the upper Hanjiang basin in the middle Yangtze, which cuts off a tremendous amount of sediment but does not alter the mean discharge greatly (Tong and Han, 1982), also contributes to the poor relationship. The poor correlation between discharge and sediment load still occurs in the lower Yangtze River (Fig. 6). Low flow velocity and further reduced riverbed slope accounts for this low correlation.

3.4. Sediment and runoff discharge fluctuations over the last 30 years

The 7–8-year cycles of sediment and discharge during 1950–1980 along the Yangtze drainage basin (Fig. 7a) may be related to variations in precipitation driven by the El Niño southern oscillation (Neelin and Latif, 1998) although more research is required on this possibility. The decreasing trend in sediment load for Yichang and Hankou is due to reduced discharge over the last 30 years (Fig. 7a,c). This reduction in discharge over that time period is possibly caused by water diversion for intensifying agriculture along the upper and middle Yangtze stream. In contrast, the slight increase in sediment load at Datong on the lower Yangtze is associated with the increase in sediment concentration at all three stations, especially Yichang (Fig. 7b). The overall increase in sediment concentration along the river probably reflects the recent intensive human impact, such as widespread deforestation in the upper Yangtze drainage basin (Higgitt and Lu, 1996). We would expect sediment changes due to human activity in the upper Yangtze to cause greater increase in sediment concentration downstream than the low rates that we have observed, particularly at Hankou and Datong (Fig. 7b). This low increase in sediment concentration possibly results from numerous small to medium size river dams constructed in the upper Yangtze drainage basin, mostly during 1950s to 1970s. This has reduced the large volume of sediment discharging downstream (cf. Lu and Higgitt, 1998).

3.5. Seasonal variation of runoff and sediment flux

Fluctuation of the Yangtze discharge and sediment load varies seasonally, primarily reflecting runoff from monsoonal precipitation (Table 2). Variability of discharge and sediment load can be characterised by two extremes: maximum peak and minimum low events (Figs. 4 and 8). For instance, at Yichang, the maximum discharge reaches 5.1×10^4 $m^3/s/month$, and minimum can be as low as 0.45×10^4 $m^3/s/month$. At Datong, the maximum peaks to 8.5×10^4 $m^3/s/month$ and the minimum is only 0.89×10^4 $m^3/s/month$. Rainfall along the Yangtze drainage basin directly controls the pattern of annual discharge distribution (Fig. 8; Table 2). The rainy season along the entire Yangtze drainage basin usually occurs from May to September, but varies in the upper, middle and lower Yangtze basins. Precipitation along the upper basin is concentrated from May to September, which amounts to 79.1% of the year total. Precipitation along the middle and lower basin is primarily between March and August, amounting to 70.9% and 72.8% of the annual total, respectively. Precipitation in the winter season (January and December) usually represents $< 1\%$.

During the wet season (May to October), the sediment load measured at Yichang makes up 93% of the annual total (Shen et al., 1992). Over the same period, the sediment load at Datong station approximates 85% of the total, and July alone represents 22.7% of the annual load. This may be contrasted to the month of February, when sediment load is 0.66% of the annual total. At Yichang station, mean suspended sediment concentration is only 0.205 kg/m^3 in the dry season (November to April; Table 3), and can be as high as 1.310 kg/m^3 in the rainy season (May to October). Similar patterns occur in Hankou and Datong stations, showing 0.253 and 0.221 kg/m^3 in the dry season, and 0.701 and 0.647 kg/m^3 in the rainy season (Table 3).

Based on the 30-year database (Fig. 8), distribution pattern of mean monthly discharge and sediment load through the entire Yangtze drainage basin did not fluctuate coevally in the wet season. Apparently, there is a time lag between the two. A generally symmetrical annual precipitation pattern results in a symmetrical increase in mean monthly hydrograph (starting from early April). In contrast, the sediment load pattern is asymmetrical, indicating a nearly 2-month lag in the sediment pulse over the same time scale. This time-lagged sediment load pattern based on 30-year (1950–1980) observation may also record the human-impacted sediment transport along the river channel. A large volume of sediment is primarily trapped behind the dams in wet season flood. As subsequent high-river stage occurs, numerous dams from all tributaries in the upper drainage basin release highly concentrated sediment downstream, causing this asymmetrical sediment load distribution pattern.

4. Summary

This study demonstrates that the Yangtze discharge in the middle and lower reaches tends to increase by about 50% over that in the upper reach above Yichang. This results from the contribution of numerous tributaries that join the middle and lower Yangtze and from an increase in precipitation from the upper drainage basin towards the lower Yangtze.

On the basis of a century long database, annual sediment load has decreased by 0.8×10^8 tons in the middle Yangtze, which reflects significant siltation along the main river channel and in the large interior Dongting Lake of central China, next to the Yangtze River. This can be explained primarily by the striking decrease in channel slope along the middle Yangtze downstream of the Three Gorges. The sediment load in the lower Yangtze is much less than that of the upper Yangtze, but slightly higher than that in the middle Yangtze. The additional sediment sources are probably from in-channel erosion of sand bars and soft banks, coupled with input from the tributaries that join the main channel along its lower course.

A statistically significant linear relationship exists between the discharge and sediment load in the upper, middle and lower Yangtze during the dry season. This relationship reflects that low discharges during the dry season carry very low sediment loads. In the wet season, a strong correlation also occurs in the upper Yangtze, where high flow velocities and stream power during high stages are able to mobilize and transport commensurately high sediment loads. Conversely, linear correlation coefficients are weak or even negative for the middle and lower Yangtze in the wet season. This may indicate a high increase in suspended sediment concentration as wash load processes, in association with decreased flow velocity downstream to the estuary.

Over the 30-year time scale (1950–1980), sediment load in the upper and middle Yangtze had been decreasing along with discharge, which is possibly due to water diversion for intensive agriculture of the region. In contrast, an overall, but very slight increase in sediment concentration had occurred along the entire Yangtze and caused an increase in sediment load in the lower Yangtze. This phenomenon can be attributed to human activity, such as deforestation and dam construction in the upper Yangtze drainage basin.

Mean monthly discharge and sediment load along the Yangtze are highly affected by seasonal precipitation. During the wet season, sediment load peaks almost 2 months after the discharge throughout the Yangtze drainage basin, probably recording dam-released sediment load during the high river water stage.

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