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Erosion and recovery of sediment concentration in the river channel downstream from Danjiankou Reservoir

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ABSTRACT This paper describes the characteristics of the sediment transport capacity of the Hanjiang River downstream from Danjiankou Reservoir and the phenomena of recovery of sediment concentration by the scouring process. Using the theory of nonequilibrium transportation of nonuniform sediment, the mechanism and a method of calculating sediment concentration recovery have been derived.

INTRODUCTION

The clear water released from a reservoir will scour the downstream channel of an alluvial river and the sediment concentration should gradually increase along the river course. Usually, the length of river reach required is rather long. For example, the eroded reach of the Yellow River downstream from Sanmenxia Reservoir extended about 800 km as far as its estuary. Similarly, the eroded reach downstream of Danjiankou Reservoir extends 650 km to Hankou, where the Hanjiang River joins the Yangtze River.

Results of flume tests and calculations with uniform particles and uniform flow, however, suggest that the degrading reaches will be very short. In the case of a natural river, the calculated length of the eroded reach is generally no more than 10 km. Why this difference occurs remains a problem which has to be explained.

During the scouring process caused by clear water, the suspended load is mainly supplied by the river bed, and the processes of degradation and of recovery of sediment concentration can be viewed as synonymous and will therefore not be distinguished in this paper. Using the theory of nonequilibrium transportation of nonuniform sediment developed by the first author Han (1979) and data from the Hanjian River, the paper describes the recovery of sediment concentration along the river, including the variation of sediment transport capacity, the nature of sediment concentration recovery and the mechanisms involved, and a calculation method.

CHANGES IN SEDIMENT TRANSPORT CAPACITY

Since clear water is released from the reservoir, the sediment-carrying capacity downstream will be changed in two respects:

(a) In the same river reach the sediment transport capacity will

TABLE 1 Average settling velocities of suspended load before and after dam construction

Name of gauging station	*Distance from dam site (km)*	*Average settling velocity (cm s^{-1})*	
		Before dam construction	*After dam construction*
Huangjiangang	6	0.262	
Xiangyang	109	0.412	1.230
Huangzhuang	240	0.266	0.900
Xiantao	457	0.171	0.541

be much less than before dam construction, for the following reasons:

(i) The particles of suspended load are mainly supplied by the river bed and become coarser with larger settling velocities. This is clearly shown in Table 1.

(ii) The flood peak will be attenuated by the reservoir. Take $Q_K = \sqrt{<Q^2>}$ as a characteristic discharge of the sediment transport capacity of a river, as given by Han *et al.* (1980). In 1958 and 1975, respectively, before and after the dam was built, the annual discharge changed very little but the values of $<Q_K>$ were reduced from 4087 to 3041 m^{3}s^{-1} and thus the annual sediment transport capacity of the river channel was reduced by as much as 41%.

(iii) As a result of erosion during the initial stage of reservoir operation, the flow velocity becomes smaller and the depth larger for the same discharge. This is more obvious in the upper part of the river channel reach downstream of the dam. For example, from Huangjiagang to Xiangyang the average flow velocity is only 70-80% of that before the dam was built.

(b) The sediment transport capacity will increase along the river channel. This is mainly caused by the fact that the size of the bed material and the suspended load becomes finer and hence the settling velocities are smaller (Table 1).

In spite of these conditions, the sediment transport capacity can still be calculated by the expression:

$$S^*(w^*) = 0.147 \times 10^{-3} \left(\frac{V^3}{ghw^*}\right)^{0.92} \tag{1}$$

where

$$w^{*\,0.92} = \Sigma P^*_{4.\ell} w_\ell^{0.92} \tag{2}$$

V = average velocity of the flow, h = average water depth, g = acceleration of gravity, $P^*_{4.\ell}$ = size distribution of sediment transport capacity, w_ℓ = settling velocity of ℓ-th size group. The data observed at Xiantao and Huangzhuang before and after dam construction and during the attenuation of floods are all consistent with equation (1).

TABLE 2 Average sediment concentrations during each month of 1974 (kg m^{-3})

Name of station	Month: 1	2	3	4	5	6	7	8	9	10	11	12	Annual
Huangjiagang	0.004	0.004	0.003	0.007	0.019	0.019	0.008	0.012	0.044	0.116	0.007	0.004	0.035
Xiangyang	0.177	0.170	0.129	0.186	0.200	0.071	0.057	0.425	0.163	0.386	0.049	0.061	0.205
Huangzhuang	0.358	0.317	0.230	0.342	0.558	0.235	0.263	1.11	0.448	0.997	0.322	0.441	0.576
Xiantao	0.776	0.700	0.460	0.384	0.657	0.331	0.250	1.12	0.515	1.40	0.519	0.635	0.740

CHARACTERISTICS OF SEDIMENT CONCENTRATION RECOVERY

There are five characteristics of sediment concentration recovery in the river course below Danjiankou Reservoir.

(a) Sediment concentration recovers over a long distance. Table 2 shows the recovery of average sediment concentration for individual months. Except in July, the scoured reach always extends to Xiantao. In fact, it has extended to the estuary of the Hanjian River.

(b) The rate of increase of sediment concentration along the river channel is rather uniform as shown in Table 2.

(c) Corresponding to the change in sediment concentration, the size distribution of the suspended load becomes more uniform and finer along the river channel (Table 1).

(d) The degradation and aggradation characteristics of each particle size group are different. Generally, the fine fractions are scoured more than the coarse fractions. The coarse particles may even be deposited during the scouring process. As a result, the average particle size of the suspended load becomes finer and hence the settling velocity becomes smaller along the river reach. Data covering the degradation and aggradation observed between the gauging stations at Huangzhuang and Xiantao are listed in Table 3.

TABLE 3 Amount of degradation and aggradation for each size group from Huangzhuang to Xiantao

Range of particle size (mm)	*<0.01*	*0.01–0.025*	*0.025–0.05*	*0.05–0.10*	*0.10–0.25*	*0.25–0.50*	*Total*
Degradation and aggradation (10^4 t)	*-287*	*-269*	*-190*	*-160*	*+20*	*+132*	*-754*

Between these two stations, the annual net eroded sediment amounted to 7.53 Mt, while 9.06 Mt of sediment with particle sizes smaller than 0.1 mm were actually eroded and 1.53 Mt with particles sizes larger than 0.1 mm were deposited. In other words, during the scouring process the bed material is exchanged with suspended load and the settling velocity of suspended load thus decreases from 0.09 m s^{-1} at Huangzhuang to 0.00541 m s^{-1} at Xiantao.

(e) The development of the degradation and the increase in sediment transport along the river are not due to an increase in flow intensity. According to equation (1) the intensity of the flow may be indicated by $V^{2.76}/h^{0.92}$. Field data show that although the sediment transport increases along the river course, the value of $V^{2.76}/w^{0.92}$ in Xiantao is less than in Huangzhuang.

ANALYSIS OF THE RECOVERY OF SEDIMENT CONCENTRATION

According to the preceding statements, the mechanism of sediment concentration recovery along the river channel can be summarized as follows. Because bed material is getting finer along the river reach and mutual exchange exists between the suspended load and the bed material, the coarse particles of the suspended load are deposited and the fine particles are eroded. Thus along the river reach the average particle size of suspended load becomes finer, the settling velocity becomes smaller and the sediment transport capacity increases. Therefore, the amount of fine particles which are eroded exceeds that of the coarse particles which are deposited. The decrease in settling velocity and the increase in sediment transport capacity both occur at a low rate. As a result, the recovery of sediment concentration extends over a very long distance and sediment concentration increases at a uniform rate.

Based on the general theory of nonequilibrium sediment transport of nonuniform sediment, the recovery of sediment concentration can be calculated. Simplifying the result presented by Han *et al.* (1980), the differential equation of sediment concentration may be expressed as:

$$\frac{dS_\ell}{dx} = S^*(w_\ell)\,\frac{P_{1.\ell} - P_{1.\ell.0}}{x} \qquad (3)$$

where S_ℓ = the sediment concentration of ℓ-th group, $S^*(w_\ell)$ = the sediment transport capacity for the same group, given by equation (1) and $P_{1.\ell}$ = the equivalent size distribution of bed material, the definition and expression of which is given in the paper by Han *et al.* (1981). If the size distribution of the suspended load at the upstream section is given and the size distribution of bed material $P_{1.\ell.1}$ is getting finer along the reach, then so is the equivalent size distribution of the bed material. For fine sediment, $P_{1.\ell} > P_{1.\ell.0}$, so that $dS_\ell/dx > 0$, i.e. the sediment concentration increases along the river course, while for the coarse sediment, $P_{1.\ell} < P_{1.\ell.0}$, so that $dS_\ell/dx < 0$, i.e. the sediment concentration decreases. Summing up the sediment concentration of all size groups, then

$$\frac{dS}{dx} = \frac{S^*(w^*) - S^*(w_0^*)}{x} \qquad (4)$$

where S is the total sediment concentration, $S^*(w^*)$, $S^*(w_0^*)$ are the sediment transport capacity at the upstream and downstream sections respectively. When the flow conditions remain constant along the river reach, the equivalent size distribution of bed material becomes finer and $S^*(w^*) > S^*(w_0^*)$. So that $dS/dx > 0$ and total sediment concentration increases along the river channel. Thus the phenomena of sediment concentration recovery may be described theoretically. Besides, if the size distribution of bed material $P_{1.\ell.1}$ becomes finer linearly along the river reach, i.e.

$$P_{1.\ell.1} = P_{1.\ell.1.0} + \frac{P_{1.\ell.1.L} - P_{1.\ell.1.0}}{L}\,x$$

where L = the length of the reach taken into consideration and the subscripts O and L express the value at the upstream and downstream sections respectively, then a series of explicit conclusions may be

TABLE 4 Comparison of observed and calculated sediment concentrations

Name of gauging station (distance from dam site)		Sediment concentration ($kg\ m^{-3}$)	Percentage of sediment concentration of each size (mm) group (%)							
			0-0.005	0.005-0.010	0.010-0.025	0.025-0.050	0.050-0.100	0.10-0.25	0.25-0.50	0.5-1.0
Huanjiagang	observed	0.141	58.8	14.9	11.4	7.2	6.4	1.0	0.30	
(6 km)	calculated									
Xiangyang	observed	0.472	8.7	6.9	14.7	16.9	13.7	21.4	16.7	1.0
(109 km)	calculated	0.777	10.5	2.9	2.2	14.9	9.6	47.8	12.1	
Huangzhuang	observed	1.16	8.0	3.8	10.3	19.8	24.7	26.4	7.0	
(240 km)	calculated	1.18	7.2	2.5	2.2	18.6	12.9	46.9	9.4	0.3
Xiantao	observed	1.72	10.8	7.3	16.4	21.1	23.9	19.4	11.1	
(457 km)	calculated	1.31	6.5	2.2	1.8	36.2	24.3	26.6	2.4	

obtained as follows: Along the river reach, the equivalent bed material becomes finer, the sediment transport capacity and the reciprocal of average settling velocity w^* increase; the total sediment transport becomes larger; the sediment concentration of fine particles increases while that of coarse particles decreases; and the total concentration becomes larger; all these values vary linearly. In addition to this, the size distribution of sediment transport capacity and suspended load become finer along the river reach.

CALCULATION OF SEDIMENT CONCENTRATION RECOVERY

The process of sediment concentration recovery along the river is by no means abrupt. Based on earlier studies on nonequilibrium transportation of nonuniform suspended load the sediment concentration and the size distribution of suspended load may be determined by the following equation:

$$P_{4.\ell}\, S = P^*_{4.\ell}\, S^* + S_o P_{4.\ell.o} \exp\left(-\frac{\alpha_\ell w_\ell x}{q}\right) + S^*_o P^*_{4.\ell.o} \left(-\frac{\alpha_\ell w_\ell x}{q}\right)$$

$$+ \frac{q}{\alpha_\ell w_\ell x}\left[1 - \exp\left(-\frac{\alpha_\ell w_\ell x}{q}\right)\right]\left(S^*_o P^*_{4.\ell.o} - S^* P^*_{4.\ell}\right) \tag{5}$$

where α_ℓ = the coefficient of saturation, q = the flow discharge of unit width, $P_{4.\ell}$ = the size distribution of suspended load at the downstream section and $P^*_{4.\ell}$ = the size distribution of sediment transport capacity which may be determined by

$$P^*_{4.\ell} = \begin{cases} P_{4.\ell} & \text{(during aggradation)} \\ \dfrac{w^{*\,0.92}}{w_\ell^{\,0.92}} P_{1.\ell} & \text{(during degradation)} \end{cases} \tag{6}$$

where $P_{1.\ell}$ = the equivalent size distribution of bed material. $P^*_{4.\ell.o}$ can be calculated by the same way. w^* is given by

$$w^{*m} = \left(\Sigma^{c}_{\ell=1} \frac{P_{1.\ell}}{w_\ell^{0.92}}\right)^{-1} \tag{7}$$

When the parameter $P_{4.\ell.o}$, S_o at the upstream section and $P_{1.\ell.1}$, $P_{1.\ell.1.o}$ of the river reach are known, S can be calculated from equations (5)-(7).

Two sets of data observed in the Hanjian River downstream from Danjiankou Reservoir have been compared with the calculation results. The comparison is listed in Table 4 and shows that both are in good agreement.

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