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Sediment rating parameters and their implications: Yangtze River, China

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Abstract

This study examines the characteristics of sediment rating parameters recorded at various gauging stations in the Yangtze Basin in relation to their controls. Our findings indicate that the parameters are associated with river channel morphology of the selected reaches. High b-values (>1.600) and low log(a) values (<−4.000) occur in the upper course of the steep rock-confined river, characterizing high unit stream power flows. Low b-values (<0.900) and high log(a) values (>−1.000) occur in the middle and lower Yangtze River associated with meandering reaches over low gradients, and can be taken to imply aggradation in these reaches with low stream power. Higher b-values (0.900–1.600) and lower log(a)-values (−4.000 to −1.000) characterize the reaches between Yichang and Xinchang, immediately below the Three Gorges. These values indicate channel erosion and bed instability that result from changes in channel gradient from the upstream steep valley to downstream low slope flood plain settings. Differences in channel morphology accompany these changes. Confined, V-shaped valleys occur upstream and are replaced downstream by broad U-shaped channels. The middle and lower Yangtze shows an apparent increase in channel instability over the past 40 years. This inference is based on sediment rating parameters from various gauging stations that record increasing b-values against decreasing log(a)-values over that time. Analysis of the sediment load data also reveals a strong correlation between changes in sediment rating curve parameters and reduction of annual sediment budget (4.70×10^8 t to 3.50×10^8 t/year, from the 1950s to 1990s), largely due to the damming of the Yangtze and sediment load depletion through siltation in the Dongting Lake. Short-term deviations from the general trends in the sediment rating parameters are related to hydroclimatic events. Extreme low b-values and high log(a)-values signify the major flood years, while the reverse indicates drought events. When compared with rivers from other climate settings, it is evident that the wide range of values of the Yangtze rating parameters reflects the huge discharge driven by the monsoon precipitation regime of eastern China.
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Keywords: Riverbed erosion and siltation; Hydromorphology; Monsoon climate; Sediment rating parameter; Sediment transport; Yangtze River

1. Introduction

During recent decades, river erosion and sedimentation have been linked to questions of variations in fluvial sediment transport and sediment flux (Vansinckle and Beschta, 1983; Fenn et al., 1985; Ferguson, 1986; Milliman

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and Syvitski, 1992; Miller and Gupta, 1999; Chen et al., 2001a; Zhao and Chen, 2003). Riverbed stability and its significance as a factor in sediment yield and transport estimates have been evaluated over time and space (Belperio, 1979; Ferguson, 1987; Jansson, 1996; Córdpva and González, 1997; Moog and Whiting, 1998; Whiting et al., 1999; Asselman, 1999, 2000; Syvitski et al., 2000; Horowitz, 2003; Morehead et al., 2003; Simon et al., 2004).

The sediment rating curve is defined as the statistical relationship between suspended sediment concentration (SSC) or sediment load (Q_s) and stream discharge (Q). The relationship generally takes the form of a power function, although other types of relationships have also been advocated (Syvitski et al., 1987; Córdpva and González, 1997). The general relationship between Q and SSC is expressed as:

$$\log \mathrm{SSC} = \log a + b \ \log Q$$

Asselman (2000) argued that the parameters a and b in the sediment rating curve contain no particular physical meaning. Other studies see the sediment rating parameter a as an index of erosion severity in the river channel (Peters-Kümmerly, 1973; Morgan, 1995). Usually, high a-values occur in areas characterized by easily eroded and transported materials. The rating parameter b is taken to depict the erosive power of the river. Large values are thought to be indicative of rivers that show a strong increase in entrainment and transport with increasing discharge. However, b can also reflect the extent to which new sediment sources become available when discharge increases (Asselman, 2000). According to Walling (1974), b-values can be affected by the grain-size distribution of the material available for transport. Syvitski et al. (2000) stated that in North American rivers the sediment rating parameters are often influenced by sediment rating, erosion and climate.

Due to the inverse correlation between log(a) and b-values of the sediment rating curve, it has been suggested that a combination of the log(a) and b-values may act as a measure of soil erodibility and erosivity (Rannie, 1978; Thomas, 1988; Asselman, 2000). Steep rating

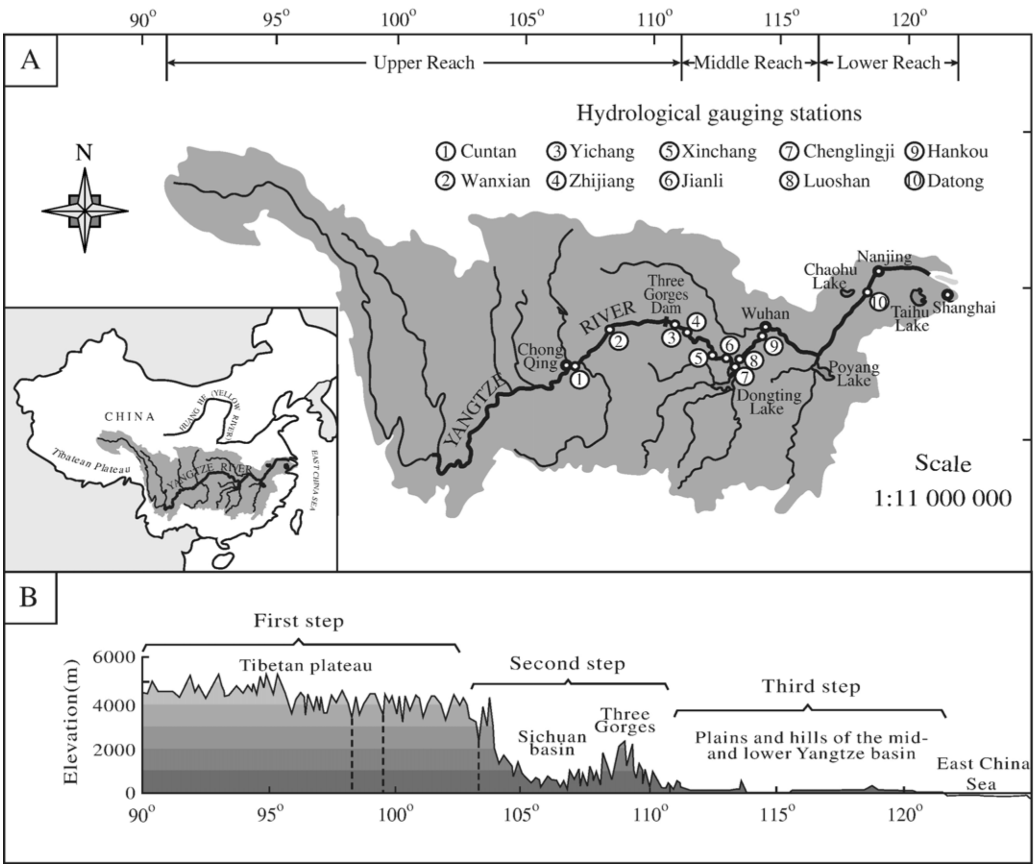

Fig. 1. A. Sketch map of Yangtze drainage basin showing ten gauging stations selected for the present study and Dongting Lake of the middle Yangtze Basin; B. Three morphological levels of the basin.

Table 1
The sediment rating parameters recorded at the various gauging stations in the Yangtze River (shaded boxes indicate the maximum or minimum values of sediment rating parameters)

Year	Cuntan		Wanxian		Yichang		Zhijiang		Xinchang		Jianli		Chenglinji		Luoshan		Hankou		Datong	
	log(a)	b	log(a)	b	log(a)	b	log(a)	b	log(a)	b	log(a)	b	log(a)	b	log(a)	b	log(a)	b	log(a)	b
1950					–1.796	1.078														
1951					–4.301	1.668	–2.538	1.244					1.533	0.159					–1.873	0.998
1952			–3.222	1.459	–2.959	1.364	–3.398	1.452					2.736	–0.123						
1953	–3.699	1.595	–3.523	1.532	–3.398	1.466	–3.523	1.490					2.840	–0.119					–3.155	1.284
1954	–3.301	1.466	–2.921	1.351	–3.155	1.406	–3.699	1.491			–0.105	0.690	3.439	–0.294	1.838	0.150	2.845	–0.103	0.520	0.419
1955	–4.523	1.756	–5.046	1.850	–3.699	1.542	–3.046	1.378					2.992	–0.220	1.633	0.232	–0.217	0.648	–2.444	1.119
1956	–5.699	2.076	–3.222	1.442	–3.398	1.517	–3.523	1.518	–2.174	1.223	–0.431	0.841	2.436	–0.039	1.453	0.289	–0.989	0.853	–2.509	1.158
1957	–4.398	1.768			–4.000	1.621	–3.699	1.583	–1.917	1.161	–1.553	1.115	3.164	–0.230	1.140	0.377	–0.921	0.827	–3.699	1.391
1958	–4.155	1.705			–4.000	1.628	–4.000	1.623	–2.009	1.195	–1.510	1.112	2.682	–0.110	0.258	0.433	–0.975	0.846	–3.398	1.346
1959	–5.523	2.055			–5.000	1.900	–4.222	1.707	–3.523	1.561	–1.658	1.145	2.238	0.029	2.346	0.098	–0.578	0.761	–2.114	1.071
1960					–3.523	1.499	–4.097	1.683	–1.370	1.015			2.191	0.020	0.898	0.432	–1.693	1.019	–4.000	1.451
1961	–4.523	1.760			–4.301	1.696			–3.155	1.447					0.512	0.508	–1.726	1.007	–3.523	1.364
1962	–4.523	1.731			–2.770	1.308			–2.174	1.195					1.455	0.270	–0.652	0.745	–2.553	1.134
1963	–5.301	1.961			–4.398	1.725			–0.965	0.930					–0.503	0.759	–2.081	1.107	–5.097	1.761
1964	–3.301	1.449											3.843	–0.416	0.876	0.413	0.816	0.421	–2.174	1.077
1965	–4.699	1.773			–3.398	1.475			–1.607	1.069					0.678	0.470	–1.726	1.006	–3.699	1.399
1966	–3.699	1.571			–4.699	1.790			–3.155	1.461					–0.131	0.679	–2.252	1.152	–2.854	1.241
1967	–5.046	1.921			–4.097	1.661			–2.119	1.226	–1.636	1.124			0.620	0.503	–0.943	0.845	–2.538	1.171
1968	–4.523	1.776			–4.523	1.749			–1.500	1.070	–0.182	0.757			1.209	0.357	–0.854	0.801	–2.602	1.171
1969	–4.523	1.811	–4.155	1.672	–4.222	1.691			–1.124	0.994	0.010	0.717			1.035	0.396	–0.613	0.743	–2.041	1.028
1970													2.791	–0.151	0.335	0.537	–1.045	0.834		
1971	–6.000	2.111	–6.000	2.108									1.915	0.071	–0.397	0.741	–2.081	1.107		
1972													1.327	0.242	–0.054	0.671	–1.821	1.057	–4.301	1.568
1973															0.946	0.390	–1.017	0.821	–2.244	1.050
1974	–4.155	1.674	–4.222	1.665									2.031	–0.003						
1975	–4.301	1.719	–4.523	1.751	–4.398	1.720			–1.427	1.045	–0.437	0.820	2.219	–0.037	0.795	0.458	–1.672	0.991		
1976					–4.000	1.591			–2.824	1.378	–0.769	0.895	1.889	0.097	0.914	0.434	–1.280	0.904	–2.921	1.225
1977	–6.398	2.239	–5.523	1.986	–5.398	1.958			–2.469	1.311	–0.473	0.828			0.682	0.478	–2.056	1.074	–3.046	1.246
1978	–4.699	1.835	–5.301	1.942	–5.523	2.008			–1.724	1.135			1.842	0.080	–0.611	0.808	–2.678	1.251	–4.046	1.514
1979	–4.699	1.829	–4.699	1.820											0.244	0.606	–1.951	1.069	–4.000	1.484
1980	–4.301	1.717	–4.000	1.616	–3.699	1.543			–0.473	0.810	–0.534	0.824	2.012	0.005					–2.796	1.185
1981	–4.301	1.737			–6.523	2.206			–1.772	1.132	–1.513	1.084	1.358	0.192	–1.321	0.949	–2.824	1.250	–4.523	1.579
1982	–4.699	1.804	–2.347	1.219	–6.097	2.091			–1.860	1.131	–1.162	0.977	2.302	–0.064	–0.180	0.666	–2.187	1.084	–3.398	1.320
1983	–5.301	1.974			–7.222	2.341			–1.625	1.080	–1.100	0.956			–0.475	0.731	–1.780	0.981	–2.886	1.185
1984					–7.699	2.460			–2.086	1.190	–1.117	0.982			–1.717	1.034	–2.770	1.235	–4.699	1.607
1985	–4.699	1.803			–6.523	2.199					–2.215	1.233			–1.708	1.036	–2.770	1.242	–5.097	1.713
1986	–5.398	2.007	–6.000	2.077															–4.523	1.589
1987	–4.699	1.825	–4.523	1.731							–2.357	1.261							–4.000	1.422
1988	–4.398	1.743																		
Maximum	–3.301	2.239	–2.347	2.108	–1.796	2.460	–2.538	1.707	–0.473	1.561	0.010	1.261	3.843	0.242	2.346	1.036	2.845	1.251	0.520	1.761
Minimum	–6.398	1.449	–6.000	1.219	–7.699	1.078	–4.222	1.244	–3.523	0.810	–2.357	0.717	1.327	–0.416	–1.708	0.098	–2.824	–0.103	–5.097	0.419
Long-term average	–4.649	1.806	–4.327	1.701	–4.438	1.721	–3.574	1.517	–1.957	1.171	–1.041	0.964	2.371	–0.043	0.426	0.530	–1.350	0.919	–3.195	1.290

curves, characterized by high b-values and low $\log(a)$-values, reflect river sections in which little sediment transport takes place at low discharges. In such channel reaches, an increase in discharge is matched by an increase in sediment concentration. This relationship implies that either the power of the river flow to erode material is high, or important sediment sources have become available (Asselman, 2000). In contrast, rating curves with low slopes indicate rivers flowing through intensively weathered materials, or the availability of easily entrained channel sediments (Asselman, 2000).

A number of research papers, concerned with fluvial sediment transport and monitoring of environmental change in the Yangtze Basin have recently been published (Lu and Higgitt, 1998; Shen et al., 2000; Zhu, 2000; Chen et al., 2001a; Chen and Zhao, 2001; Pan, 2001; Shi et al., 2002; Yang et al., 2002, 2003; Fu et al., 2003; Xia and Li, 2004; Yin et al., 2004). Little attention, however, has been given to the possible significance of the rating parameters. This paper examines the correlation between sediment rating parameters and their controls, and their close association with the regional geology and climate in the Yangtze Basin. We evaluate the likely riverbed changes represented by channel erosion and aggradation along the Yangtze River, based on long-term daily discharges and SSC records at a series of gauging stations (Fig. 1). The present study will shed light on monitoring river channel change and associated catchment issues, emphasizing the intensifying anthropogenic activity, such as the well-known Three Gorges Dam project.

2. The Yangtze River

The Yangtze River originates from the Tuotuo River on the southwestern side of the snow-draped Geladandong Mountains on the Tibetan Plateau. It flows eastward across Qinghai, Tibet, Sichuan, Yunnan, Hubei, Hunan, Jiangxi, Anhui and Jiangsu provinces into the East China Sea at Shanghai. More than 700 tributaries join this 6300 km long river draining a 1.8 million km^2 basin, accounting for 19% of China's national area (Chen et al., 2001a). The mean average annual discharge to the sea is 9.24×10^{11} m^3 and the mean annual SSC 4.70×10^8 t (Chen et al., 1988).

The Yangtze River consists of three segments. The upper segment extends from the source to Yichang, with a length of 4504 km and a drainage basin area of 100×10^4 km^2. The Yangtze flows primarily across mountainous regions with steep channel slopes ($10–40 \times 10^{-5}$). The middle Yangtze lies between Yichang and Hukou, extending over a distance of 955 km and draining an area of 68×10^4 km^2. Low relief topography with channel slopes of $2–3 \times 10^{-5}$, and meandering platforms are characteristics of the region. The segment from Hukou to the river mouth constitutes the lower Yangtze. It is 938 km long and has a drainage basin area of 12×10^4 km^2. An anabranching river pattern accompanies the lower channel gradient of about $0.5–1.0 \times 10^{-5}$ (Chen et al., 2001b). The main stream is tidally influenced below Datong gauging station.

Three morphological levels occur in the Yangtze drainage basin. The Tibetan Plateau in the southwest serves as the highest step. The second step comprises a series of high mountains and mountain-girt basins with a southwest to northeast orientation. The third step constitutes the lower fluvial to coastal plains of eastern China.

The climate of the Yangtze drainage basin is typically subtropical, wet and warm in summer and moist and cool in winter. High humidity (relative humidity — 65–80%), particularly during the summer, is typical of the basin (Shen, 1986; Chen et al., 2001a). The annual mean

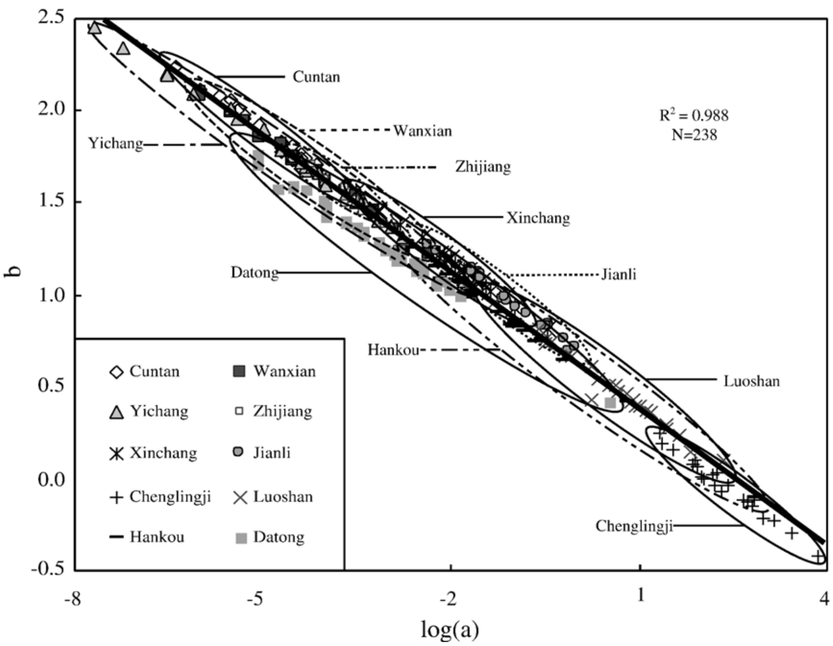

Fig. 2. An inverse linear relationship between annual rating parameters. Log(a) and b values for the 10 gauging stations on the Yangtze (Data: Changjiang Water Resources Commission, 1950–1988).

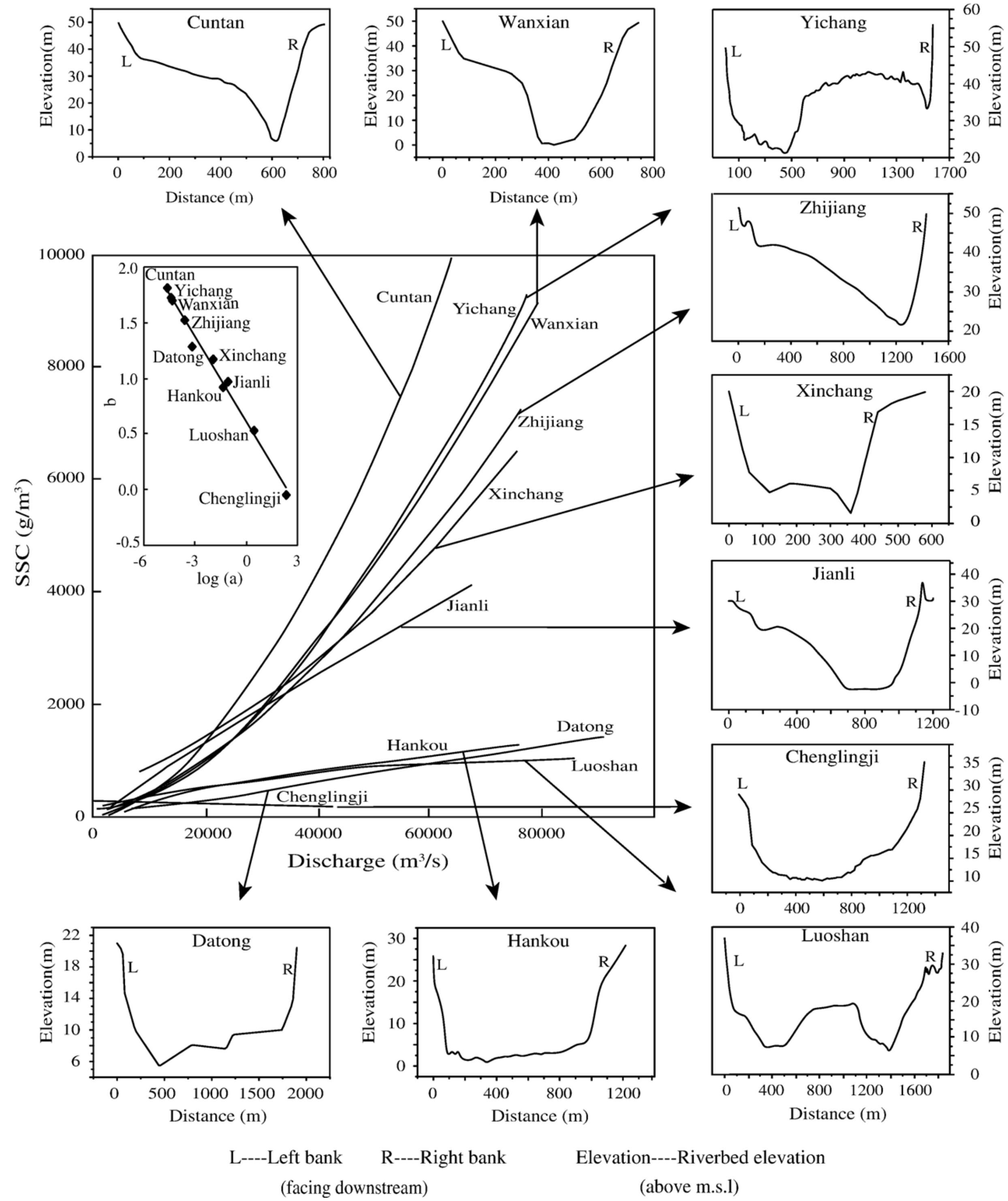

Fig. 3. Two groups (with high and low slopes) of sediment rating curves from the 10 gauging stations. The inset indicates the reverse correlation between log(a) and b values. The 10 channel cross-sections with V and U-shaped morphology are shown to correlate to the rating parameters.

precipitation is about 1000–1400 mm, with an annual mean evaporation of 700–800 mm (Shen, 1986; Yang et al., 2002). The precipitation arrives in the East Asian summer monsoon, resulting in a clear seasonality in the riverflow regime, 80% precipitation occurring between June and October (Chen et al., 2001a).

3. Methodology

Ten gauging stations on the Yangtze were selected for the present study. These are Cuntan, Wanxian, Yichang, Zhijiang, Xinchang, Jianli, Chenglingji, Luoshan, Hankou, and Datong in the downstream direction along the river (Fig. 1). Daily measurements of discharge and SSC were recorded at these stations, and documented in 'Hydrological Records on the Changjiang River Water and Sediment' by Changjiang Water Resources Commission (1950–1988). This database serves as the key for the present study. The database extends up to 1989. The hydrological records of the subsequent period have not been released. Furthermore, certain gaps occur in the records at some stations, mostly during the 1970s or 1980s.

Sediment rating parameters (*a* and *b*) were obtained from annual rating curves for a period exceeding 20 years (Table 1 and Fig. 2). The sediment rating curves of the 10 stations were constructed in order to examine the relationship between the parameters and river morphology (Fig. 3). The channel cross-sections at the stations were established from surveyed traverses (Changjiang Water Resources Commission, 1950–1988), and from unpublished historical maps on a scale of 1:25000 (Changjiang Water Resources Commission, 1997; 1:25000; Changjiang Water Resources Commission, 2000). Available data on decadal time scale on erosion and sedimentation in the river channel for the middle and lower Yangtze, were also used (Fig. 2 in Yin et al., 2004). Unit stream power was calculated for these stations, using data collected from on-site field investigations along the Yangtze River channel in 2002. In addition, water surface slopes provided by a series of maps (Changjiang Water Resources Commission, 1997; 1:25000; Changjiang Water Resources Commission, 2000) were utilized (Fig. 4). The variations in time in the values of the rating parameters log (*a*) and *b* were computed (Fig. 5).

4. Observation

Table 1 shows the sediment rating parameters of the 10 gauging stations, chronologically and along the river. The values of log(*a*) ranges from −7.669 to 3.843 and that of *b* from −0.416 to 2.460. The two parameters show a negative linear correlation with $R^2=0.988$ (Fig. 2). Generally, high *b* (>1.600) and low log(*a*) (<−4.000) occur in the upper river (Cuntan, Wanxian and Yichang) and the values gradually change in a downstream direction from Zhijiang, Xinchang, Jianli to Hankou, as *b* decreases from 1.600 to 0.900 and log(*a*) increases from −4.000 to −1.000). However, the rating parameters from Chenglingji ($b=2.371$; log(a)$=-0.043$) and Luoshan ($b=0.426$; log(a)$=0.530$) in the middle river and the values from Datong ($b=-3.195$ and log(a)$=1.290$) in the lower river do not follow this general trend (Fig. 1). The parameters at Datong have a range, which encompasses that of most stations in the middle Yangtze.

The 10 river channel cross-sections from the gauging stations exhibit distinctive channel morphologies. Usually, the V-shaped narrower river channel (generally <800 m wide) with deeper water (commonly >50 m deep) occurs in the upper Yangtze (Fig. 3: Cuntan and Wanxian). Although the river begins to widen its channel (about 1600 m wide at Yichang below the exit from the Three Gorges), it still exhibits a distinctive V-shaped form. Zhijiang and Xinchang, about 70–230 km downstream from Yichang are beyond the rocky gorges, but, their river cross-sections remain resemble a V-shaped channel (Fig. 3). The river cross-sections further downstream from Jianli to Datong takes on a U-shaped morphology, marked by wider (>1200 m) and shallower (about 20–30 m deep) channels (Fig. 3).

Fig. 4 indicates the change in unit stream power at the 10 gauging stations. As expected, the extreme high values (3–4 times higher when compared with the figures for the downstream stations) occur in the upper Yangtze valley. Unit stream power values drop abruptly below the Three Gorges, from Yichang to Datong. The unit stream power at Zhijiang, Xinchang, Jianli, and Datong is higher than that at Yichang, Chenglingli, Luoshan, and Hankou (Fig. 4). Inter-annual deviations

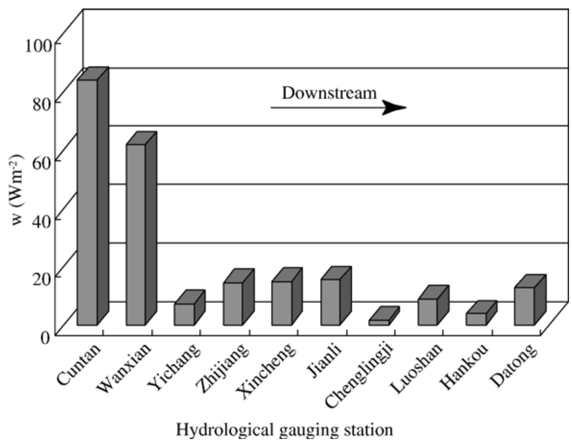

Fig. 4. Unit stream power at the 10 gauging stations on Yangtze River.

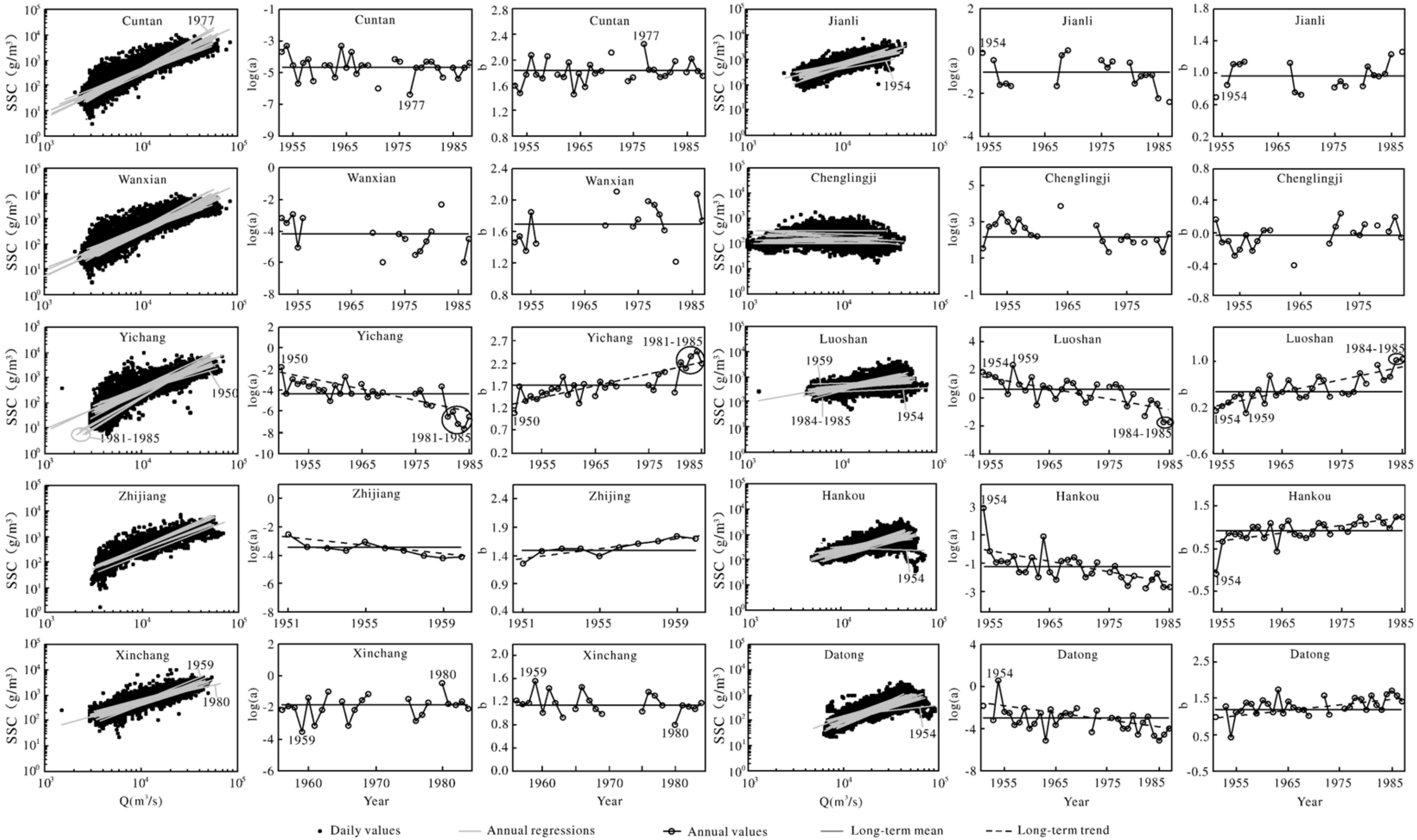

Fig. 5. The interannual variability series of the rating parameters of the 10 stations, indicating change in sediment rating parameters with time. The changes in parametric value suggest large floods and droughts in the past 40 years. A decreasing trend in log(a) and increasing one in b values shown Yichang, Zhijiang, Luoshan, Hankou, and Datong.

from the general trend of the sediment rating parameters are prominent for certain stations (Fig. 5: Cuntan, Yichang, Xinchang, Jianli, Luoshan, Hankou, Datong). A decrease in log(a) values is recorded at Yichang, Zhijiang, Luoshan, Hankou, and Datong over the last 40 years, but the b increases for the same time period.

5. Discussion

The distribution of sediment rating parameters is closely associated with riverbed morphology, gradient, and unit stream power, etc. (Peters-Kümmerly, 1973; Walling, 1974; Fenn et al., 1985; Morgan, 1995; Asselman, 1999, 2000; Syvitski et al., 2000; Horowitz, 2003; Morehead et al., 2003). The negative linear correlation between log(a) and b of the 10 gauging stations on the Yangtze actually reflects the coupling relationship among the variables controlled by local geology and hydroclimate. Generally speaking, the higher b and lower log(a) values in the study area imply the high SSC (Figs. 2 and 3), which occurs in the upstream bedrock-confined V-shaped Three Gorges. High gradient, high-flow settings, and a deep river channel upstream (Figs. 2–4) produce higher unit stream power with the potential for riverbed erosion and sediment transport (Asselman, 1999, 2000; Chen et al., 2005). In contrast, a combination of low b and high log(a) values relates to lower unit stream power in the less confined, wider and low channel slope of the U-shaped reaches of the middle and lower Yangtze (Jansen and Panter, 1974; Crawford, 1991).

The rating curve parameters for Chenglingji, Luoshan, and Datong, are at variance with the general upstream–downstream trend apparent along the river. Chenglingji, located immediately downstream of Dongting Lake (Fig. 1), and Luoshan, about 30 km further downstream, exhibit remarkably lower b-values and higher log(a)-values. These could be the result of long-term aggradation of the riverbed, partially due to extra-sediment sources (amounting to about 0.50×10^8 t a year) from Dongting Lake, sourced from both the upper Yangtze River Basin and its own watershed in southern China (Fig. 1; Changjiang Water Resources Commission, 1999; Chen et al., 2001b; Yin et al., 2004).

The wide scatter for Datong, is likely to be associated with an increasing trend in riverbed and bank erosion with time, although the river section has been stable over the last >100 years (Fig. 2 in Yin et al., 2004). The long-term observation demonstrates that the lower Yangtze River has virtually acted as a ‘sediment transport corridor’ for material arriving from upstream on the way to the East China Sea (Chen et al., 2001b). This inference is supported by the apparent balance in the annual sediment load of the middle Yangtze (4.30×10^8 t) and the lower Yangtze (4.70×10^8 t). There has been a decreasing trend in the annual sediment load recorded in Datong station over the last 40 years, from about 4.70×10^8 t to 3.50×10^8 t (Chen et al., 2001a; Yang et al., 2002). This change, most likely due to intensifying human activities, including damming, dyke construction and sediment mining in the upstream, can cause riverbed and bank erosion in the lower Yangtze River channel, particularly during the flood season.

The parameters of the sediment rating curves (Fig. 5) of the Yangtze River relate to the normal discharge regime (Syvitski et al., 2000; Morehead et al., 2003). During years with abnormally high flow events, often reaching more than $5–8 \times 10^4$ m^3 s^{-1} on the Yangtze (Changjiang Water Resources Commission, 1999; Chen et al., 2001a), changes in rating curve parameters become apparent, with low b and high log(a)-values, clearly different from the general trend (Fig. 5: Yichang, 1950; Hankou, 1954; Datong, 1954; Jianli, 1954; Luoshan, 1954, 1959; Xinchang, 1980). But there also have been years with anomalously high b and low log (a) values (Fig. 5: Xinchang, 1959; Cuntan, 1977; Yichang, 1981–1985; Luoshan, 1984–1985). Such values occurred during lower than average discharges coincident with droughts in the river basin (Changjiang Water Resources Commission, 1950–1988).

A general decrease is seen in log(a) values as well as an increase in b from the 1950s to 1980s at Yichang, Zhijiang, Luoshan, Hankou, and Datong (Fig. 5). This could be linked to the reduced sediment flux over the last 40 years throughout the river, from 4.70×10^8 t/year to 3.50×10^8 t (Yang et al., 2002).

Reid and Frostick (1987), after reviewing a number of world rivers, proposed parameters of arid rivers with log(a) values of 2.000–4.903, and b values of 0.200–0.700 and temperate and humid rivers with log(a) values between −2.398 and 1.602 and b values of 1.400–2.500. Our study computes figures such as log(a) values of −7.699–3.843, and b values of −0.416–2.460. The Yangtze parameters, especially the low b values of the middle and lower Yangtze (Table 1), reflect the large annual stream discharge, which, together with the wide range of the parametric values, appears to characterize the distinctive monsoon hydroclimatic setting of the Yangtze basin of eastern Asia (Chen et al., 2001a).

6. Conclusions

The sediment rating parameters obtained from the 10 gauging stations on the Yangtze highlight the river channel morphology in relation to channel aggradation and degradation controlled by regional geology and the monsoonal climatic settings. The high b and low $\log(a)$ values that occur in the upper Yangtze, reflect the high erosion potential of the mountainous reaches with high unit stream power. In contrast, low b and high $\log(a)$ values are found in the downstream alluvial floodplain of the middle and lower Yangtze, where unit stream power is significantly lower. Rating curves with high slopes and high b values relate to rock-confined V-shaped channel morphology whereas those with low slopes and high $\log(a)$ values are associated with U-shaped channels in floodplains.

Sediment rating curves with very high $\log(a)$ and very low b-values represent unusually high discharges and those with the opposite characteristics indicate very low flows. A progressive decrease in $\log(a)$ accompanied with the increase in b in the middle and lower Yangtze River over the last 40 years, coincides with reduced annual sediment load from 4.70×10^8 t to 3.50×10^8 t.

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