Impacts of Danjiangkou reservoir on sediment regime of the Hanjiang River

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ABSTRACT

With population increase and economic growth, the development of water resources and hydropower resources of the Hanjiang River has been intensified by dam building, and consequently the sediment regime of the Hanjiang River has been altered to some extent. To assess dam-induced alterations in the sediment regime of the Hanjiang River quantitatively, we selected three key hydrological stations (Baihe, Huangzhuang and Xiantao) as case study sites above and below the Danjiangkou reservoir respectively, and the whole study period was divided into two sub-periods according to the year when the reservoir started to store water. On the basis of time series of daily sediment data from the three stations, the alterations in their annual, seasonal, monthly and daily sediment load, and the relationships between water quantity and sediment load in different sub-periods were investigated, and the driving forces for the alterations were also explored. The output of this paper could provide reference for the assessment of the impacts of human activities on the long-term health and stability of the Hanjiang River ecosystem.

Key words | Danjiangkou reservoir, Hanjiang River, human activities, sediment regime

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INTRODUCTION

Global river systems have been intensively altered by human activities, particularly dam construction (Nilsson *et al.* 2005; Syvitski *et al.* 2005). Dam construction and operation unavoidably induce alterations in river flow regimes, sediment regimes and water temperature regimes (Vörösmarty *et al.* 2003; Liu *et al.* 2005; Wang *et al.* 2006; Li *et al.* 2007; Lu *et al.* 2009), and alterations in the sediment regimes consequently influence river morphology and geomorphology, and river ecosystem health and stability (Li *et al.* 2007). According to Milliman & Syvitski (1992), fluvial sediment delivered to the oceans has been estimated to be about 20 billion (10^9) tonnes per year (Bt/y), but the world's registered 45,000 large reservoirs can effectively trap as much as 4–5 Bt/y (Vörösmarty *et al.* 2003). The deposition of sediment in reservoirs can variously impact design performance through storage capacity losses, changes in water quality, reduced flood-attenuation, damage to valves and conduits and diminished amenity value (Rowan *et al.* 1995). 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 interaction, has been attracting worldwide attention, particularly in large river basins (Li *et al.* 2007). This is even more so where human-induced alterations in river hydrological regimes are increasingly becoming 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 Hanjiang River in China as the study case. On the basis of the 54-year long time series of daily sediment discharge data collected from the Changjiang River

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Water Resource Commission, an attempt 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 Hanjiang River is almost totally dominated by suspended load.

CASE STUDY SITES

The Hanjiang River, having a length of 1,577 km and a catchment area of 159,000 km^2, accounting for 8.8% of the Yangtze River basin area, is the longest tributary of Yangtze River and rises in southwestern Shaanxi and then crosses into Hubei. It merges with the Yangtze at Wuhan, a city of several million. It plays a critical role in promoting the socio-economic development of the Hanjiang River basin. Located in the sub-tropical monsoon zone, the Hanjiang River basin has an average annual rainfall of 873 mm, an average annual runoff of 51.7 billion (10^9) m^3 and an average annual sediment discharge of roughly 2.5 kg/m^3 with relatively good land cover. With intensified human activities, the sediment regime has been altered to some extent. The focus of this paper is on the impacts of the Danjiangkou (DJK) reservoir on the sediment regime of the Hanjiang River (Figure 1).

To assess dam-induced alterations in the sediment regime of the Hanjiang River quantitatively, we selected three key hydrological stations (Baihe, Huangzhuang and Xiantao) as case study sites, above and below the Danjiangkou reservoir respectively. The Danjiangkou reservoir, the second largest in terms of storage capacity in the Yangtze River basin, is a seasonal-storage reservoir and was built in 1967. It is located at the end of the upper reach of the Hanjiang, and its catchment area accounts for 60% of the river basin total. The reservoir has a normal pool level of 157 m and a capacity of 17.45 billion m^3. It is also the water source of the central route of China's South–North water transfer project. Currently, second-stage engineering works are underway with an aim of increasing the normal pool level to 170 m and the storage capacity to 29.05 billion m^3, expected to be completed by 2010. Baihe station, above the Danjiangkou reservoir, is the upper controlling station for water and sediment discharges to the Danjiangkou reservoir, located at the upper reach of the Hanjiang River. Huangzhuang is located at the end point of the middle reach of the Hanjiang River, 223 km below the Danjiangkou reservoir. Xiantao, below the Danjiangkou, 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

Hydrological data time series of daily water discharge and suspended sediment concentration from 1955 to 2008 of

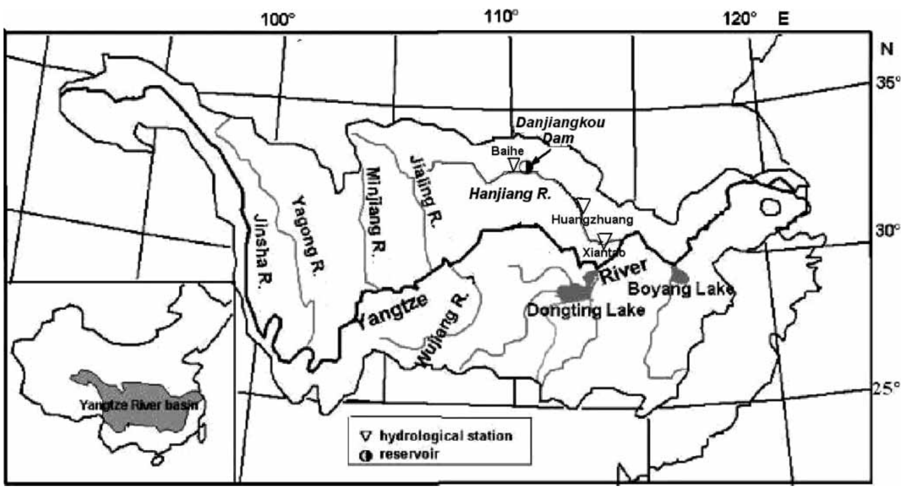

Figure 1 | Sketch map of the Hanjiang River.

Baihe, Huangzhuang and Xiantao stations along the mainstream of the Hanjiang River were collected from the Yangtze River Water Resources Commission, China. With Baihe station as reference, the purpose of the study focused mainly on the impacts of Danjiangkou reservoir on sediment regime downstream of the Hanjiang River. The whole study period was divided into two sub-periods by the year when the reservoir started to store water (1955–1966 and 1967–2008). On the basis of time series of daily sediment concentration and daily water discharge from three stations, simple linear regression and Mann–Kendall trend test were used to detect trend and tested its significance of the annual sediment load. Wet seasonal (May–October), dry seasonal (November–April) and monthly sediment load at the three stations in different sub-periods were also computed and analysed. Daily frequency distribution curves were used in daily sediment load in different sub-periods at the three stations. Furthermore linear regression analysis was carried out in the relationship between the sediment load entering the Danjiangkou reservoir and the trapped sediment load by the reservoir, and double accumulated curves and correlation analysis were performed in the relationships between water quantity and sediment load in different sub-periods at the three stations.

RESULTS

Figures 2–5 show the temporal variations of annual sediment load, the correlation between annual sediment load entering the Danjiangkou reservoir and that trapped by the reservoir, the relationship between accumulated annual sediment load and accumulated water quantity at the three locations, and the correlations between annual water quantity and annual sediment load at the three stations in different periods respectively. Figures 6 and 7 illustrate the temporal variations of seasonal sediment load, the correlations between seasonal sediment load entering the Danjiangkou reservoir and that trapped by the reservoir in 1967–2008. The percentage of wet seasonal sediment load in annual sediment load at the three stations in the two sub-periods is presented in Table 1. Figure 8 demonstrates the monthly distribution of sediment load in different periods. Figure 9 shows the distribution of daily sediment load at the three locations in the two periods.

DISCUSSION

Annual sediment load

From Figure 2, it can be seen that annual sediment at Baihe, Huangzhuang and Xiantao showed similar patterns of variation before and after 1967. The fluctuations in the annual sediment loads at the three stations corresponded well with their annual runoff variations (Lu *et al.* 2009). This means that the annual sediment load in the middle and lower reaches of the Hanjiang River is closely associated with that in the upper reach. From Figure 2, it can be noted that the fluctuation at Xiantao was less pronounced than that at Huangzhuang before 1967 due to the Huangzhuang–Xiantao river stretch acting as regulator of river

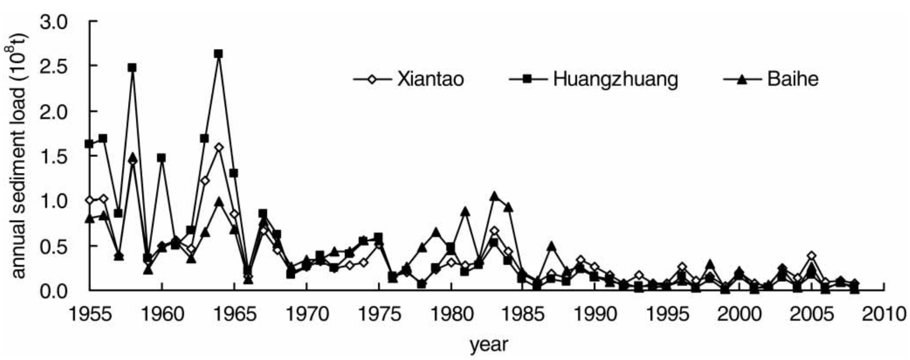

Figure 2 | Temporal variations of annual sediment load.

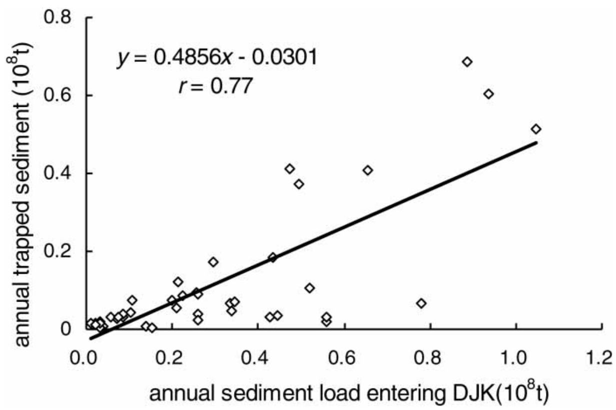

Figure 3 | Correlation between annual sediment load entering the Danjiangkou reservoir and that trapped by the reservoir.

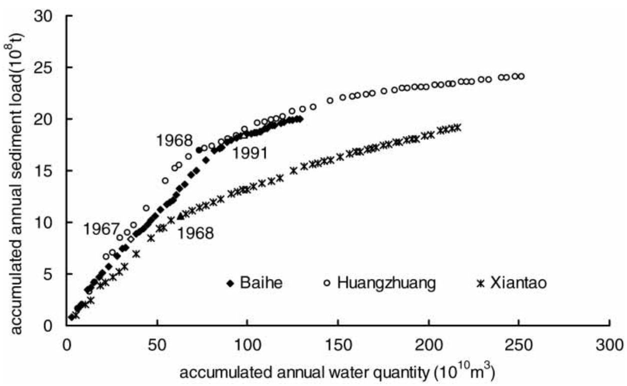

Figure 4 | Relationship between cumulative annual water and cumulative sediment load at the three hydrological stations of the Hanjiang River for 1955–2008.

sediment load. However, after the Danjiangkou reservoir having been put into operation, the fluctuations at both Xiantao and Huangzhuang became much gentler, and the annual sediment load at Huangzhuang was even lower than that at Xiantao in most of years. Because of a number of dams having been built with time and the implementation of soil and water conservation measures, the annual sediment loads at the three stations showed a significant decrease. The nonparametric Mann–Kendall tests for Baihe, Huangzhuang and Xiantao, which revealed Mann–Kendall values of –4.73, –6.34 and –5.03 respectively, also verified the decreasing tendency with a significance of 95%.

Before 1967, the annual sediment load at Baihe was clearly lower than that at Xiantao and Huangzhuang and the annual sediment load at Huangzhuang was higher

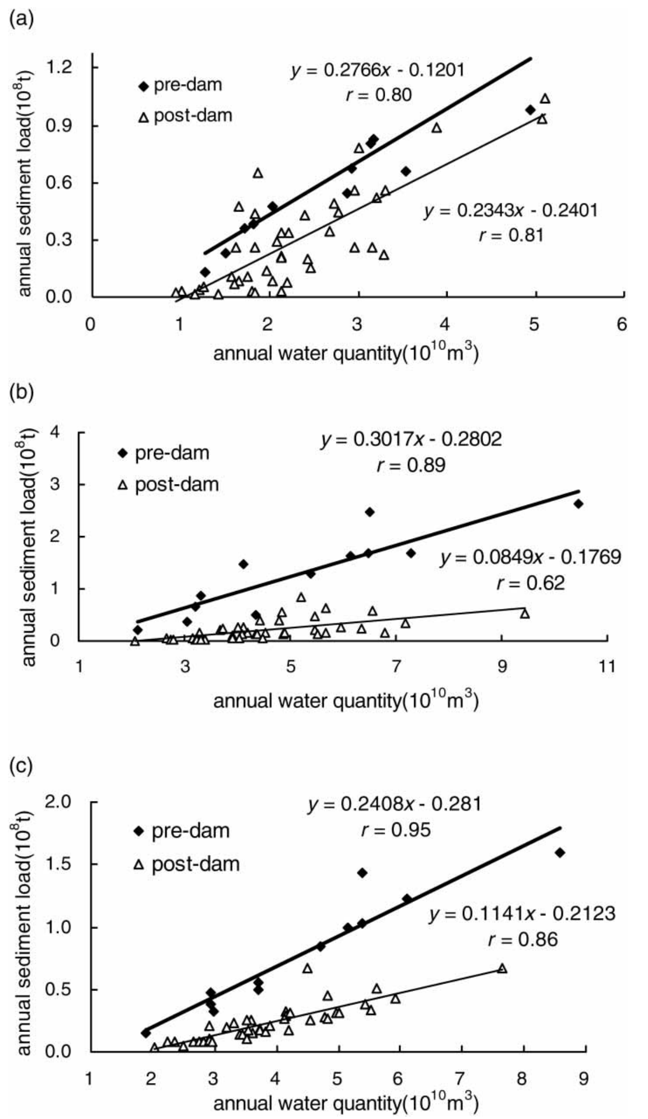

Figure 5 | Correlation between annual water quantity and annual sediment load at the three stations in different sub-periods: (a) Baihe, (b) Huangzhuang, (c) Xiantao.

than that at Xiantao. However, after 1967 the annual sediment load of Huangzhuang and Xiantao decreased significantly, and the annual sediment load at Huangzhuang was even lower than that at Baihe (Figure 2). This implies that the role of the Danjiangkou reservoir in sediment trapping is significant, particularly in wet years. 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. According to Figure 3, it can be seen that the annual sediment load entering the Danjiangkou reservoir correlated

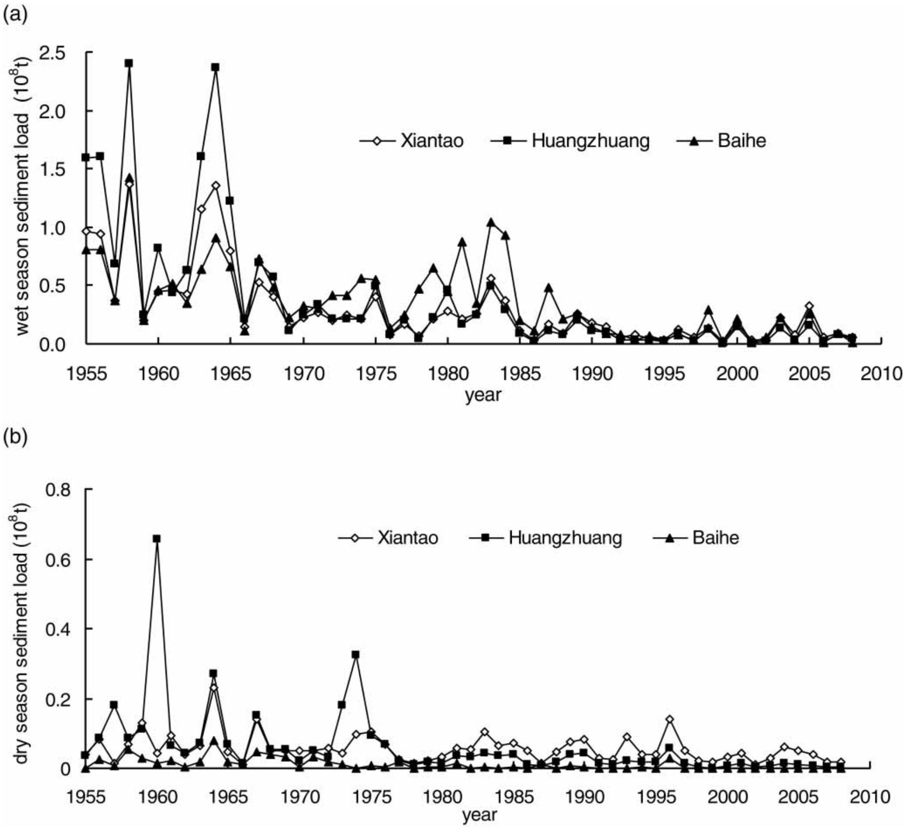

Figure 6 | Temporal variations of seasonal sediment load: (a) wet season, (b) dry season.

significantly with trapped sediment in the reservoir during 1967–2008, i.e. the more sediment supplied from upstream of the Danjiangkou reservoir, the more sediment was trapped inside the reservoir. Figure 3 reveals that approximately 50% of the annual sediment entering the Danjiangkou reservoir was trapped.

Relationships between annual water quantity and annual sediment load

From Figure 4 it can be seen that the bending points on the curves of Huangzhuang and Xiantao occurred in 1968 after the Danjiangkou reservoir started to store water. These phenomena disclosed that the operation of the Danjiangkou reservoir changed the relationship between water and sediment downstream of the Danjiangkou reservoir, and that the water–sediment relationship was affected more significantly by the reservoir at Huangzhuang than at Xiantao. The relationship between annual water quantity and annual sediment load at Baihe was unchanged until 1991 when sediment load decreased apparently, due to the operations of numerous comparatively large reservoirs as well as the implementation of soil and water conservation measures, while there was no significant change at Huangzhuang and Xiantao in 1991 due to the long distance from the upper stream and local river regulation. The alterations in water–sediment relationship indicated that dam construction changed the downstream sediment regime by trapping sediment.

The correlation of annual water quantity and annual sediment load for the periods of 1955–1966 and 1967–2008 at Baihe, Huangzhuang and Xiantao is shown in Figure 5. It can be seen that the curves of the water–sediment relationship at the three stations in the pre-dam period are above those in the post-dam period, but the differences between the two curves at Huangzhuang and Xiantao are larger than that at Baihe, with Huangzhuang showing the biggest difference. This indicates that the annual

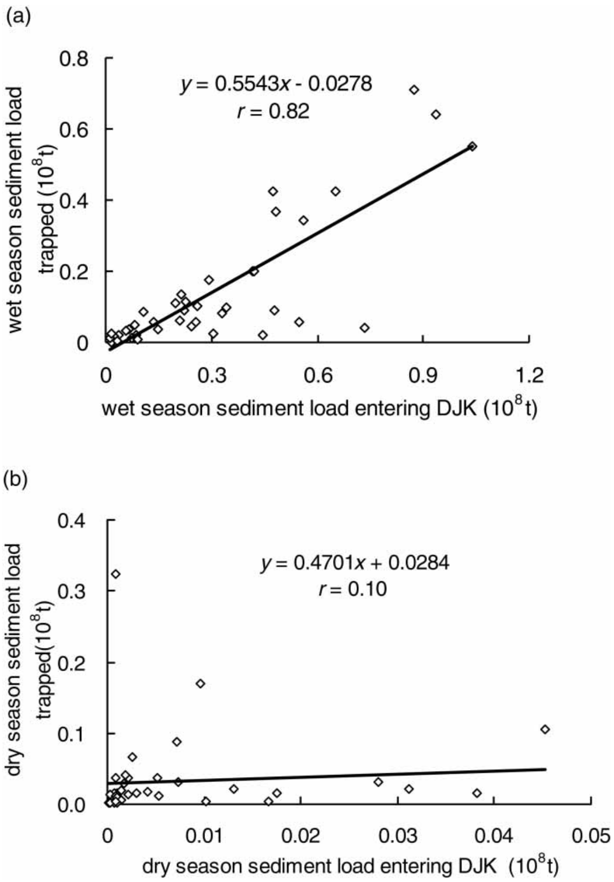

Figure 7 | Correlations between seasonal sediment load entering the Danjiangkou reservoir and seasonal sediment trapped by the reservoir: (a) wet season, (b) dry season.

sediment load at both Huangzhuang and Xiantao was greatly affected by the Danjiangkou reservoir, most significantly at Huangzhuang. Figure 5 also shows that the impact of the reservoir on the downstream sediment regime was more considerable in wet years than in dry

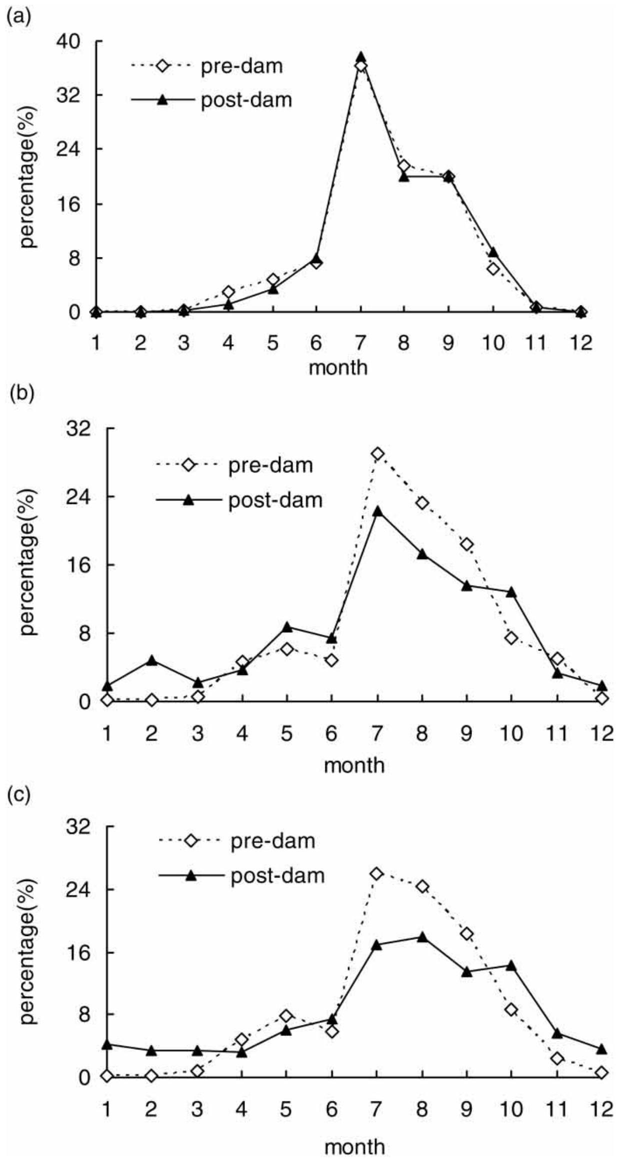

Figure 8 | Impact of Danjiangkou reservoir on monthly distribution of sediment load: (a) Baihe, (b) Huangzhuang, (c) Xiantao.

Table 1 | Mean annual sediment load in different periods and proportion of sediment load in wet season

Station	Period	Sediment load (10^8t) Wet season	Dry season	Mean annual	Wet season sediment load as percentage of annual sediment load (%)
Baihe	1955–1966	0.605	0.023	0.628	96.4
	1967–2008	0.298	0.007	0.305	97.7
Huangzhuang	1955–1966	1.149	0.140	1.290	89.1
	1967–2008	0.172	0.037	0.209	82.3
Xiantao	1955–1966	0.720	0.072	0.792	90.9
	1967–2008	0.169	0.053	0.222	76.1

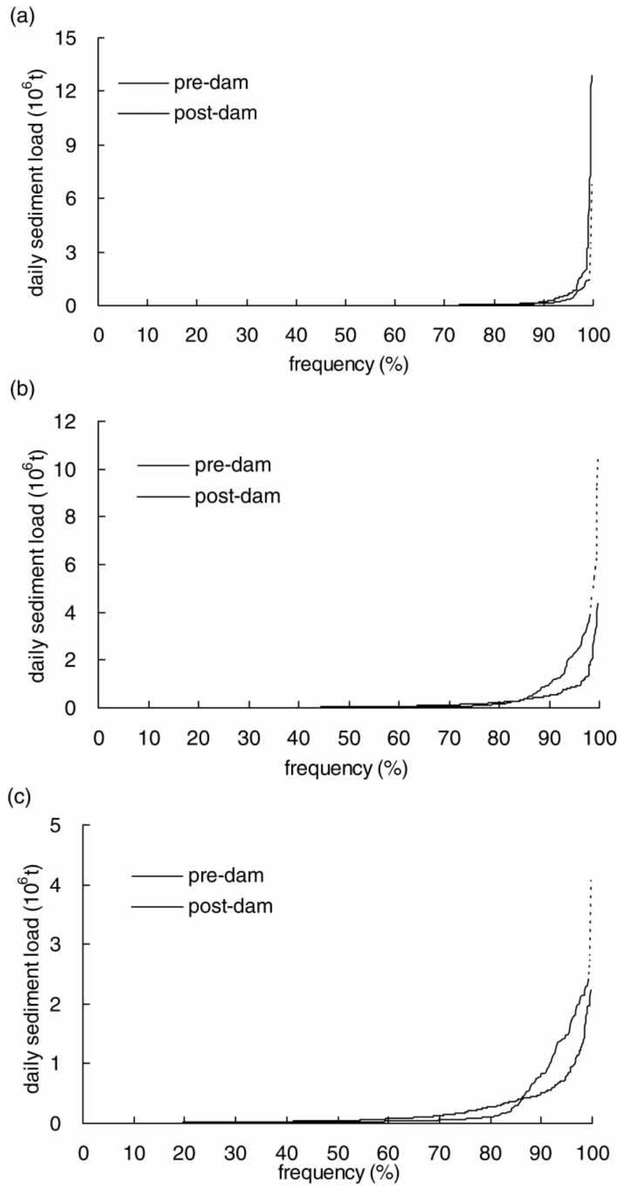

Figure 9 | Distributions of daily sediment load: (a) Baihe, (b) Huangzhuang, (c) Xiantao.

years. Although annual sediment load at Baihe in the post-dam period was on average lower than that in the pre-dam period, the alteration of water–sediment relationship is not significant due to the dams above Baihe having relatively less influence compared to the Danjiangkou reservoir.

This analysis suggests that the influence of the Danjiangkou reservoir on annual sediment load varied with the distance between the Danjiangkou reservoir and the target site.

Seasonal sediment load

Before 1967, the wet-season sediment load accounted on average for 89.1 and 90.9% of the annual sediment load at Huangzhuang and Xiantao and less than 96.4% at Baihe (see Table 1). However, after 1967, this percentage decreased to 82.3 and 76.1% at Huangzhuang and Xiantao and rose a little to 97.7% at Baihe. The reduction in the percentage at Huangzhuang is mainly due to the operation of the Danjiangkou reservoir to 'retain high floods in wet season'. The decrease in the percentage at Xiantao is more obvious owing to the decreased sediment supply from Huangzhuang and the sediment siltation in the river stretch between Huangzhuang and Xiantao, which was induced by water withdrawal from the stretch for offstream uses (Lu *et al*. 2009).

Before 1967, both wet- and dry-season sediment loads at Huangzhuang and Xiantao were generally higher than those at Baihe (Figure 6). However, after 1967, the wet- and dry season sediment loads at Huangzhuang and Xiantao were both lower and higher, respectively, than those at Baihe (Figure 6). Since sediment load is closely related to runoff, sediment trapping by the Danjiangkou reservoir is exacerbated by operations to retain high floods in wet seasons.

The correlation analysis demonstrates that the sediment load trapped by the Danjiangkou reservoir is strongly associated with the sediment load entering the reservoir in wet seasons, see Figure 7(a), while the sediment load trapped by the reservoir did not vary much with the increase of the sediment load entering the reservoir in dry seasons (Figure 7(b)). This is because most sediment was produced in wet seasons and the operation of 'retaining high floods in wet seasons' was adopted by the reservoir.

Monthly sediment load

Impacts of the Danjiangkou reservoir on the monthly distribution of sediment load at Baihe, Huangzhuang and Xiantao were analysed (Figure 8). The *y*-axis represents the percentage of monthly sediment load in the annual sediment load. From Figure 8 it can be seen that 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 loads at both stations were 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.

Daily sediment load

From Figure 9(a) it can be seen that the distributions of daily sediment load at Baihe were very similar during pre-dam and post-dam periods. There was little change in the distribution of daily sediment load below 1.3×10^5 tonnes and limited change in the distribution of daily sediment load above 1.3×10^5 tonnes occurred. Since the Danjiangkou reservoir was operated to retain high floods in wet seasons, which contained high sediment concentration, frequencies of daily sediment load less than 1.0×10^5, 2.0×10^5 and 3.0×10^5 tonnes at Huangzhuang increased to 96, 98 and 99% respectively in the post-dam period from 89, 93 and 96% in the pre-dam period (Figure 9(b)). Frequencies of daily sediment load less than 6.0×10^5, 9.0×10^5 and 1.3×10^5 tonnes during 1955–1966 at Xiantao were 88, 91 and 93% respectively, but in the period of 1967–2008 they increased to 92, 96 and 98% respectively (Figure 9(c)). With a frequency of 99%, daily sediment loads at Huangzhuang and Xiantao were 5.5×10^5 and 2.4×10^5 tonnes during the pre-dam period, but they significantly decreased by 45.5 and 25.0% to 1.8×10^5 and 2.5×10^5 tonnes respectively in the post-dam period. This implies that the sediment regime of the middle and lower Hanjiang River is becoming more and more dominated by lower daily sediment load. As the daily sediment load from the Huangzhuang–Xiantao river basin is an important component in the total daily sediment load at Xiantao, the daily sediment load at Huangzhuang was more affected by the operation of the Danjiangkou reservoir in comparison with Xiantao.

CONCLUSIONS

This paper has evaluated the impacts of human activities, in particular dam construction, on the sediment regime of the Hanjiang River. The results revealed that the Danjiangkou reservoir imposed significant effects on the river sediment regime and the impacts varied with the distance between the target reservoir and the study site. Sediment trapping in reservoirs together with soil and water conservation caused a significant reduction in annual, seasonal, monthly and daily sediment load at Huangzhuang and Xiantao stations, and the sediment load trapped by the Danjiangkou reservoir was closely related to the sediment load entering the reservoir in wet seasons. The reservoir operation mode of 'retain high floods in wet seasons' altered the distribution of monthly and daily sediment load at Huangzhuang and Xiantao, i.e. the percentage of sediment load in high flow months decreased and that in low flow months increased. Furthermore it caused a reduction in the percentages of high daily sediment load at Huangzhuang and Xiantao. The relationship between water and sediment significantly changed, i.e. with the same amount of water quantity, the contained sediment load decreased significantly due to dam operation.

We hope that the results of this paper might provide a reference point for the assessment of the impact of human activities on the long-term health and stability of the Hanjiang River ecosystem.

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