Hydrology & Earth
System Sciences

Research Note:
Effects of human activities on the Yangtze River suspended sediment flux into the estuary in the last century

S.L. Yang[1], Z. Shi[2], H.Y. Zhao[1], P. Li[1], S.B. Dai[1] and A. Gao[1]

[1]State Key Lab of Estuarine and Coastal Research, East China Normal University, Shanghai 200062, China
[2]School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiaotong University, 1954 Huashan Road, Shanghai 200030, China

E-mail for corresponding author: slyang@sklec.ecnu.edu.cn; shilunyang@hotmail.com

Abstract

The surface erosion area in the Yangtze River basin increased from 364×10^3 km^2 in the 1950s to 707×10^3 km^2 in 2001 due to a great increase in population. Based on the regression relationship between surface erosion area and population, the surface erosion area was predicted to be about 280×10^3 km^2 at the beginning of the 20th century. The sediment yield, which increased by about 30% during the first six decades of the 20th century, was closely related to the surface erosion area in this river basin. The Yangtze annual suspended sediment flux into the estuary was about 395×10^6 t a^{-1} at the beginning of the century, and this gradually increased to an average of 509×10^6 t a^{-1} in the 1960s. The increase in the suspended sediment flux into the estuary was accelerated in the 1950s and the 1960s due to the rapid increase in population and land use immediately after the Second World War and the Liberation War. After the riverine suspended sediment flux reached its maximum in the 1960s, it decreased to $<206 \times 10^6$ t a^{-1} in 2003. Construction of dams was found to be the principal cause for this decreasing trend because, during the same period, (a) the riverine water discharge did not show a decreasing trend, (b) water diversion was not influential and (c) sedimentation in lakes and canals of the middle and lower reaches did not increase. The total storage capacity of reservoirs has increased dramatically over the past half century. The amount of sediment trapped in reservoirs has increased to more than half a billion t a^{-1}. As a result, the suspended sediment flux into the estuary dramatically decreased, even though the sediment yield from many areas of the basin increased in recent decades. Human activities gradually increased the suspended sediment flux into the estuary before the 1960s and then rapidly decreased it. The last century was a period when the Yangtze suspended sediment flux into the estuary was dramatically affected by human activities.

Keywords: riverine sediment flux, human activities, surface erosion, dam, Yangtze (Changjiang) River

Introduction

Riverine sediment flux into an estuary usually governs the $10^0 \sim 10^2$ year evolution of deltas (Innocenti and Pranzini, 1993; Fanos, 1995; Guillen and Palanques, 1997; Barusseau *et al*., 1998; Stanley and Warne, 1998; Carriquiry and Sánchez, 1999; Ly, 1980; Panin and Jipa, 2002; Yang *et al*., 2003a). It also affects short-term sediment transport in the estuarine and coastal areas (Yang *et al*., 2003b; Shi, 2004). Human activities have strongly influenced the riverine sediment supply to the estuary in many rivers during the 19th and 20th centuries (Guillen and Palanques, 1997; Trenhaile, 1997; Walling, 1999; Milliman, 2001). Compared with the scientific knowledge of many rivers such as the Nile in Egypt (Fanos, 1995; Stanley and Warne, 1998), the

Ebro in Spain (Guillen and Palanques, 1997; Sanchez-Arcilla *et al.,* 1998), the Mississippi (Coleman *et al.*, 1998) and the Colorado River in USA (Carriquiry and Sánchez, 1999), the Niger River in Niger (Abam, 1999), the Senegal River in Senegal (Barusseau *et al*., 1998), the Yellow River in China (Yang *et al*., 1998), and the Volta River in Ghana (Ly, 1980), less is known of the Yangtze (Changjiang), especially in terms of its history before the 1950s. The measurement of sediment flux in the Yangtze River began in the 1950s. Although the recent decrease in Yangtze River suspended sediment load has preliminarily been revealed and related to human activities (Yang *et al*., 2002), further studies are needed. The primary objective of this paper is to examine the effects of human activities on the Yangtze River

suspended sediment flux into the estuary in the last century.

Physical settings and data collection

The Yangtze originates from the Tibetan Plateau at an elevation of more than 5000 m. It flows eastward for 6300 km before entering the East China Sea. Its catchment covers an area of 1.94×10^6 km^2 and currently has a population of about 400 million. Its mean annual water flux is 908×10^9 m^3 (1950–2003) and its annual suspended sediment flux is 422×10^6 (1951–2003). The mean annual precipitation and evapotranspiration for the basin are 1000–1400 mm and 700–800 mm respectively (Shen, 1986). The Yangtze ranks third in the world in length (Wang and Zhu, 1994), ninth in catchment area (Chen and Gupta, 2001), fourth in sediment flux and fifth in water flux (Eisma, 1998), and probably ranks first for population. The upper reaches of the river end at Yichang, 1840 km away from the estuary. The bed level of the main stream at Yichang is about 60 m above the estuary, suggesting that the gradient of the trunk stream is more than one magnitude order higher in the upper reaches than in the middle and lower reaches. The upper reaches account for 52% of the catchment area. There are many lakes scattered throughout the middle and lower reaches. Among them, Lake Dongting and Lake Poyang are the two largest. These lakes, especially Lake Dongting, act as sinks for riverine sediment. The tidal limit of the Yangtze estuary is at Datong. Datong accounts for 93% of the catchment area (Fig. 1). The water and sediment fluxes at Datong are 2.04 and 0.86 times that at Yichang respectively (Yang *et al.*, 2002).

Data on water and sediment fluxes for the river were provided by the Yangtze River Water Conservancy Committee, Ministry of Water Conservancy of China. Data for population, surface erosion area and sediment yield were derived from different sources in the literature. SPSS software was employed for regression analysis.

Results and discussions

THE TIME SERIES OF ANNUAL DISCHARGE

Annual discharge was measured in 1923–1924, 1930, 1935–1937, 1948 and since 1950 at the Datong Hydrological Station. Annual discharge was therefore not available for most of the first half of the 20th century. Fortunately, annual flow discharges has been measured since 1865 at the Hankou Hydrological Station where the Hanjiang River flows into the trunk stream (Fig. 1) of the Yangtze. Although Hankou is about 500 km upstream from Datong, its annual flow is significantly correlated with the annual flow at Datong (r=0.95 P<0.001). Thus the missing annual flow discharges for Datong could be estimated by utilizing the regression relationship for annual flow between Hankou and Datong.
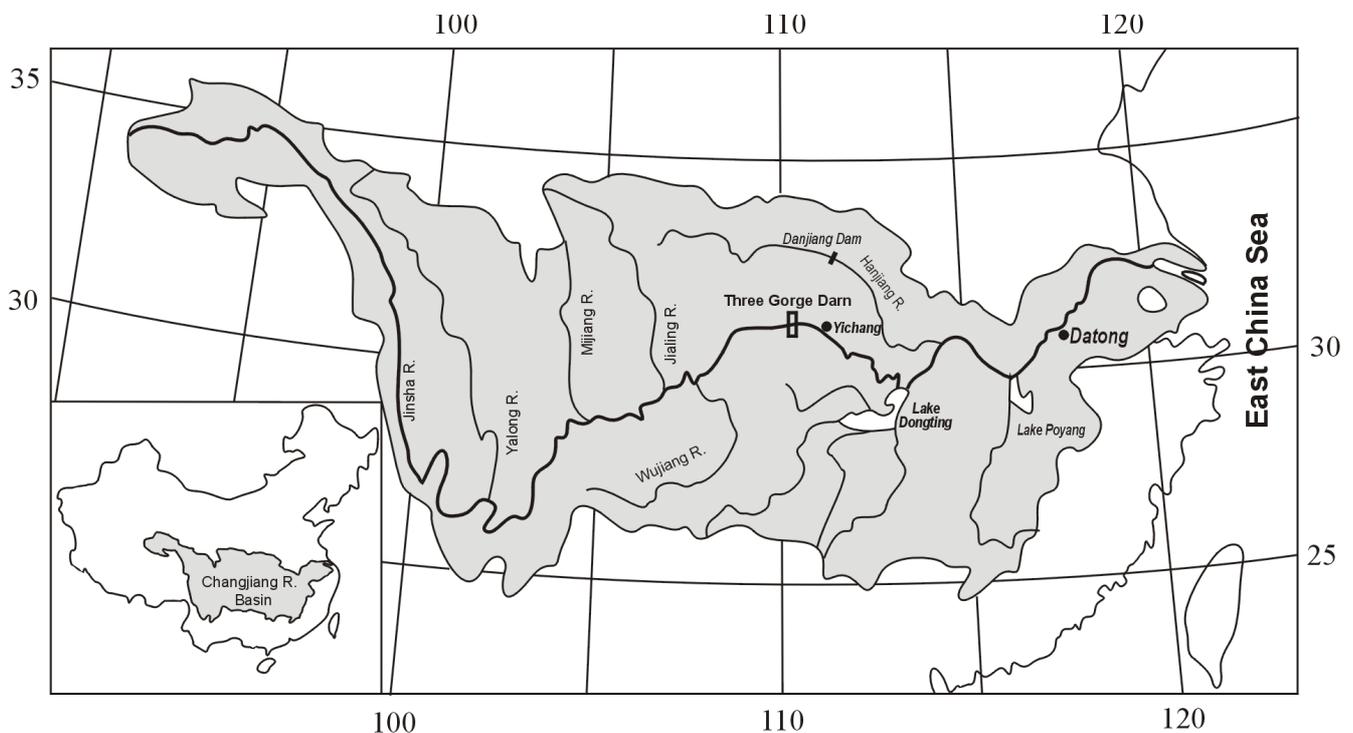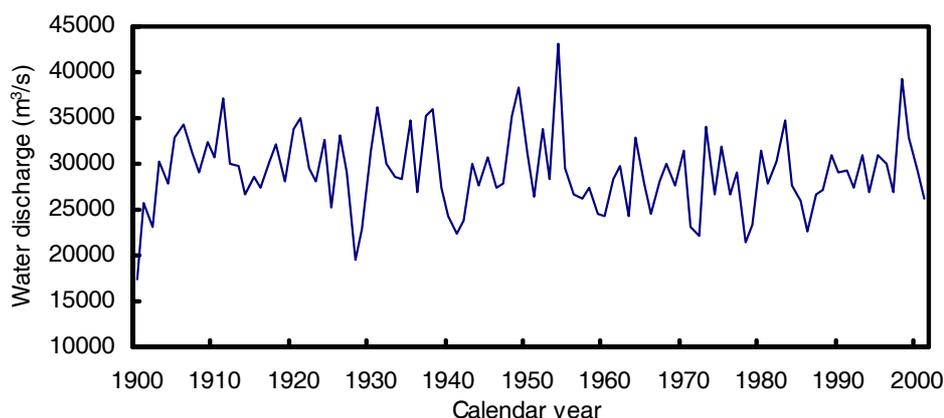

Fig. 2. *The Yangtze River basin in China.*

Fig. 1. *Annual flow discharges at Datong (observed in 1923–1924, 1930, 1935–1937, 1948 and since 1950; data for the missing years were estimated using the regression between flows at Datong and Hankou.*

A time series of annual flow discharge at Datong was reconstructed for the whole 20th century (Fig. 2). According to this time series, the annual flow discharge increased by 1.5% from 1900 to 1949.

INCREASE IN SEDIMENT FLUX DUE TO DEFORESTATION FROM THE 1900S TO THE 1960S

The surface erosion area in the Yangtze catchment has nearly doubled over the past five decades. The surface erosion area was estimated to be 364×10^3 km^2 in the 1950s (Shi, 1999; Zhang and Zhu, 2001) and 707×10^3 km^2 in 2001 (CRWCCWCMC, 2002). The increase in surface erosion area is attributed to the increase in population. The population of the river basin was 178 million in 1949 and increased to nearly 400 million in 2001 (Zhang, 2000). Assuming that 364×10^3 km^2 represents the surface erosion area in the mid-1950s and the increase in surface erosion was proportional to the increase in population from 1949 to 2001, the surface erosion area was estimated to be about 319×10^3 km^2 in 1949, and the relationship between surface erosion area (A) and population (P) is

$$A = 0.001748P + 9701 \tag{1}$$

where A represents surface erosion area in km^2 and P population. The surface erosion area at the beginning of the 20th century is estimated to be about 280×10^3 km^2, because the population at that time was 155 million.

Although the sediment yields measured for the gauging stations within the basin are highly variable because of natural diversity in the catchment, this variability is reduced when the data are integrated (Lu and Higgitt, 1999). Averaged over the basin, the sediment yield was 3980 t km^{-2} a^{-1} (Table 1). The coefficient of the independent variable A in the regression equation in Fig. 3 suggests a similar sediment yield. The very good correlation shown in Fig. 3 suggests that the differences in sediment yield among the subcatchments are very low. The total surface erosion area in Table 2 and Fig. 3 amounts to 81% of the whole

Table 1. Distribution of area of surface erosion and sediment yield among different intensity types in the Yangtze River basin in 1985 (based on Shi, 1998)

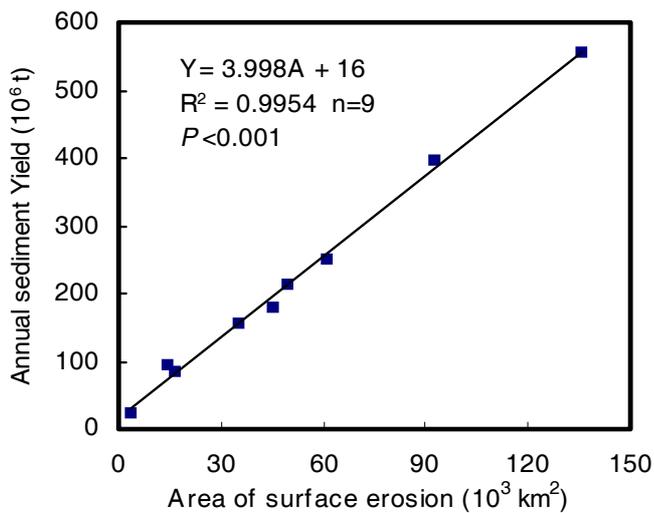| Intensity types of surface erosion (t/km²·a)	Sediment yield rate (t km^{-2} a^{-1})	Area of surface erosion (10^3 km^2)	Annual sediment yield surface erosion (10^6 t)
Very low-grade	500-2 500	210	247
Low-grade	2 500-5 000	190	658
Middle-grade	5 000-8 000	103	652
High-grade	8 000-13 500	40.8	417
Very high-grade	>13 500	18.6	265
Total	3980	562	2239

Y = 3.998A + 16
R² = 0.9954 n=9
P <0.001

Fig. 3. Regression between area of surface erosion (A) and annual sediment yield (Y) (data in Table 2).

catchment. In Anhui Province around Datong in the lower reaches where the surface erosion area was 33.6×10^3 km^2 (6.0% of the total catchment area), the sediment yield rate, 2054 t km^{-2} a^{-1} on average, was lower than those in Table 2 and Fig. 3 (Zhang *et al*., 1999). On the other hand, in the Three Gorges region where the surface erosion area was 34.6×10^3 km^2 (6.2% of the total catchment), the sediment yield rate, 5780 t km^{-2} a^{-1} on average, was higher than those in Table 2 and Fig. 3. Because the surface erosion area in these two regions was only 12% of the total, the spatial variation in sediment yield rate was assumed to be low. In view of this, the regional difference in sediment yield was ignored when predicting the sediment yield before the 1950s. There will be a 'natural' background sediment yield in the

catchment. Table 1 suggests that *surface erosion* is defined as an area where sediment yield rate is $\geq$500 t km^{-2} a^{-1}. In other words, the sediment yield rate is < 500 t km^{-2} a^{-1} in the rest of the catchment. In the Yangtze catchment, the annual sediment yield on forestland was found to be 6 t km^{-2} (Li *et al*., 2002). The forest cover in the Yangtze catchment was 60–80% in the distant past and decreased to 22% in 1957 and 10% in 1986 (Zhang and Zhu, 2001). Assuming (a) the forest cover was 30% in 1900 and 25% in 1949 and (b) the average sediment yield for the remaining uncleared land is 300 t km^{-2} a^{-1}, the average sediment yield for the uncleared land in the basin was 196 t km^{-2} a^{-1} in 1900, 211 t km^2 a^{-1} in 1949 and 219 t km^{-2} a^{-1} in the 1950s, which was comparable to the corresponding sediment yield in the United States (Langbein and Schumm, 1958). Based on the above assumption and using the catchment area above Datong Hydrological Station (1.81×10^6 km^2), the annual sediment yield would be $196 \times (1\,810\,000–280\,000) + 3980 \times 280\,000 = 1.414 \times 10^9$ t in 1900, $211 \times (1\,810\,000 – 319\,000) + 3980 \times 319\,000 = 1.584 \times 10^9$ t in 1949, and $219 \times (1\,810\,000 –364\,000) + 3980 \times 364\,000 = 1.765 \times 10^9$ t in the 1950s.

Only part of the sediment derived from surface erosion enters the river system, including waterways, lakes and reservoirs. The sediment entering the river system either flows into the estuary or settles down in the river system. To estimate the missing sediment flux into the estuary before the 1950s, the amount of sediment entering the river system and the amount of sediment deposited in the river system need to be known. In the 1950s, the sediment flux into the estuary was 466×10^6 t a^{-1} and the deposition in lakes and river channels was 195×10^6 t a^{-1}, on average, and deposition in reservoirs can be effectively ignored because few dams had been constructed by then (Zhu, 2000). Therefore, the

Table 2. Area of surface erosion and sediment yield in subcatchments of the Yangtze in 1985

Subcatchments	Area of surface erosion (10³km²)	Annual sediment yield (10⁶ t)	Data sources
Jinshajiang R.	135.4	557.4	Shi, 1999
Jialinjiang R.	92.5	397	Shi, 1999
Hanjiang R.	61.0	250	He, 1997
Minjiang R.	49.2	215	Shi, 1999
Four rivers into Lake Dongting	45.3	180	Zhang *et al*., 1999 Zhang and Zhu, 2001
Five rivers into Lake Poyang	35.2	155	Zhang *et al*., 1999
Tuojiang R.	16.3	84.1	Shi, 1999
Wujiang R.	14.6	95.4	Shi, 1999
Chishuihe R.	3.86	23.6	Shi, 1999
Total	453.4	1958	

ratio of the sediment entering the river system to the sediment yield was $(466 \times 10^6 t + 195 \times 10^6 t) / 1.765 \times 10^9$ t = 0.374, which is similar to the ratio of 0.34 from Zhu (2000). This ratio can be expected to be sensitive to changing land use. However, taking the whole catchment, the different land uses can be expected to change nearly proportionally with the total surface erosion area, and the influence on the ratio is expected to be limited. Using a ratio of 0.36, the average of this study and that of Zhu (2000), the sediment entering the river system was predicted to be $509 \times 10^6 t$ in 1900 and $570 \times 10^6 t$ in 1949.

The lakes and channels in the middle and lower reaches acted as an adjustor for the riverine sediment. The greater the amount of sediment supplied to them, the higher the deposition rate. The deposition was 195, 108 and $\approx 0 \times 10^6$ t a^{-1} when the sediment supplied to them was 661, 510 and $\approx 300 \times 10^6$ t a^{-1}, respectively (unpublished data of the authors), which suggests a regression equation D=0.5385S – 163, r^2 = 0.999, P<0.001, where D (10^6 t a^{-1}) is the deposition rate and S (10^6 t a^{-1}) is sediment supply, respectively. According to this equation, the deposition was 111×10^6 t in 1900 and 144×10^6 t in 1949. Thus, the suspended sediment flux into the estuary was about 398×10^6 t a^{-1} in 1900 and 426×10^6 t a^{-1} in 1949, if the influence of water discharge is not considered.

In natural river systems, sediment flux is positively correlated to flow discharge (Chernicoff and Venkatakrishnan, 1995). Taking the 1.5% increase of flow discharge into account, the suspended sediment flux was predicted to be 395×10^6 t a^{-1} in 1900 and 429 in 1949, respectively. Assuming that the suspended sediment flux increased progressively from 1900 to 1949, the decadal suspended sediment flux would be as shown in Fig. 4. The sharp increase in annual sediment flux in the 1950s

$(466 \times 10^6$ t a$^{-1})$ and in the 1960s $(509 \times 10^6$ t a$^{-1})$ was likely caused by the population boom after the Second World War and the Liberation War which ended in 1949.

DECREASE IN SEDIMENT FLUX DUE TO DAM CONSTRUCTIONS SINCE THE 1970S

Dam construction in the Yangtze River basin began to flourish in the late 1950s, much later than on rivers of other countries such as the Nile (Fanos, 1995; Stanley and Warne, 1998), the Ebro (Guillen and Palanques, 1997) and the Colorado (Carriquiry and Sánchez, 1999). Up to now, nearly 50 000 dams have been constructed in the Yangtze River basin. Along with the rapid increase in the cumulative reservoir storage capacity, more and more riverine sediment was trapped in the reservoirs. For example, in the upper reaches (upstream from Yichang), the total amount of deposition in reservoirs was 2.85 and 19.1×10^6 t a^{-1} in the 1950s and the 1960s, respectively. The largest reservoir put into operation in the 20th century, the Danjiangkou Reservoir (Fig. 1), with a storage capacity of 17.45×10^9 m^3 began to impound water in 1959. From 1960 to 1994, 1.41×10^9 m^3 of sediment was trapped by this reservoir (www.cjh.com.cn, 2003), giving a mean depositional rate 53.3×10^6 t a^{-1}

The total storage capacity of these reservoirs amounted to approximately 200×10^9 m^3 by the end of 2003. This represents 22% of the annual flow discharge into the estuary. The total amount of sediment trapped by the reservoirs was positively related to the total storage capacity (Fig. 5). Annual suspended sediment flux into the estuary has shown a significant decrease since the late 1960s (Fig. 6). Annual suspended sediment flux in the 1990s, 343×10^6 t a^{-1}, was one-third lower than the annual suspended sediment flux in
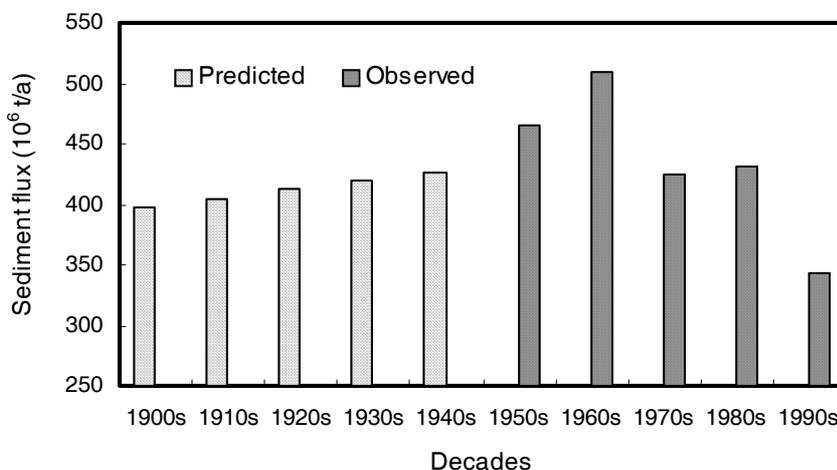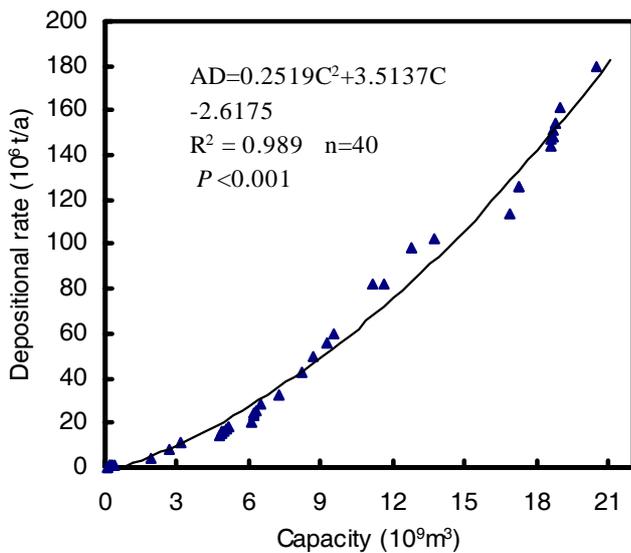
Fig. 4. *Decadal suspended sediment flux into the estuary.*

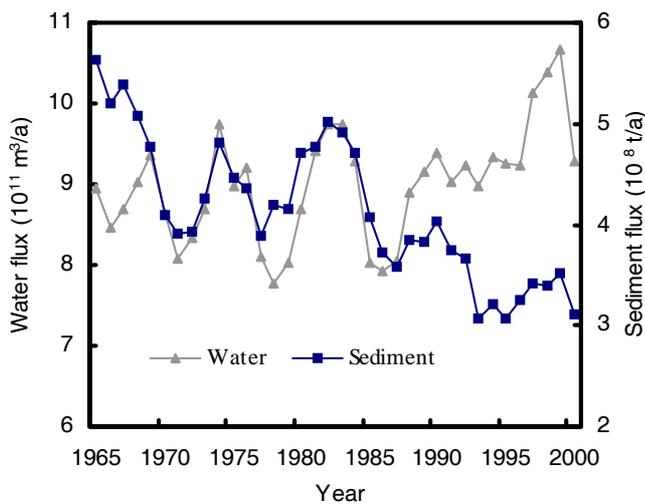Fig. 5. *Correlation between deposition rate and storage capacity of the reservoirs in the upper Yangtze.*

$$AD=0.2519C^2+3.5137C-2.6175$$
$$R^2 = 0.989 \quad n=40$$
$$P <0.001$$

Fig. 6. *Three-year running water and suspended sediment fluxes into the estuary.*

the 1960s, and it decreased to 276, 275 and 206 × 10⁶ t a⁻¹ in 2001, 2002 and 2003, respectively.

The inter-annual fluctuations in annual suspended sediment flux can be attributed to cyclic changes in climate, because they were in phase with the fluctuations of the annual water flux (Fig. 6). Nevertheless, the decreasing trend in annual suspended sediment flux was caused by human activities because neither the annual water flux showed a decreasing trend nor the deposition in the lakes and channels in the river system showed an increasing trend.

Along with the dramatic increase in number of dams and total storage capacity of reservoirs, the annual deposition in the reservoirs increased from a few million tons in the 1950s to more than 500 million tons in recent years. Since the late 1960s, dam construction has replaced land use as the dominant factor influencing the riverine suspended sediment flux into the estuary. In recent years, reservoirs have replaced the estuary as the principal sink for riverine sediments from the Yangtze.

Sediment extraction from river beds was also responsible for the decrease in riverine sediment flux. The Economic Reformation in China begun in the early 1980s, greatly intensified construction activity and promoted the demand for sand material in the Yangtze River basin. The sediment extraction from the trunk stream of the middle and lower Yangtze was estimated to be 40×10^6 t a⁻¹ in the early 1980s to 80×10^6 t a⁻¹ in the late 1990s (Chen, 2004). In fact, sand extraction was also observed in the upper Yangtze and many tributaries. Although it is unclear how much suspended sediment was lost to compensate for sand extraction, the amount was likely to be considerable.

The Yangtze suspended sediment flux into the estuary is expected to decrease to less than 200×10^6 t a⁻¹ in the coming decades due to the construction of the widely publicised Three Gorges Dam as well as other new dams. In addition, sediment extraction in the Yangtze will continue although the amount of sediment extraction will be controlled, for example, to 34×10^6 t a⁻¹ in the middle and lower reaches (Chen, 2004).

Conclusions

Human activities, especially deforestation and dam construction, dramatically changed the Yangtze River suspended sediment flux into the estuary in the last century. The continuous increase in population enhanced land-use change and intensified surface erosion. The sediment yield was proportional to the surface erosion area. Along with the expansion of the surface erosion area, the suspended sediment flux into the estuary increased from less than 400×10^6 t a⁻¹ at the beginning of the 1900s to more than 500×10^6 t a⁻¹ in the 1960s. Dam construction began to replace land use as a dominant factor controlling the suspended sediment flux after the late 1960s, and has been responsible for the decreasing the suspended sediment flux into the estuary. The 1960s were probably the decade when the suspended sediment flux of the Yangtze River reached its maximum. The last century is likely to be recognised as a special period when human activities changed the suspended sediment flux from the Yangtze River into the estuary most dramatically.

S.L.Yang, Z. Shi, H.Y. Zhao[1], P. Li, S.B. Dai and A. Gao

Acknowledgements

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