Impacts of human activities on the sediment regime of the Yangtze River

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Abstract The Yangtze River (Changjiang) is one of the most important rivers in the world, and the alterations in its hydrological regime have global-scale impacts. However, with population increase and economic growth, the sediment regime of the Yangtze River has been altered to some extent by human activities, including dam construction, deforestation, soil and water conservation, etc. The alteration in the sediment regime of the Yangtze River will unavoidably influence its morphology and geomorphology, the delta evolution and the ecosystem health and stability. To assess dam-induced alterations in the sediment regime of the Yangtze River quantitatively, the Danjiangkou Reservoir, the Gezhouba Reservoir and the Three Gorges Reservoir have been selected as case study sites, and the whole study period was divided into four sub-periods according to the years when these three reservoirs started to store water. On the basis of the time series of daily sediment discharge from six key hydrological stations (Wanxian, Yichang, Hankou, Datong, Baihe and Xiantao), the changes in annual, seasonal and monthly sediment load in different sub-periods, and the driving forces, were explored. The results in this paper could provide a reference for the assessment of impacts of human activities on the health and stability of the Yangtze River ecosystem.

Key words Yangtze River; Danjiangkou Reservoir; Gezhouba Reservoir; Three Gorges Reservoir; sediment regime; hydrological changes

INTRODUCTION

The Yangtze River (Changjiang) is one of the most important rivers in the world. It is the third longest, ninth largest in catchment area (Wang & Zhu, 1994), third largest in annual runoff (Xia *et al.*, 2006), and fourth largest in sediment load (Eisma, 1998). As one of the major rivers on the Earth, it plays a critical role in the global water cycle, sediment cycle, energy balance, climate change and ecological development (Xia *et al.*, 2006). The changes in its hydrological regime therefore have global-scale impacts. However, with population increase and economic growth, the sediment regime of the Yangtze River has, to some extent, been altered by human activities, particularly by dam construction.

According to incomplete statistics, 45 694 reservoirs, with a total storage capacity of 1.586×10^{11} m^3 had been built on the upper main stem and tributaries of the Yangtze River by the end of 2000. Of these reservoirs, 134 large/medium-sized ones have a total storage capacity of 1.064×10^{11} m^3 (Zhang, 2003). Human-induced changes in the sediment regime of the Yangtze River will unavoidably influence its morphology and geomorphology, the delta evolution and the ecosystem health and stability. Recently, the study of human impacts on river hydrological regimes, as an important topic associated with the world water cycle, the world sediment cycle, and land–ocean interactions, attracted worldwide attention, particularly in large river basins. This is even more so where human-induced alterations in river hydrological regimes are becoming increasingly crucial with the intensive and extensive development of their water and hydropower resources.

The investigation and assessment of human-induced impacts on river sediment regimes could provide a vital basis for river management and restoration. This is also the aim of the present study, with the Yangtze River in China as a study case. On the basis of the past several decades of sediment data collected from the Changjiang River Water Resources Commission, an attempt, focusing on the middle and lower reaches of the Yangtze River, was made to quantitatively evaluate the spatio-temporal variations in sediment load. This paper also investigates the driving forces of sediment regime changes in detail. It should be stressed that sediment load in this paper denotes suspended sediment load. Actually, the sediment flux of the Yangtze River is almost totally dominated by suspended load.

CASE STUDY SITES

With intensified human activities, in particular the large number of dams/reservoirs constructed on the Yangtze River, the sediment regime has been altered to some extent. This paper focuses on the impacts of the Danjiangkou Reservoir, the Gezhouba Reservoir and the Three Gorges Reservoir (Fig. 1). The Danjiangkou Reservoir, the second largest in the Yangtze River basin in terms of storage capacity, was built in 1967. It has a capacity of 1.745×10^{10} m^3 and is located on the Hanjiang River, which is the largest tributary of the Yangtze River. The Three Gorges Reservoir has the largest storage capacity (3.93×10^{10} m^3) in the Yangtze River basin, and is located on the main stem 44 km above the end of the upper reach. The Gezhouba Reservoir, has a capacity of 1.58×10^9 m^3, is a run-of-river reservoir, and is located on the main stem of

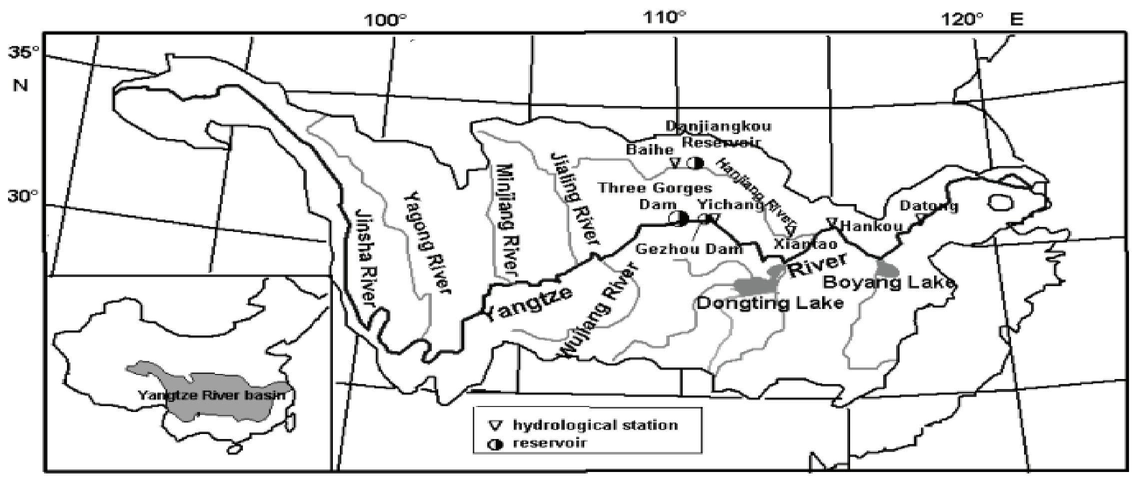

Fig. 1 Location map of study stations and reservoirs.

the Yangtze River, 38 km below the Three Gorges Dam. To assess the impacts of these three reservoirs, the six key hydrological stations of Wanxian, Yichang, Hankou, Datong, Baihe and Xiantao were selected (Fig. 1). Wanxian station is located in the upper reach of the Yangtze River, 277 km above the Three Gorges Reservoir. Yichang station is the control point of the upper Yangtze River basin and is located at the start of the middle reach of the Yangtze River, 44 km below the Three Gorges Dam and 6 km below the Gezhouba Dam. Hankou station is located on the middle reach of the Yangtze River, 1.15 km below the confluence of the Yangtze and Hanjiang rivers. Datong station is located at the tidal limit of the Yangtze River and is the controlling station for the measurement of water and sediment discharges from the Yangtze River to the East Sea. Baihe station is the upper controlling station for water and sediment discharges to the Danjiangkou Reservoir. Xiantao station, below the Danjiangkou Reservoir, is the most downstream station on the Hanjiang River, and controls water and sediment discharges to the main stem of the Yangtze River from the Hanjiang River.

DATA AND METHODS

Time series of daily sediment concentration for the six key hydrological stations were collected from the Yangtze River Water Resources Commission. Due to difficulties in data collection, the lengths of data records for the six stations are different (Table 1). Given that the Danjiangkou, Gezhouba and the Three Gorges Reservoirs may impose different impacts on the sediment regime of the middle and lower reaches of the Yangtze River, the whole study period was divided into four sub-periods according to the years when these three reservoirs started to store water (Table 1). Changes in their annual, wet-season (May–October), dry-season (November–April) and monthly sediment loads in different sub-periods were computed and analysed.

Table 1 Length of data records and division of study periods.

Hydrological station	Sub-periods				
	I	II	III		IV
Yichang	1955–1966	1967–1980	1981–1986	1981–2002	2003–2004
Hankou	1955–1966	1967–1980	1981–1986	1981–2002	2003–2004
Datong	1955–1966	1967–1980	1981–1986	1981–2002	2003–2004
Wanxian		1969–1980	1981–1986		
Baihe	1955–1966	1967–1980	1981–1986		
Xiantao	1955–1966	1967–1980	1981–1986		

Note: Due to difficulties in data collection for the period 1987–2002 at Wanxian, Baihe and Xiantao, the third sub-period was divided into two periods.
Daily sediment concentration data at Wanxian in 2001 and at Yichang in 2005 were also collected.

RESULTS

The temporal variations and mean annual values of annual, wet-season and dry-season sediment loads at the study stations are presented in Figs 2–4 and Table 2,

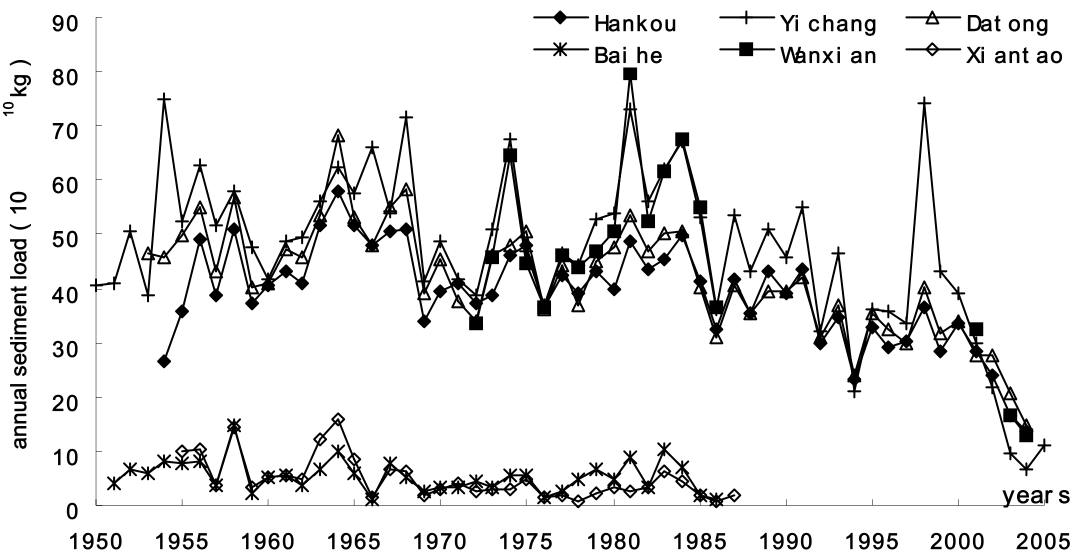

Fig. 2 Variation of annual sediment load at the study stations.

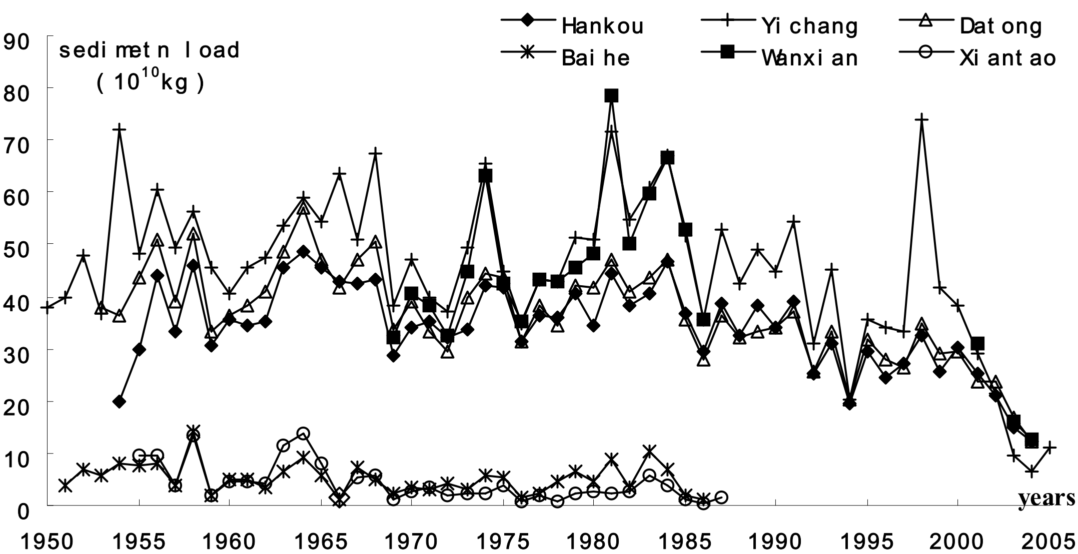

Fig. 3 Variation of wet-season sediment load at the study stations.

respectively. Figures 5–7 show the monthly distributions of sediment load at Baihe, Huangzhuang, Xiantao, Wanxian and Yichangduring in pre-dam and post-dam periods.

DISCUSSION

Annual sediment load

From Fig. 2, it can be seen that the annual sediment at Wanxian, Yichang, Hankou and Datong showed similar patterns of variation, with the sediment load in the upper

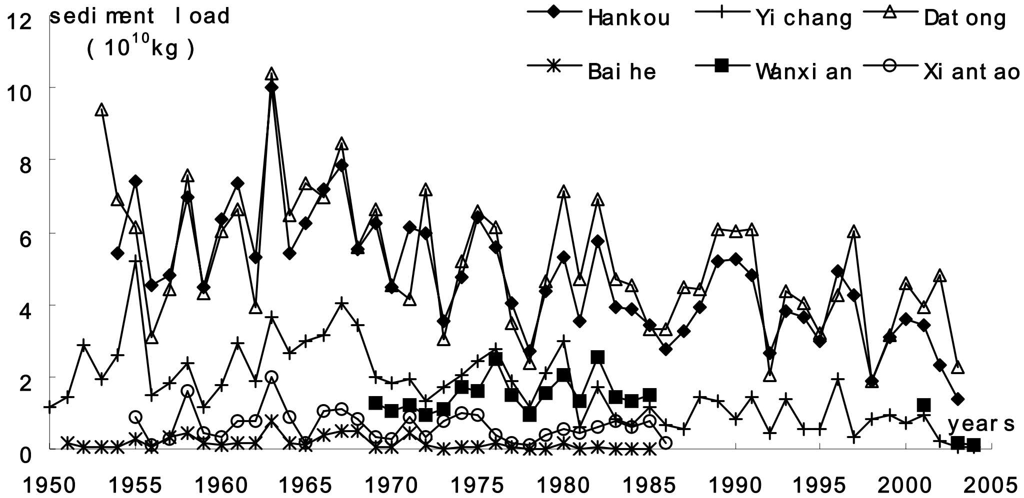

Fig. 4 Variations of dry-season sediment load at the study stations.

Table 2 Mean annual values at six hydrological stations in different sub-periods.

Station	Periods	Sediment load (10^{11} kg)			Percentage of wet-season sediment load in annual sediment load
		Wet season	Dry season	Annual	
Yichang	1955–1966	5.201	0.258	5.453	95.4
	1969–1980	4.542	0.202	4.746	95.7
	1981–1986	5.684	0.099	5.792	98.1
	1981–2002	4.494	0.091	4.589	97.9
	2003–2004	0.803	0.005	0.811	99.0
Wanxian	1969–1980	4.247	0.145	4.392	96.7
	1981–1986	5.722	0.163	5.880	97.3
Hankou	1955–1966	3.929	0.634	4.546	86.4
	1967–1980	3.660	0.522	4.192	87.3
	1981–1986	3.939	0.411	4.353	90.5
	1981–2002	3.230	0.374	3.612	89.4
	2003–2004	1.350	0.137	1.508	89.5
Baihe	1955–1966	0.598	0.026	0.621	96.3
	1967–1980	0.421	0.015	0.438	96.2
	1981–1986	0.544	0.002	0.548	99.3
Xiantao	1955–1966	0.718	0.078	0.790	90.9
	1967–1980	0.265	0.057	0.322	82.3
	1981–1986	0.259	0.057	0.321	80.6
Datong	1955–1966	4.415	0.611	5.012	88.1
	1967–1980	3.919	0.537	4.455	88.0
	1981–1986	4.035	0.483	4.538	88.9
	1981–2002	3.278	0.441	3.725	88.0
	2003–2004	1.458	0.226	1.764	82.6

reaches being higher than that in the middle and lower reaches in the same year. This means that the annual sediment load downstream is closely associated with that upstream and most sediment in the middle and lower reaches of the Yangtze River originated from the upper Yangtze River basin. The fluctuations in the annual sediment loads at the four stations corresponded well with their annual runoff variations (Li *et al.*, 2007), and the fluctuations at Hankou and Datong were less pronounced than those at Yichang, because the Yichang–Hankou and Hankou–Datong river stretches acted as regulators of river sediment load. Because of a large number of reservoirs/dams and the implementation of soil and water conservation measures, the annual sediment loads at the four stations show a significant decrease in recent decades. In general, the annual sediment loads at Wanxian were slightly lower than those at Yichang before 1981, whilst from 1981 to 2002 the annual sediment load at Wanxian was slightly higher than that at Yichang in some years. In particular, in 1981, when the Gezhouba Reservoir started to store water, the annual sediment load at Yichang was clearly lower than that at Wanxian. However, with respect to sediment trapping, the role of the Gezhouba Reservoir, which has a relatively small capacity, is generally not very obvious. Therefore, it can be concluded that the Gezhouba, as a run-of-river reservoir with a relatively small capacity, has limited impacts on annual sediment load downstream.

The annual sediment load at Xiantao is clearly higher than that at Baihe before 1967, but lower thereafter (Fig. 2). This implies that the role of the Danjiangkou Reservoir in sediment trapping is significant. The reduction in the annual sediment load at Xiantao had a direct effect on the sediment flux to the main stem of the Yangtze River below the confluence of the Yangtze River and the Hanjiang River. Variations in the annual sediment load at Hankou depended on the variations in the sediment load from Yichang, and the Hanjiang and Yichang-Hankou sub-basins. After Danjiangkou Reservoir had been put into operation, the contribution of sediment from Hanjiang to Hankou was reduced, particularly in wet years. Sediment trapping in this reservoir also caused a reduction in the contribution of sediment from the Hanjiang River to Datong. Compared with Yichang, the impact of the Gezhouba Reservoir on the annual sediment load at Hankou and Datong was very limited.

From 2003, the stations at Yichang, Hankou and Datong showed a significant reduction in annual sediment load due to the operation of the Three Gorges Reservoir. The magnitude of reduction varied with distance downstream from the reservoir, and the sediment load at Yichang was most strongly affected (Fig. 2).

Seasonal sediment load

During 1969–1980, the wet-season sediment load accounted on average for 95.7% of the annual sediment load at Yichang, and less than 96.7% at Wanxian. However, during 1981–1986 this percentage rose to 98.1% at Yichang and to 97.3% at Wanxian. This suggests that operations to "scour sediment with high floods", adopted by the Gezhouba Reservoir, has caused an increase in the percentage of wet-season sediment load at Yichang and is an effective way to reduce reservoir sedimentation. Therefore, the role of the Gezhouba Reservoir in sediment trapping in dry seasons is more obvious than that in wet seasons (Figs 3 and 4; Table 2). The relatively small storage capacity of the Gezhouba Reservoir, a high percentage of sediment transport in wet seasons, and operations aimed at reducing reservoir sedimentation, have limited the effect on the seasonal distribution of sediment load at Yichang. During 2003–2004, the contribution made by the wet-season load at Yichang increased further, due to operations in the Three Gorges Reservoir to store clear water and release turbid water.

Before 1967, both wet- and dry-season sediment loads at Xiantao were generally higher than those at Baihe (Figs 3 and 4). However, after 1967, the wet- and dry-season loads at Xiantao were lower and higher, respectively, than those at Baihe (Figs 3 and 4). In the period 1967–1986, compared with Baihe, the contribution of the wet-season to the annual sediment load at Xiantao decreased markedly due to sediment trapping by the Danjiangkou Reservoir. Since sediment load is closely related to runoff, sediment trapping by the Danjiangkou Resevoir is exacerbated by operations to retain high floods in wet seasons.

In contrast to Xiantao and Yichang, the contribution to annual sediment loads of the wet season increased in the period 1967–1980 at Hankou, reflecting the fact that the Yichang–Hankou sub-basin experienced some wet years in the 1970s, while the upper Yangtze River basin experienced dry years. During 1981–2002, the contribution of the wet-season to annual loads at Hankou and Yichang showed a similar pattern of variation, although sediment trapping in the Danjiangkou Reservoir reduced the sediment load contributed by the Hanjinag River to Hankou. This is because most of the sediment load at Hankou originated upstream of Yichang. The Gezhouba Reservoir also had impacts on the seasonal distribution of sediment load at Hankou, but weaker than at Yichang, because Hankou is located approx. 632 km downstream of the Gezhouba Reservoir (Table 2). During 2003–2004, the operation of the Three Gorges Reservoir had an impact on the percentage contribution of wet-season load at Hankou, but this was less significant than at Yichang, because Hankou lies approx. 670 km downstream of the Three Gorges Reservoir (Table 2).

The Danjiangkou and Gezhouba reservoirs have much less effect on the seasonal pattern of sediment loads at Datong than at Hankou, reflecting the larger distances involved in the case of the former and regulation of the Yichang–Hankou and Hankou–Datong reaches in the case of the latter. As a result, in the first three sub-periods, the wet season contribution to sediment load was less variable at Datong than at Hankou. In the fourth sub-period (2003–2004), the wet season contribution decreased at Datong and had a different pattern of variation compared with Yichang and Hankou. Dramatic reductions in both wet- and dry-season sediment load at Datong in 2003 and 2004 resulted from the operation of the Three Gorges Reservoir (Figs 3 and 4).

Monthly sediment load

The impacts of the Danjiangkou, Gezhouba and Three Gorges reservoirs on the monthly distribution of sediment load at Xiantao, Huangzhuang and Yichang were analysed (Fig. 5). The Danjiangkou Reservoir had a significant influence on the monthly distribution of sediment loads at Huangzhuang and Xiantao, particularly during the wet season, when the sediment load at both stations was strongly reduced due to the retention of large floods with high sediment concentration in the reservoirs. The operation of the Danjiangkou Reservoir made the monthly distribution of sediment load downstream more even. Huangzhuang was more strongly affected than Xiantao, because of its closer proximity to the reservoir.

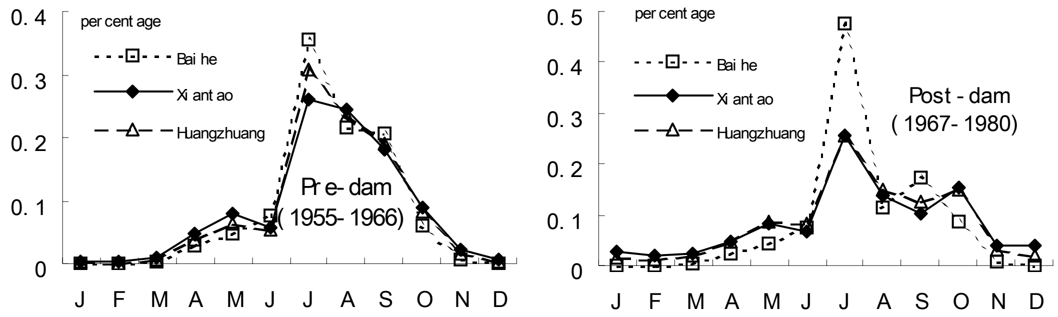

Fig. 5 Impacts of the Danjiangkou Reservoir on the monthly distribution of sediment load.

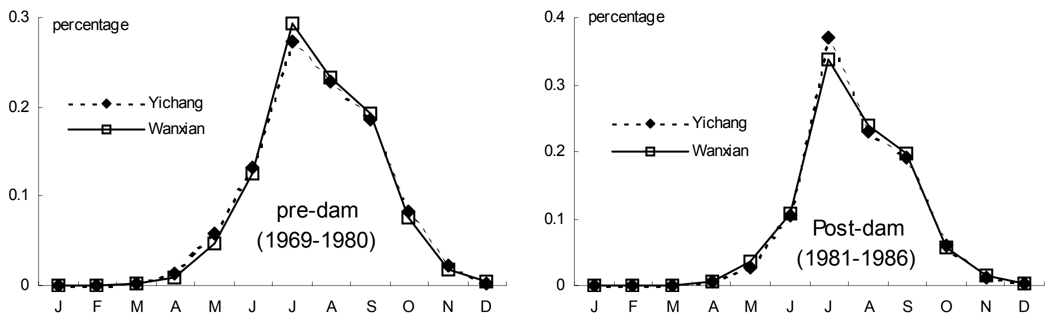

Fig. 6 Impacts of the Gezhouba Reservoir on the monthly distribution of sediment load.

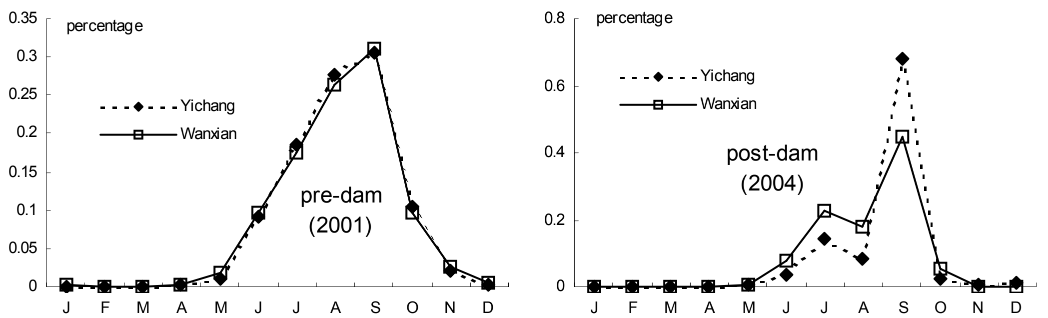

Fig. 7 Impacts of the Three Gorges Reservoir on the monthly distribution of sediment load.

The operation of the Gezhouba Reservoir has resulted in a more uneven distribution of monthly sediment loads downstream (Fig. 6), because, as a run-of-river project, this reservoir only played a minor role in sediment trapping.

Figure 7 shows that the effect of the Three Gorges Reservoir on the monthly distribution of sediment load at Yichang is considerable and made the distribution much more uneven. However, it can be anticipated that the sediment deposition regime in the reservoir will change as the volume of stored water further increases.

CONCLUSIONS

This paper has evaluated the impacts of human activities, in particular dam construction, on the sediment regime of the Yangtze River. The results revealed that impacts varied with reservoir regulation capacity, reservoir operation pattern, and the distance between the target reservoir and the case study site. Sediment trapping in reservoirs, together with soil and water conservation measures, has resulted in significant reductions in annual, wet-season and dry-season sediment loads, but the occurrence of extreme rainfall events could cause sediment loads to increase. The operation of Gezhouba Reservoir to scour sediment with high floods, and the Three Gorges Reservoir to store clear water and release turbid water, has made the seasonal and monthly distribution of sediment loads more uneven. However, the operation of the Danjiangkou Reservoir to "retain high floods in wet seasons" had the opposite effect. The 1200-km river stretch between Yichang and Datong acts as a regulator for sediment load, although most sediment measured at Datong comes from the Yichang. The results presented in this paper could provide a baseline for the assessment of longer-term human impacts on the Yangtze River and the health and stability of its ecosystem.

Acknowledgement The financial support is gratefully acknowledged from the National Science Foundation Commission (Grant no. 30490235), the Project sponsored by SRF for ROCS, SEM and Jiangsu Qing-Lan Project.

REFERENCES

Eisma, D. (1998) *Intertidal Deposits: River Mouths, Tidal Flats and Caostal Lagoons*. CRC Press, Boca Raton, Florida, USA.

Li, Q., Zou, Z., Xia, Z., Ma, Y. & Guo, J. (2007) Impacts of human activities on the flow regime of the Yangtze River. In: *Changes in Water Resources Systems: Methodologies to Maintain Water Security and Ensure Integrated Management* (ed. by N. van de Giesen, Xia Jun, D. Rosbjerg & Y. Fukushima) (Proc. Perugia Symp. HS3006, July 2007). IAHS Publ. 315. IAHS Press, Wallingford, UK.

Wang, Y. & Zhu, D.K. (1994) *Coastal Geomorphology*. Higher Education Press, Beijing (in Chinese).

Xia, Z., Li, Q., Jiang C. & Chen Q. (2006) Impacts of human activities on the natural functions of the Yangtze River. In: *Proc. 15th APD-IAHR & ISMH Conference: Water for Life-Development and Management* (ed. by V. Sundar, R. Sundaravadivelu, S. A. Sannasiraj & K.Murali), vol. I, 543–548. M/S Allied Publishers, Chennai, India.

Yangtze River Water Resources Commission (2006) *Dictionary of the Yangtze River—Dams and Hydropower Stations*, Wuhan, China. http://www.cjw.com.cn/index/cidian/cidian01.asp. Accessed July 2006.

Zhang, J. (2003) Integrated planning and management of water resources in the Yangtze River Basin. In: *Proc. Forum on "Implementation of Water Law and Strategies for Harnessing and Exploitation of the Yangtze River Basin"*, 253–257. The Changjiang River Water Resources Commission, Wuhan, China.