Complex behaviour of suspended sediment grain size downstream from a reservoir: an example from the Hanjiang River, China

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Abstract A study on the suspended sediment transportation downstream from the Danjiangkou Reservoir in China has shown that the dynamics of suspended sediment grain size are complicated. During the period when the reservoir was used for flood retention, the suspended sediment median size decreased gradually; after entering the period when the reservoir was used for water storage, the median size started to increase, reaching a maximum, and then decreased again. These variations correspond to different stages of channel adjustment. At the stage with dominant downcutting, most of the downstream reservoir sediment comes from bed downcutting, and thus the suspended sediment median size becomes coarser and coarser; at the succeeding stage with dominant channel widening, a majority of the suspended sediment comes from bank erosion, and so its median size becomes finer. This phenomenon can be regarded as a reflection of the complex response of channel adjustment in the characteristics of suspended sediment transportation downstream from a reservoir.

Le comportement complexe de la taille des particules de matières en suspension à l'aval d'un réservoir : un exemple sur la rivière Hanjiang (Chine)

Résumé Une étude menée sur le transport en suspension de sédiments à l'aval du réservoir Danjiangkou en Chine a montré que la dynamique de la taille des particules de matières en suspension était complexe. Pendant les périodes où le réservoir est utilisé pour écréter les crues, la médiane de la taille des sédiments en suspension décroît progressivement; quand on entre dans une période où le reservoir est utilisé comme réserve d'eau, la médiane de la taille commence par croître, atteint un maximum puis décroît. Ces variations correspondent à différents stades de l'ajustement du chenal. Au stade d'approfondissement, la plupart des sédiments présents à l'aval proviennent de l'affouillement du lit, et la médiane de la taille des sédiments en suspension augmente de plus en plus; au stade suivant caractérisé par l'élargissement du chenal, l'essentiel des sédiments en suspension provient de l'érosion des berges et la médiane de la taille des particules diminue donc. Ce phénomène peut être interprété comme le reflet, au niveau des caractéristiques du transport des matières en suspension à l'aval d'un réservoir, du processus complexe d'ajustement du chenal.

INTRODUCTION

The characteristics of river sediment involve both quantitative and qualitative aspects. Sediment quality includes the grain size composition of the sediment,

Open for discussion until 1 June 1997

its mineral composition and the nutrient elements and pollutants adsorbed by and moving together with the sediment. If the issue of sediment quantity is of great significance in engineering, then the issue of sediment quality is of great significance in environmental research and protection.

Much research has been conducted on the dynamics of suspended sediment grain size composition. The variation in composition of suspended sediment grain size depends on the variation in sediment sources and the delivery process downstream (Walling & Webb, 1992; Walling & Moorehead, 1989). At short time scales, it is controlled by the relative contribution of sediment from different sources in the basin during different rainstorm events; at a relatively long time scale, it may be influenced by changes in land cover and land use in the river basin. Human activities have a great influence on the composition of suspended sediment, in that the quantity and quality of suspended sediment are greatly altered after the natural vegetation is destroyed by man. Furthermore, after reservoir construction, due to the runoff and sediment regulation by the reservoir, the downstream sediment composition will be changed. This change may have some effect on both the water quality and the river environment, and thus deserves study, but so far little has been done in this aspect of research. In the present study, an effort has been made to examine the dynamics of suspended sediment grain size downstream from the Danjiangkou reservoir, based on data from Huangjiagang and Nianpanshan stations (Fig. 1). The middle reaches of the Hanjiang River, with a length of 270 km, stretch from Danjiangkou to Zhongxiang.

After the construction of a reservoir for water storage, appreciable degradation usually occurs downstream because the reservoir intercepts most

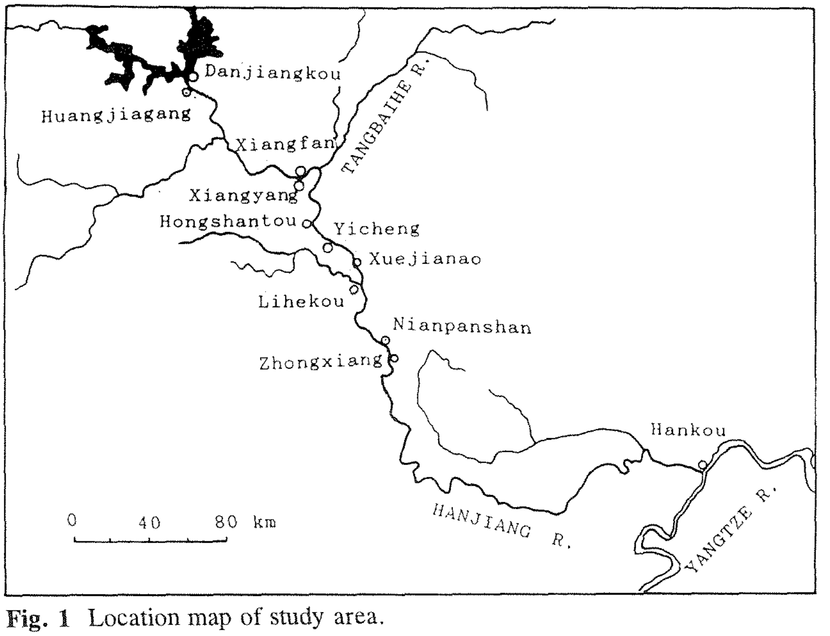

Fig. 1 Location map of study area.

of the sediment from the river basin above the dam. The degradation includes bed scouring and bank erosion which constitute the major sediment source for the downstream channel. Sediment from downstream tributaries cannot be influenced by the dam so, in a sense, the quantity and grain size composition of sediment from such tributaries may be considered as a constant. With the ongoing channel adjustment, bed scouring and bank erosion vary with time, and thus the relative contribution of the two processes to sediment production is also dynamic. Because in general bed material is coarser than bank material, then the downstream suspended sediment grain size can be expected to vary with time. The study conducted in the Hanjiang River showed that this variation could be regarded as a reflection of a complex response in channel adjustment; the results are reported in this paper.

CHANGE IN WATER AND SEDIMENT DUE TO RESERVOIR CONSTRUCTION

The Hanjiang River, the longest tributary of the Yangtze River, is 1567 km in length and drains an area of 159 000 km^2. The mean annual discharge at Huangjiagang is 1308 $m^3 s^{-1}$, increasing to 1590 $m^3 s^{-1}$ at Nianpanshan. In the pre-dam period, the mean annual suspended sediment concentrations were 2.92 and 2.42 kg m^{-3}, respectively, at the two stations. The dam was built in 1959, located where the river leaves mountain areas and enters a wide valley plain. From 1960 to 1967, the reservoir was used for flood retention and, afterwards, was used for water storage. The year to year variation in the annual flood at the Huangjiagang station, 7 km downstream from the dam, is plotted in Fig. 2, indicating that the annual flood declined markedly after the construction of the dam except for some years when an extremely large flood occurred. The coefficient of variation of monthly discharge also declined.

Figure 3 gives the relationship of the inflow sediment of the reservoir to the outflow. It can be seen that during the period when the reservoir was used for flood retention, most of the inflow sediment could be released through the dam, but in the period when the reservoir was used for water storage, the outflow sediment was very little compared with the inflow, and the former did not vary with the latter. In terms of sediment load gauging data, from 1968 to 1980, the sediment transported into the reservoir totalled 603.90 million tonnes, and during the same period, the sediment transported out of the reservoir totalled 15.11 million tonnes, with deposition accounting for 97.5% of the inflow total. Obviously, the dam intercepts most of the sediment from the upstream river basin, and therefore the sediment sources for the downstream channel have been entirely altered. Before the construction of the reservoir, the sediment transport through the middle and lower reaches of the Hanjiang River came mainly from erosion in the upper river basin, but afterwards it has come mainly from bed scouring, bank erosion and also from some major tributaries. The major tributary in the middle of the Hanjiang River is the Tangbaihe

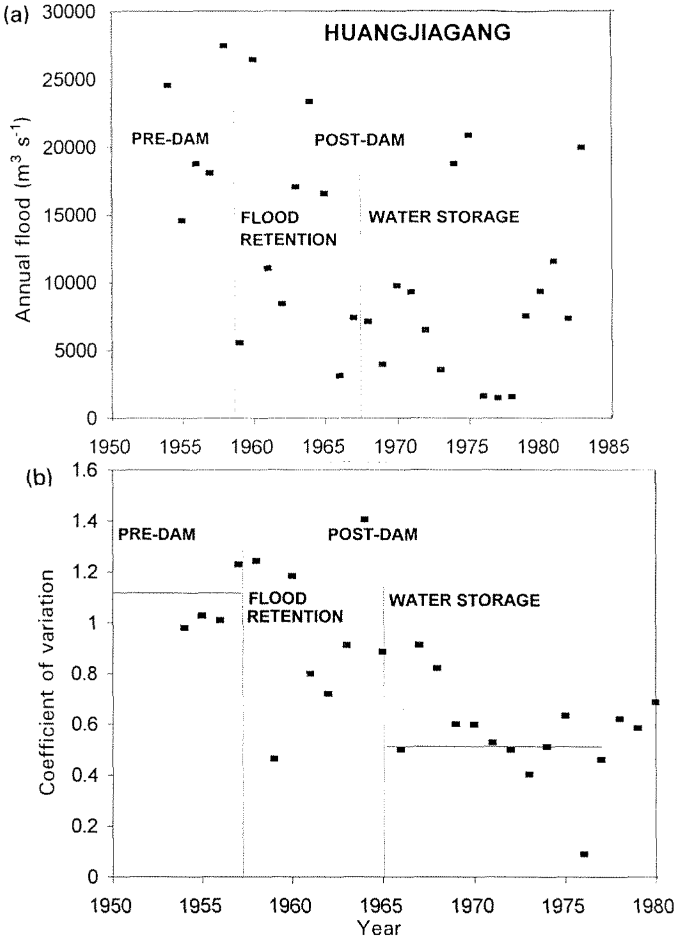

Fig. 2 Year to year variation in (a) annual flood and (b) coefficient of variation of monthly discharge at Huangjiagang station.

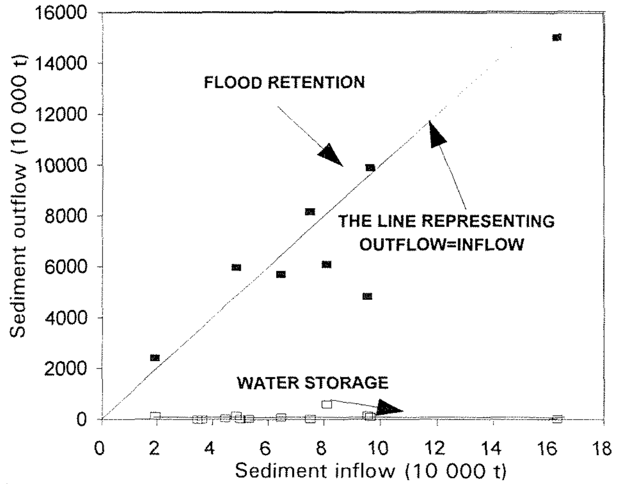

Fig. 3 Relationship of annual inflow and outflow sediment transport of the Danjiangkou Reservoir.

River, whose mean annual suspended sediment load is 7.80 million tonnes. Sediment from other small tributaries is very limited and thus can be neglected.

The year to year variations in mean annual suspended sediment concentration and annual suspended sediment load at the Huangjiagang and Nianpanshan stations are plotted in Fig. 4, and the annual sediment fill and scour between these two stations, expressed as the difference between the suspended sediment load of the two stations, is given in Fig. 5. It can be seen that, during the water storage phase, the annual suspended sediment concentration at Huangjiagang station was very low, ranging from 0.005 to 0.189 kg m^{-3}, and the flow in most of a year could be regarded as a clear water. However, due to the scour in a 240 km reach between Huangjiagang and Nianpanshan, the annual suspended sediment concentration at the downstream station increased to 0.24-1.10 kg m^{-3}. Careful observation indicates a progressive decline in sediment concentration and sediment load at the Nianpanshan station, indicating that, with the ongoing channel adjustment the sediment supply from the channel becomes less and less, and the channel is tending to reestablish equilibrium.

It can also be seen from Fig. 5 that bed scouring started during the flood

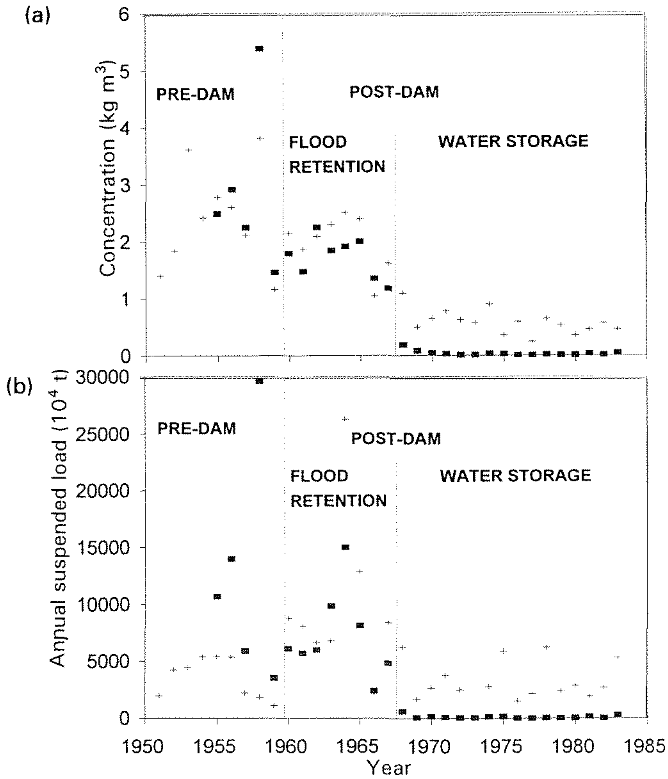

Fig. 4 Year to year variation in (a) mean annual suspended sediment concentration and (b) annual suspended sediment load at Huangjiagang and Nianpanshan stations.

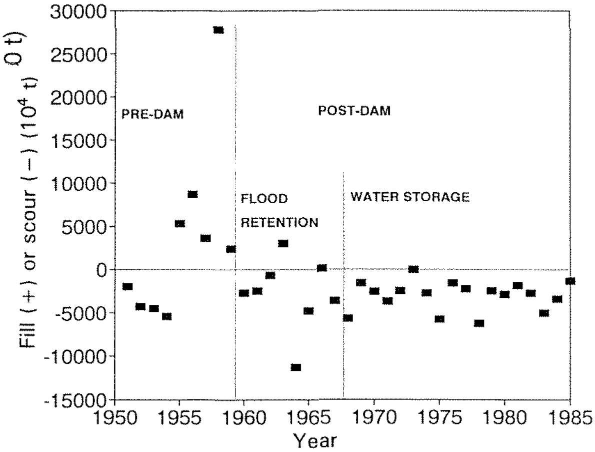

Fig. 5 Year to year variation in fill or scour between Huangjiagang and Nianpanshan.

retention phase, and intensified during the water storage phase. Due to the interannual variation in runoff, the fluctuation in scour was marked.

TEMPORAL VARIATION IN SUSPENDED SEDIMENT GRAIN SIZE

Since the sediment sources for the downstream channel were totally changed after the reservoir construction, the grain size composition of suspended sediment also changed. Because the suspended sediment grain size sampling and analysis were started in 1960 at the gauging station, it is not possible to make a comparison between the pre- and post-dam periods. However, measurements show that the variation in suspended sediment median size at Nianpanshan station is pronounced since 1960 (Fig. 6), and some notable

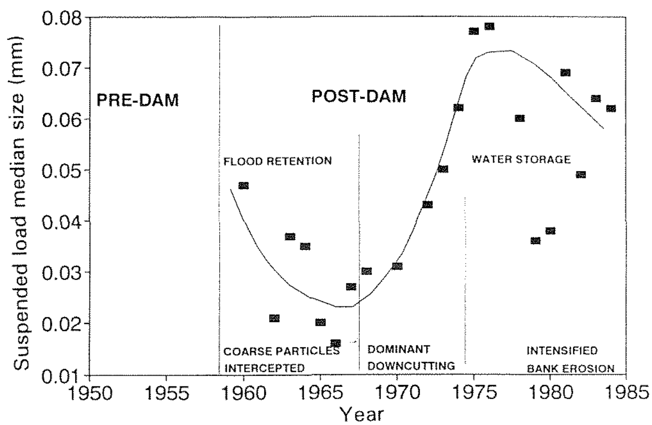

Fig. 6 Year to year variation in suspended sediment median size at Nianpanshan station.

tendency can be identified. Starting from 1960, suspended sediment median size decreased gradually, reaching a minimum value around 1966, and then increased; after reaching a maximum value around 1976, it decreased again.

The regularity shown by Fig. 6 is so obvious that it cannot be considered as a random feature. This variation has to be considered as a reflection of a complex response in downstream reservoir channel adjustment. In what follows, the mechanism for Fig. 6 will be explained.

DYNAMICS OF BED SCOURING AND BANK EROSION AND THEIR CONTRIBUTION TO SEDIMENT PRODUCTION IN THE DOWNSTREAM CHANNEL

Composition of bed and bank material

The middle Hanjiang River has a sand bed, and the bed material median size varied from 0.35 to 0.15 mm downstream before the reservoir construction (Fig. 7). Underlying the bed surface there is a gravel layer, with its depth increasing downstream from 4-5 m to more than 20 m underneath the bed surface. The composition of bank material varies with the landform units in which it is located. The bank can be classified into different units such as the second terrace, the first terrace, the higher floodplain and the lower floodplain, with the material becoming coarser in this sequence. The double-layer structure is well developed, with the upper layer composed of floodplain-phase silt and clay and the lower layer fine to medium sands. The alternative occurrence of sand and silt-clay layers in bank sections is also a common feature. Therefore the composition of the bank material shows a complicated variation downstream (Fig. 7). Generally speaking, the bank material is much finer than the bed

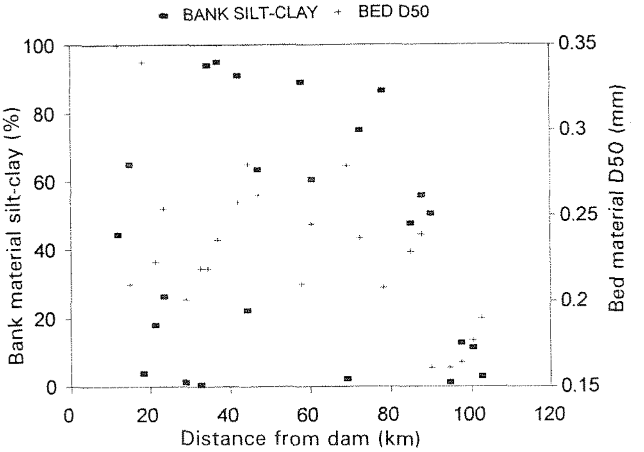

Fig. 7 Downstream variation in bed material median size and bank material silt-clay percentage from Danjiangkou to Xiangfan.

material. The bed material composition becomes coarser with the ongoing scouring by clear water, and thus the sediment load also becomes coarser. On the other hand, the variation of bank material with time is very slow, and can be neglected except where the bank is a newly formed pointbar or a low floodplain composed of much coarser material than that formed in the pre-dam period.

Obviously, due to the apparent difference in bed and bank material composition, if the relationship of the sediment contributions from bed and bank erosion changes with time, the grain size composition of the sediment load can also be expected to change.

The changing process of bed scouring

Bed scour downstream from a reservoir is a nonlinear process both in time and space. At a section, the bed material becomes coarser with the ongoing scouring, leading to a larger critical shear stress for particle entrainment. At the same time, scouring leads to a larger cross sectional area, and thus a smaller flow velocity at a given discharge. Therefore, the rate of scour declines with time. Through its course of process, the sediment picked up from the cross section also becomes coarser and coarser. Figure 8 shows the temporal variation in thalweg elevation and bed material median size at the Huangjiagang station. It can be seen that the scour by clear water is very strong and the bed material coarsening is striking. By 1971, the underlying gravel layer was completely exposed by scouring, thus the bed thalweg could no longer be lowered, and the rate of scour became very slow. In the middle Hanjiang River, this case is not common, because in most reaches the gravel layer is buried rather deeply and cannot be exposed. However, the coarsening process and the slowing of scour with time are similar all over the middle Hanjiang River; the difference is that the development of these processes is much slower.

The above process has a significant effect upon sediment production in the downstream channel. Obviously, with the coarsening of bed material and the slower and slower downcutting rate, the sediment supply from the bed declines gradually, with a coarser and coarser grain size (Chien *et al.*, 1987). For the whole reach downstream from the dam, with the ongoing scouring, the point where the maximum rate of scouring appears gradually moves in the downstream direction (Chien *et al.*, 1987).

The changing process of bank erosion

Based on data from the Hongshantou-Yakou reach, the temporal variation in bank erosion rate has been studied, and the result is shown in Fig. 9. Before the reservoir construction, the bank erosion rate of this reach was rather high, because of a low erosional resistance of bank material. After reservoir construction and during the early stage of channel adjustment with dominant down-

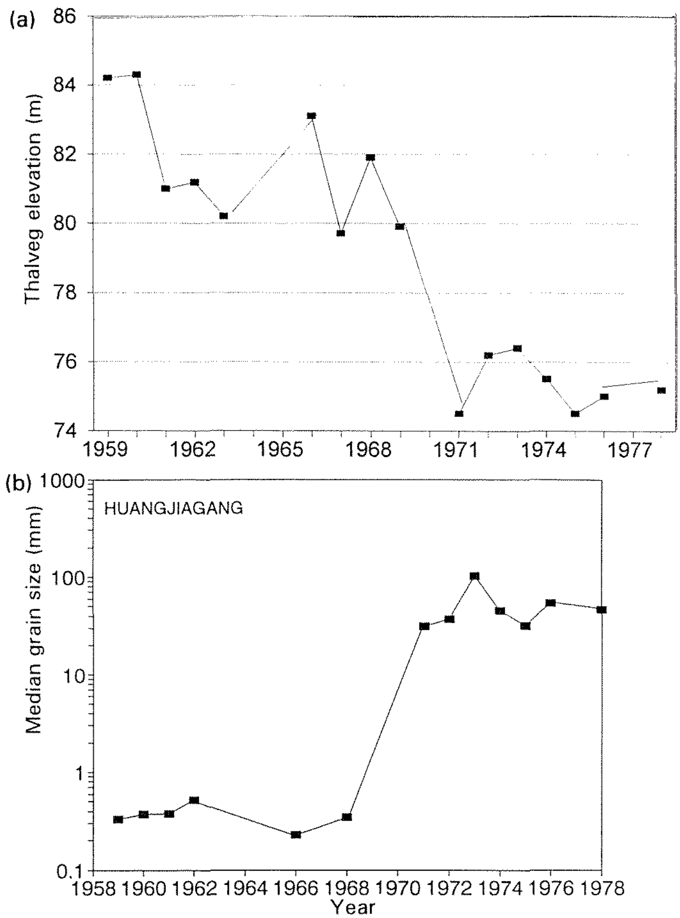

Fig. 8 Temporal variation in (a) thalweg elevation and (b) bed material median size at Huangjiagang.

cutting, the bank erosion rate was very low, much lower than that in the pre-dam period (Fig. 9(a)). With the ongoing process of bed material coarsening (Fig. 9(b)), the erosional resistance of the bed material increased. In the meantime, the change in bank material, and therefore in its erosional resistance, was negligible. If one expresses the relative erosion-resistance by the ratio of bank erosional resistance to that of the bed, then it would be decreased (Fig. 9(b)). Note that here the relative erosional resistance of bed to bank material is defined by the critical shear stress of bank material divided by that of the bed material, and the two critical shear stresses are calculated by using a formula proposed by Tang (1963). As a result, the bank erosion is intensified (Fig. 9(a)). This means that the contribution of bank erosion to sediment production gradually increases. Since the sediment from bank erosion is much finer than that from bed scouring, this can be regarded as a major factor responsible for the decline in suspended sediment median size.

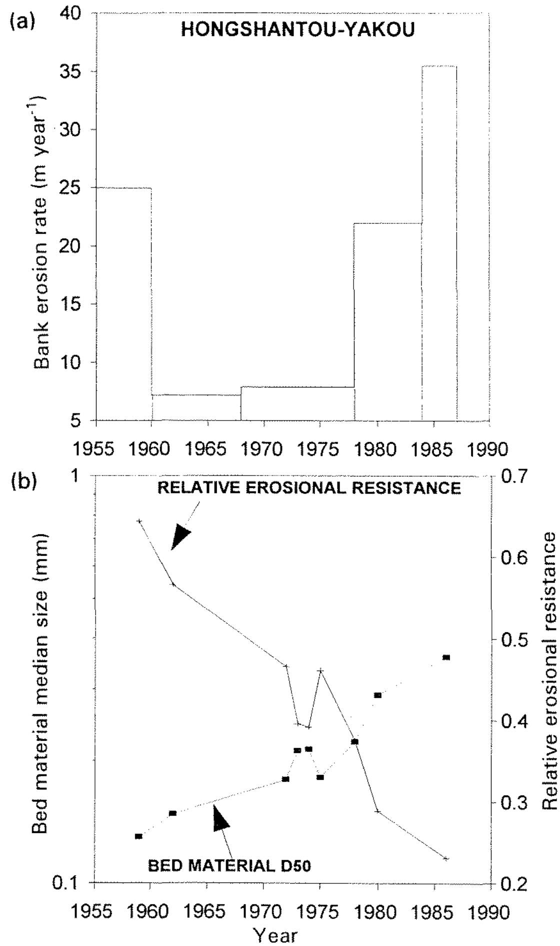

Fig. 9 Temporal variation in channel boundary material erosional resistance and bank erosion rate: (a) bank erosion rate in the reach Hongshantou-Yakou (after Xu & Shi, 1992); and (b) bed material median size and relative erosional resistance of bank to bed material at Yicheng (after Xu & Shi,1992).

EXPLANATION OF THE MECHANISM FOR THE VARIATION IN SUSPENDED SEDIMENT MEDIAN SIZE

As discussed in the foregoing sections, in the period when the reservoir was used for water storage, the sediment supply to the middle Hanjiang River was derived from bed scouring, bank erosion and tributaries. The sediment derived by tributaries may be considered as unchanged in an average sense. Therefore the regularity shown by the curve in Fig. 6 should be regarded as the result of the changing contribution of bed scouring and bank erosion to the downstream sediment supply. The variation in suspended sediment grain size in the period when the reservoir was used for flood retention may be related to this mode of reservoir operation.

The variation in suspended sediment grain size during the flood retention phase

During this period, the sediment supply for the middle Hanjiang River came primarily from the upper river basin. Although for the whole year the change in suspended sediment transport is small, this kind of reservoir operation has an important influence on the grain size composition of suspended sediment. Under the operational mode of flood retention, large quantities of sediment are intercepted during floods in high flow season, and afterwards, the previously intercepted sediment is released through the dam, usually in the successive low flow season. When sediment is deposited in the reservoir during a flood, the probability for coarse particles to deposit is higher than that for fine particles. On the other hand, after the flood, when the previously deposited sediment is scoured and released from the reservoir, the probability for fine sediment to be released is higher than that for coarse sediment. Obviously, these two processes may cause a finer suspended sediment median size, as observed at the Nianpanshan station and shown in Fig. 6 for the flood retention phase.

The variation in suspended sediment grain size during the water storage phase

Since 1968, the Danjiangkou Reservoir has been used for water storage, and clear water has been released from the reservoir. As a result, intensive scour has occurred, and the sediment supply to the downstream channel has been dominated by sediment from bed scouring. This has led to a coarser and

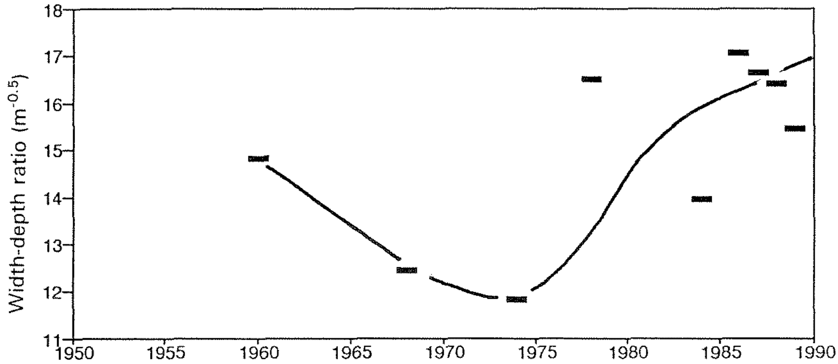

Fig. 10 Temporal variation in channel width-depth ratio in the reach from Xiangfan to Lihekou. (Note that the square root of width is used for calculating the width-depth ratio (after Xu, in press)).

coarser suspended sediment median size, which reached a maximum value around 1976. Afterwards, bank erosion became the main contributor to downstream sediment supply, and thus the suspended sediment median size became finer again. The temporal variation in the channel width-depth ratio in the reach from Xiangfan to Lihekou is plotted in Fig. 10, which shows that it reached a minimum value around 1975, and afterwards increased rapidly, indicating an intensified bank erosion. It can be seen in Fig. 9(a) that in 1978-1984 the bank erosion rate started to increase rapidly. All these can be related to the fact that the suspended sediment median size started to decline after reaching a maximum around 1976. This suggests a cause-effect relationship between the fining of suspended sediment and the intensified bank erosion.

CONCLUSIONS

Through a study of suspended sediment transportation and channel adjustment process downstream from the Danjiangkou Reservoir, it has been found that the variation of suspended sediment median size exhibits some regularity. From 1960 to 1984, the suspended sediment grain size underwent a variation of decrease, increase and decrease again, making the curve in Fig. 6 more or less similar to a sine curve. The flood-retention operation of the reservoir led to a decline in suspended sediment median size downstream. After the reservoir was used for water storage, suspended sediment size increased. Then the coarsening tendency of suspended sediment by bed downcutting was offset by the fining tendency induced by bank erosion which was intensified later and thereby the suspended sediment median size returned to its original level.

In an earlier study on post-dam channel adjustment in the middle Hanjiang River, a complex response phenomenon was identified (Xu, 1990; 1991). In effect, the temporal variation shown in Fig. 6 can also be regarded as a complex response phenomenon. This is the reflection of the complex response of channel adjustment in downstream sediment transportation, and the two aspects of the complex response can be well related. The increase in suspended sediment median size can be related to the stage when the channel adjustment was dominated be bed downcutting, while the decrease can be related to the stage when the channel adjustment was dominated by channel widening.

Acknowledgments This paper is based on part of the results of a project supported by the National Natural Science Foundation of China, and was written when the author was a visiting scholar at The University of British Columbia, Vancouver, Canada. M. Church reviewed an early manuscript, and his highly appreciated comments were invaluable in improving the paper. The author also wishes to express his gratitude to the Danjiangkou General Hydrological station, the Yangtze River Water Conservancy Commission, for access to data used in this study.

REFERENCES

Chien, Ning, Zhang, Ren & Zhou, Zhide (1987) *River Channel Processes*, Science Press, Beijing (in Chinese).
Tang Cunben (1963) Laws of sediment incipient motion. *J. Hydraul. Engng* **1**, 1-12 (in Chinese).
Walling, D. E. & Webb, B. W. (1992) Water quality I. Physical characteristics, In: *The River Handbook*, ed P. Calow & G. Petts, 48-72. Blackwell Scientific Publications, Oxford, UK.
Walling, D. E. & Moorehead, P. W. (1989) The particle size characteristics of fluvial sediment: an overview. *Hydrobiologia* **176/177**, 125-149.
Xu Jiongxin (1990) An experimental study of complex response in river channel adjustment downstream from a reservoir. *Earth Surf. Proc. Land.* **15**, 43-53.
Xu Jiongxin (1991) Complex response in channel adjustment downstream from the Danjiangkou Reservoir. *Chinese Sci. Bull.* **36**, (10), 838-842.
Xu Jiongxin & Shi Changxing (1992) River bank erosion downstream from the Danjiangkou Reservoir and its implications in river channel adjustment. In: *Proc. 5th Int. Symp. Erosion and River Sedimentation*, (Karlsruhe, Germany).
Xu Jiongxin (in press) Channel pattern change downstream from a reservoir: an example of wandering braided rivers. *Geomorphol.*

Received 7 December 1995; accepted 20 March 1996