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Sediment Flux to the Sea as Influenced by Changing Human Activities and Precipitation: Example of the Yellow River, China

XU JIONGXIN*
Institute of Geographical Sciences and Natural Resources Research
Beijing 100101, China

ABSTRACT / Since the 1970s, the sediment flux of the Yellow River to the sea has shown a marked tendency to decrease, which is unfavorable for wetland protection and oil extraction in the Yellow River delta. Thus, an effort has been made to elucidate the relation between the sediment flux to the sea and the drainage basin factors including climate and human activities. The results show that the sediment flux to the sea responds to the changed precipitation in different ways for different runoff and sediment source areas in the drainage basin. If other factors are assumed to be constant, when the annual precipitation in the area between Longmen and Sanmenxia decreases by 10 mm, the sediment flux to the sea will decrease by 27.5 million t/yr; when the precipitation in the area between Hekouzhen and Longmen decreases by 10 mm, the sediment flux to the sea will decrease by 14.3 million t/yr; when the precipitation in the area above Lanzhou decreases by 10 mm, the sediment flux to the sea will decrease by 17.4 million t/yr. A multiple regression equation has been established between the sediment flux to the sea and the influencing factors, such as the area of land terracing and tree and grass planting, the area of the land created by the sediment trapped by check dams, the annual precipitation, and the annual quantity of water diversion by man. The equation may be used to estimate the change in the sediment flux to the sea when the influencing variables are further changed, to provide useful knowledge for the environmental planning of the Yellow River drainage basin and its delta.

Erosion and sediment yield in a changing environment is an important issue attracting concern from the scientific community all over the world (Walling 1996, 1997, Walling and Webb 1996). Environmental changes occur as results of climate change and human activities, which change soil erosion and sediment delivery processes of river drainage basins (Wasson 1994, Lu and Higgitt 1998, Frangipane and Paris 1994, Glazyrin and Tashmetov 1995) and lead to variation in sediment flux to the sea at different time and space scales (Algan and others 1999, Poulos and others 1996). Elucidation of the response of sediment yield of large rivers to the change in precipitation and in human activities such as land-use change, of soil and water conservation practices, and water resources development at time scale of 10–100 years is of significance for drainage basin management both in theory and in practice. This is the aim of the present study, with the Yellow River in China as an example.

The Yellow River, draining 752,443 km^2, is one of the rivers with the highest sediment flux to the sea in the world. According to the hydrometric data during 1950–1960, the Yellow River's mean annual suspended sediment flux to the sea was 1.32 billion t, which represented a considerable part of the global total. If the total suspended sediment flux into the world oceans is taken as 6.2 billion t (Mebeck 1976), then the Yellow River alone makes up 21.3% of the total. Since the 1980s, the change in the sediment flux into the world oceans induced by the changing climate and human activities has become a central concern in the study of global changes and has drawn attention from scientific communities, the public, and governments all over the world. It is an important topic related with the world water cycle, the world sediment cycle, and land–ocean interactions. A study of Yellow River's sediment flux to the sea may contribute important basic data to the above studies. Furthermore, as the Yellow River drainage basin is located in a transitional zone from arid, semiarid, to subhumid climates and is mantled by thick loess whose erodibility is very high, its specific sediment yield and suspended sediment concentration ranks the highest of the major world rivers. The Yellow River basin (Figure 1) is regarded as the origin of the Chinese civilization; human activities began several thousand years ago and have intensified with time, especially in the last half century. Much research has been conducted concerning human impact on the Yellow River's

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KEY WORDS: Sediment flux; Sea; Land–ocean interaction; Human influence; Erosion control; Yellow River

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*email: xujx@igsnrr.ac.cn.

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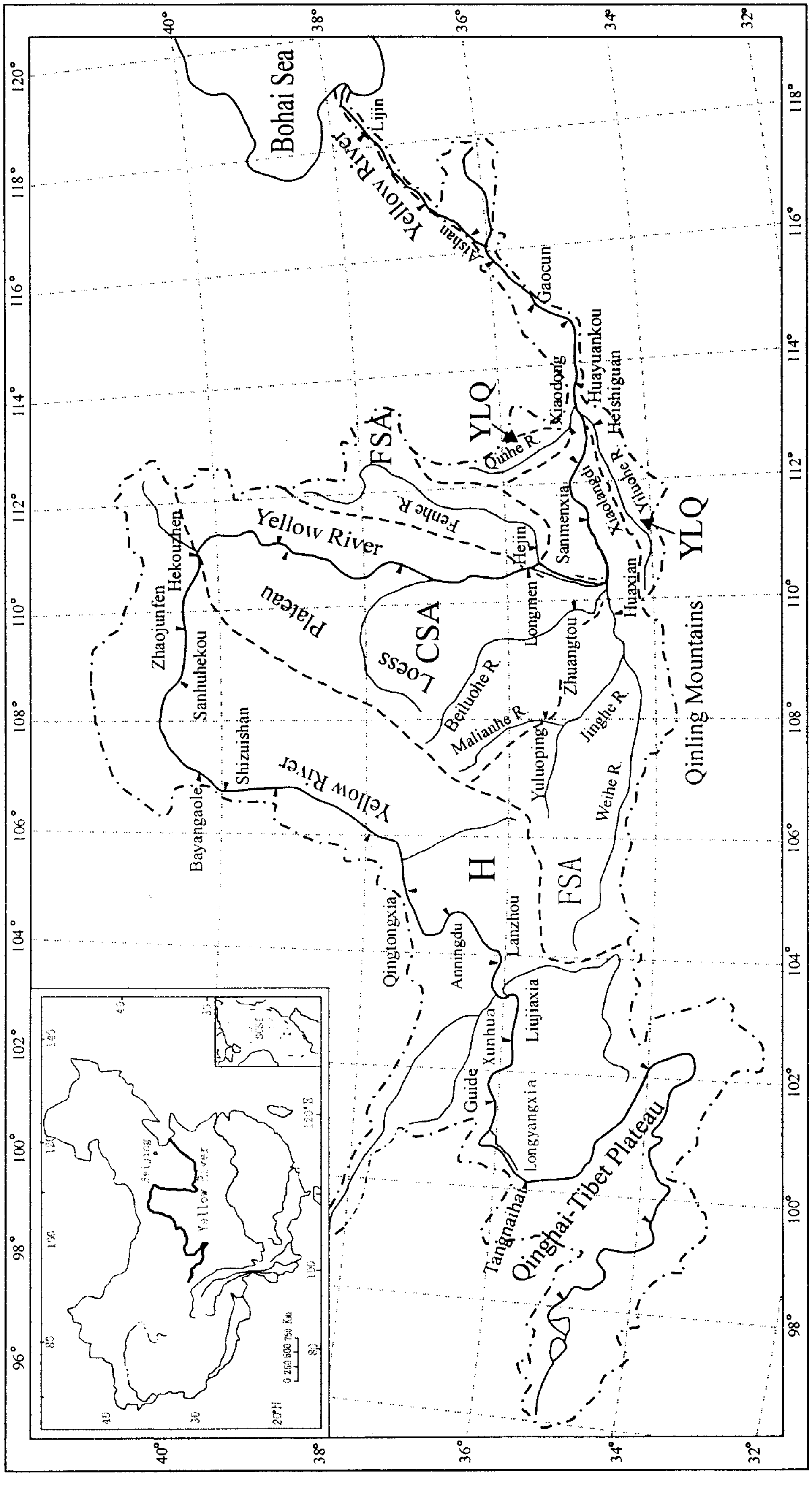

Figure 1. A sketch map of study area. H: the relatively clear water area above Hekouzhen; CSA: the "coarse sediment" producing area; FSA: the fine sediment producing area; YLQ: the relatively clear water area covering the Yiluohe and Qinhe River basins.

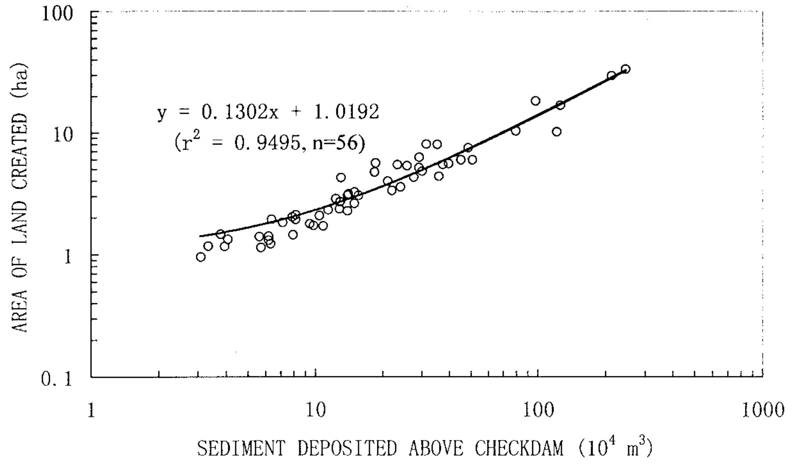

Figure 2. Relationship between the area of the land created by checkdams against the volume of sediment intercepted above the checkdams.

erosion, sediment yield, channel processes, and delta development (e.g., Ye 1994, Chen and others 1988, Tang 1990, Zeng and others 1997, Long and Chien 1986). A further study on how the river's sediment flux to the sea responds to changing human activities and climate may contribute to a better understanding of the mechanism controlling the interaction between man and nature and may also provide a stronger base for decision-making in the environmental management in the Yellow River drainage basin and the delta. The present study will focus on the effects of precipitation, erosion, and sediment control practice and water diversion by man.

Data and Methods

Since 1950, the Yellow River Water Conservancy Commission has established a network of hydrometric stations in the Yellow River basin, and systematic data of rainfall, runoff, and suspended sediment load are available. The sediment load at Lijin station, the most downstream station on the lower Yellow River, can be used as the sediment flux to the sea for the Yellow River. Based on the rainfall data from 913 stations all over the Yellow River basin, the area-averaged precipitation was calculated for different runoff and sediment source areas, by using an area-weighted method.

Basin-wide soil erosion and sediment control measures have been put in practice since the late 1960s, including land terracing, tree and grass planting, and checkdam construction for interception of sediment. The quantitative estimation of erosion and sediment reduction of these measures is an important issue in the drainage basin management of the Yellow River, to which much research has been devoted (Meng 1996, Ye 1994, Yellow River Institute 1999). Usually, the effect of erosion reduction of land terracing and tree and grass planting is investigated by comparison between the experimental plots with and without these measures. As a result, the factors of erosion reduction can be calculated. Factor F_t is defined as the ratio of erosion intensity of terracing land to that of sloping farmland, F_f is defined as the ratio of erosion intensity of reforested land to that of bare land, and F_g is defined as the ratio of erosion intensity of grass land to that of bare land. The actual values of F_t, F_f, and F_g depend on precipitation, especially on rainstorm characteristics. Thus, these factors are established for years with different level of precipitation. On this basis, erosion reduction can be calculated as the area of theses measures multiplied by the corresponding factor of erosion reduction and the unit area erosion amount without these measures. As a first approximation, in the present study, the sediment reduction of effect of land terracing and tree and grass planting is indexed by the area of these measures. In fact, the erosion reduction factors of these measures are not constants; they depend on hillslope gradient of the previous slopeland, density of vegetation and soil characteristics. Because these data are not available, these influencing factors are not taken into account for the time being.

The effect of sediment reduction by checkdams can be determined by the area of the land created by the sediment trapped above the checkdam. Large quantities of sediment are trapped by checkdams and thus some arable land forms above the checkdam. Based on the data from 56 checkdams in the middle Yellow River drainage basin (cited in Xu and others 1993, Table 1-1), we have plotted the area of land created by checkdams against the volume of sediment intercepted above the checkdams in Figure 2. A close correlation can be

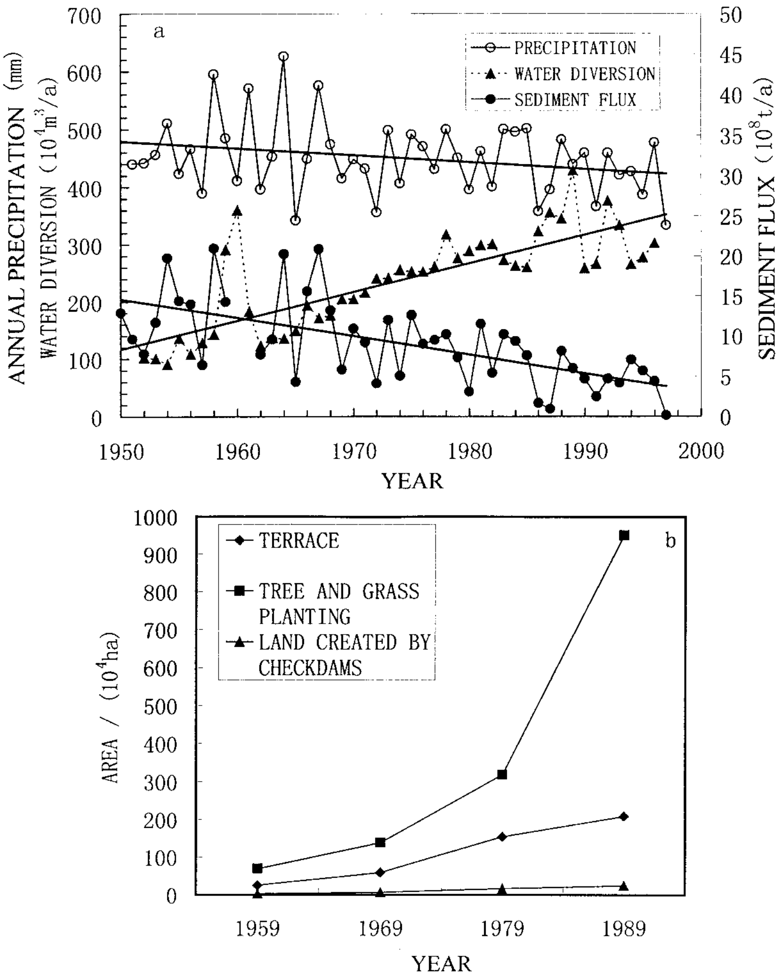

Figure 3. Yearly variations in the sediment flux to the sea, the area-averaged precipitation, water diversion by man (a) and the areas of all erosion and sediment control measures (b).

seen, and thus the area of the land so formed can be used as a measure for the effect of sediment interception. Since other factors such as the gradient of the gully channel are also influential, the expression of sediment reduction by the area of the land created by checkdams is only a first approximation.

The Yellow River Water Conservancy Commission has statistics for the area of all above erosion control measures in different periods. Another aspect of human activity is water diversion for irrigation and industrial and domestic use. The Yellow River Water Conservancy has gathered year-to-year statistics for the quantity of water diversion from the whole Yellow River basin.

All these data are used in the present study, and an empirical statistical method is adopted to elucidate the relationship between the changes in sediment flux to the sea and in the influencing factors such as precipitation and human activities.

Temporal Variations in Sediment Flux to the Sea and Influencing Factors

Based on the above-mentioned data, the yearly variations in sediment influx to the sea, the area-averaged precipitation over the whole Yellow River drainage basin, and the areas of all erosion control measures have been plotted in Figure 3. The figure shows a clear tendency of decline since the 1970s for the Yellow River sediment flux to the sea (Figure 3a). At the same time, precipitation decreases (Figure 3a), the areas of all kinds of erosion and sediment control measures increase (Figure 3b), and the water diversion by man also increases (Figure 2). This indicates that the decrease in precipitation and the basin-wide erosion control measures may be the cause for the decrease in the Yellow River's sediment flux to the sea.

The decade averages of sediment flux to the sea are calculated as 1.32, 1.089, 0.898, 0.639, and 0.418 billion t/yr for the 1950s, 1960s, 1970s, 1980s, and 1990s (up to

Table 1. Precipitation and runoff in different parts of the Yellow River drainage basin

Areas	Mean annual precipitation (mm)	Mean annual “natural” runoff (mm)	Mean annual “natural” runoff coefficient
Above Lanzhou	426.4	151.8	0.356
Lanzhou-Hekouzhen	289.4	2.2	0.008
Above Hekouzhen	379.4	92.7	0.244
Hekouzhen-Longmen	439.3	44.9	0.102
Longmen-Sanmenxia	561.2	64.5	0.115
Sanmenxia-Huayuankou	674.2	133	0.197

Table 2. Water and sediment characteristics of the Yellow River[a]

		Annual runoff		Annual suspended load	
Area	Drainage area [km (%)]	Volume (10^9 m^3)	Total at Huayuankou (%)	In 10^9 t	Total at Huayuankou (%)
Above Hekouzhen	385966 (51.3)	31.26	55.9	0.142	8.7
Hekouzhen to Longmen	111586 (14.8)	7.25	13	0.908	55.7
Longmen to Sanmenxia	190869 (25.4)	11.33	20.3	0.554	34.0
Sanmenxia to Huayuankou	41615 (5.5)	6.08	10.9	0.032	2.0
At Huayuankou	730036 (97.0)	55.92	100.0	1.63	100.0

[a] Based on data for the period 1919–1989. After Ye (1994, Table 2-1).

1997), respectively. Notice that the sediment flux in the 1990s is only 31.7% of that in the 1950s, indicating a marked decline. The decrease in sediment flux to the sea directly influences the land accretion process of the Yellow River delta, which has been discussed in Xu (2002a). The wetland in the Yellow River delta is 6000 km^2 and is one of the most important wetland ecosystems in China. The sharp decrease in runoff and sediment fluxes into the sea has greatly changed the wetland processes and therefore the function and structure of the wetland ecosystem. Moreover, the second largest oil field of China, the Shengli Oil Field is located in the Yellow River delta. The rapid accretion of the Yellow River delta provides a good perspective to exploit oil on land instead of in the sea. However, the slowing of land accretion does not favor this and would increase production costs in the future. To solve these problems, study is needed to find the cause for the decrease in sediment flux to the sea, and then some countermeasures can be proposed.

Sediment Flux to the Sea as Influenced by Precipitation in Different Source Areas of Sediment

In hydrology, the Yellow River basin is characterized by the fact that the major source areas of runoff do not coincide with the major source areas of sediment. The runoff comes mainly from the upper Yellow River basin above Hekouzhen, but the sediment comes mainly from the middle Yellow River basin between Hekouzhen and Sanmenxia (Ye 1994). The precipitation, the natural runoff (defined as the sum of measured runoff plus the water diversion) and the coefficient of natural runoff (defined as the ratio of annual natural runoff in millimeters to the annual precipitation in millimeters for different parts of the Yellow River drainage basin) are listed in Table 1. The drainage area above Hekouzhen includes two parts; a majority of the area above Lanzhou is located on the Qinghai-Tibet Plateau, and a majority of the area between Lanzhou to Hekouzhen is located in desert. Although annual precipitation in the former area is not high, evapotranspiration is low due to cold temperatures. In the high mountain areas covered by bedrock, permeability of surface material is much less than loess. Hence, both the runoff in millimeters and the runoff coefficient there are the highest of the whole Yellow river basin, making this area the major contributor of runoff of the Yellow River. The precipitation, runoff, and runoff coefficient of the latter is very low because of the arid desert environment, but the average runoff and runoff coefficient of these two areas as a whole are still relatively high.

The specific sediment yield is high and the sediment is relatively coarse in the drainage area between Hekouzhen and Longmen, and thus this area is called a “coarse sediment producing area”(CSA) (Chien and others, 1980). According to the hydrometric data in the period 1950–1989, the area of the upper drainage basin above Hekouzhen is 51.3% of the total, and the runoff from this area is 55.9% of the total, but the sediment yield is only 8.7% of the total (Table 2). Thus, this area is called a "clear water producing area". The drainage area between Hekouzhen and Longmen is 14.8% of the total, the runoff from this area is only 13% of the total, but the sediment yield represents 55.7% of the total, which is 908 million t/yr. The drainage area between Longmen and Sanmenxia represents 25.4% of the total area, and sediment yield from this area is 554 million t/yr, 34% of the total. The loess there is relatively fine, and the suspended sediment load is also fine, and thus this area is known as a "fine sediment producing area." According to an earlier study by Xu (2002b), for each ton of sediment derived from the fine sediment producing area, 0.85 tons could be transported to the sea; however, for each ton of sediment derived from the coarse sediment producing area, only 0.21 tons could be transported into the sea. Therefore, although the contribution of the fine sediment producing area to the total sediment yield of the Yellow River is smaller than that of the coarse sediment producing area, its contribution to the sediment flux to the sea is large relatively.

According to the different physical geographical settings, the whole Yellow River drainage basin can be divided into five areas: (1) the area above Lanzhou, (2) the area between Lanzhou and Hekouzhen, (3) the area between Hekouzhen and Longmen, (4) the area between Longmen and Sanmenxia, and (5) the area between Sanmenxia and Huayuankou. The sequence from area 1 to area 5 roughly follows the direction from high mountain cold subhumid and semiarid (area 1), to arid (area 2), semiarid (area 3), and subhumid (areas 4 and 5) climates. Areas 1 and 2 belong to the relatively clear water producing area as mentioned above, area 3 is the coarse sediment producing area, and area 4 is the fine sediment producing area. Area 5 includes two tributaries in the lower Yellow River, i.e., the Yiluohe and Qinhe rivers, whose suspended sediment concentrations are relatively low. Thus, area 5 is also regarded as another relatively clear water producing area in the Yellow River basin (Chien and others 1980, Xu 1997). The area-averaged annual precipitation for the five areas has been calculated and then correlated to the annual sediment flux to the sea, to show how the sediment flux to the sea is affected by the change in the precipitation in different areas. The correlation matrix is shown in Table 3. It can be seen that the correlation coefficient between the annual sediment flux to the sea (Q_{sf}) and the precipitation in the area between Longmen and Sanmenxia is 0.75, the highest of the all, and that for the area between Hekouzhen and Longmen is the second highest at 0.69. The correlation coefficients between sediment flux to the sea and the precipitation in other three areas are relatively low, but are all larger than 0.50 and significant at the level of 0.01.

Table 3. Correlation matrix among annual sediment flux to the sea (Q_{sf}) and area-averaged precipitations in areas above Lanzhou (P_{L}), between Lanzhou and Hekouzhen (P_{L-H}), between Hekouzhen and Longmen (P_{H-L}), between Longmen and Sanmemxia (P_{L-S}), and between Sanmenxia and Huayuankou (P_{S-H})

	P_L	P_{L-H}	P_{H-L}	P_{L-S}	P_{S-H}	Q_{sf}
P_L	1.00	0.63	0.51	0.37	0.30	0.50
P_{L-H}	0.63	1.00	0.74	0.54	0.38	0.52
P_{H-L}	0.51	0.74	1.00	0.69	0.50	0.69
P_{L-S}	0.37	0.54	0.69	1.00	0.85	0.75
P_{S-H}	0.30	0.38	0.50	0.85	1.00	0.56
Q_{sf}	0.50	0.52	0.69	0.75	0.56	1.00

Since precipitation in the five areas is correlated, we used stepwise regression to establish the multiple regression equation between Q_{sf} of the five precipitation variables. With $F = 2.00$ being set as the threshold, the following equation has been established:

$$Q_{sf} = -20.35 + 0.0275P_{L-S} + 0.0143P_{H-L} + 0.0174P_{L} \quad (1)$$

where Q_{sf} is the annual sediment into the sea in 10^8 t; P_{L-S}, P_{H-L}, and P_L are annual precipitation in the areas between Longmen and Sanmenxia, between Hekouzhen and Longmen, and above Lanzhou, in millimeters. The number of samples N is 47, multiple correlation coefficient (R) is 0.8034, $F = 26.10$, the probability of significance is $P < 0.00001$, and the standard deviation of the residual is 3.1933. The sequence of the three precipitation variables in the equation is the same as the sequence that they entered the stepwise regression equation. The other two variables, P_{L-H} and P_{S-H}, failed to enter the equations, indicating that their influences are less. After the data are standardized to the range 0–1, the equation is reestablished as:

$$Q_{sf} = 0.5137P_{L-S} + 0.2472P_{H-L} + 0.1800P_{H} \quad (2)$$

The values of the regression coefficients of the three precipitation variables reflect their relative contributions to Q_{sf}.

Although the decreases in P_{L-S}, P_{H-L}, and P_L all

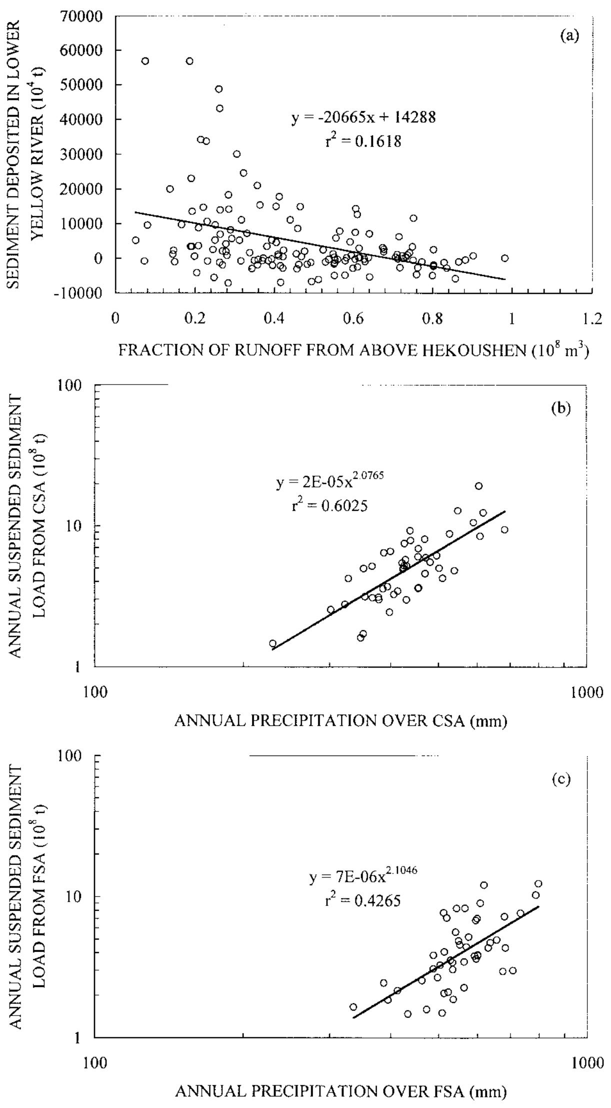

Figure 4. Influence of different source areas of runoff on sediment supply and sediment deposition in the lower Yellow River. (a) Amount of sediment deposition in the lower Yellow River plotted against the fraction of runoff from the drainage area above Hekouzhen, based on the data of 145 flood events. The critical value significant for level of 0.01 is $r^2 = 0.052$ for $N = 145$. (b) Annual suspended load from the drainage areas between Hekouzhen and Longmen (CSA) plotted against annual areal-averaged precipitation over CSA, based on the data during the period 1950–1997. The critical value significant for level of 0.01 is $r^2 = 0.138$. (c) Annual suspended load from the drainage areas between Longmen and Sanmenxia (FSA) plotted against annual areal-averaged precipitation over FSA. The critical value significant for level of 0.01 is $r^2 = 0.138$.

lead to a decline in Q_{sf}, the mechanism responsible for the decline is different. The decreased precipitation in the area above Lanzhou would lead to a reduction of the relatively clear runoff into the river; therefore the sediment carrying capacity of the lower Yellow River would be lowered, and thus the sediment deposited in the channel would increase, finally leading to a decrease in the sediment flux to the sea. Based on the data of 145 flood events, the amount of sediment deposition in the lower Yellow River has been plotted against the fraction of runoff from the drainage area above Hekouzhen in Figure 4, where a negative correlation can be seen. Although the points are scattered, the correlation is significant at the level of 0.01. This indicates that the more the runoff there is from the drainage area above Hekouzhen, the less the sediment deposition in the lower Yellow River will be. The decrease in precipitation in the two major sediment source areas, e.g., the drainage areas between Longmen and Sanmenxia and the area between Hekouzhen and Longmen, would reduce the erosivity of rainfall and storm runoff in the two areas, and thus the sediment supplied to the Yellow River decreases, and so does the sediment into the sea. In Figure 4b and 4c, annual suspended load from the drainage areas between Hekouzhen and Longmen (CSA) and between Longmen and Sanmenxia (FSA) has been plotted against annual areal-averaged precipitation over the two areas, both showing a positive correlation, which is significant at the level of 0.01.

It is notable that, in equation 1 the coefficients of $P_{\mathrm{L-S}}$, $P_{\mathrm{H-L}}$, and P_{L} are considerably different. This means the contributions of unit amounts of precipitation in the three areas to the sediment flux to the sea are different. Assuming $P_{\mathrm{H-L}}$ and P_{L} are constants and $P_{\mathrm{L-S}}$ is the variable, we can calculate the partial derivative of Q_{sf} to $P_{\mathrm{L-S}}$. As a result, we get

$$\delta Q_{sf}/\delta P_{\mathrm{L-S}} = 0.0275 \tag{3}$$

Then, assuming $P_{\mathrm{L-S}}$ and P_{H} are constants, and $P_{\mathrm{H-L}}$ is the variable; we can calculate the partial derivative of Q_{sf} to $P_{\mathrm{H-L}}$. We get

$$\delta Q_{sf}/\delta P_{\mathrm{H-L}} = 0.0143 \tag{4}$$

In a similar procedure, we also get

$$\delta Q_{sf}/\delta P_{\mathrm{L}} = 0.0174 \tag{5}$$

It can be see from equation's 3–5 that, if other variables are as constant, when the precipitation in the area between Longmen and Sanmenxia decreases by 10 mm, the sediment flux to the sea will decrease by 27.5 million t; when the precipitation in the area between Hekouzhen and Longmen decreases by 10 mm, the sediment flux to the sea will decrease by 14.3 million t; when the precipitation in the area above Lanzhou de-

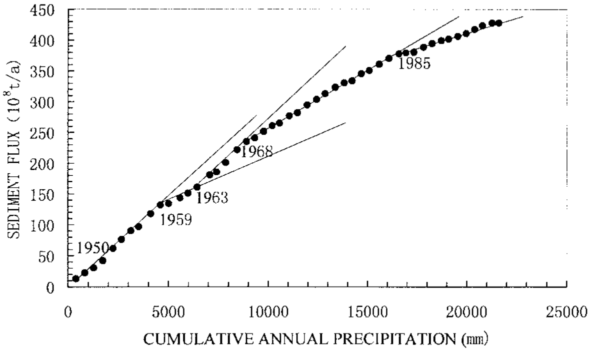

Figure 5. A double-mass plot between the cumulative annual sediment flux to the sea and the cumulative annual area-averaged precipitation over the whole Yellow River drainage basin.

creases by 10 mm, the sediment flux to the sea will decrease by 17.4 million t. It is notable that the decrease in sediment influx to the sea caused by a decrease in the precipitation from the coarse sediment producing area is not as much as that by equal decrease in the precipitation from the fine sediment producing area, although the contribution of the former to the total sediment yield is much larger than the contribution of the latter. In the recent study by Xu (2002c), it is found that, given other factors, for each ton of sediment reduced from the coarse sediment producing area, the sediment deposited in the lower Yellow River would be reduced by 0.455 tons; for each ton of sediment reduced from the fine sediment producing area, the sediment deposited in the lower Yellow River would be reduced by only 0.154 tons. Because a larger proportion of the sediment supplied by the former area is deposited in the lower Yellow River channel than that by the latter area, the latter area contributes more to the sediment flux to the sea than the former area does, given the precipitation.

Effect of Human Activities on Sediment Flux to the Sea

Result of Double-Mass Plot Based on Data of Annual Sediment Flux to the Sea and Annual Precipitation

Human activities in the Yellow River basin include several types, such as soil erosion and sediment control practices, construction of reservoirs, and water diversion. To assess the overall effect of these, the method of a double-mass curve has been employed. The cumulative annual sediment flux to the sea is plotted against the cumulative annual area-averaged precipitation over the whole Yellow River drainage basin in Figure 5, to detect if the variation in the former is consistent with that in the latter. If the variation in sediment into the sea is affected only by precipitation, then a straight line can be expected, which fits the relationship best. However, it can be seen from this figure that from 1950 to 1997, four breaks can be seen on the double-mass curve. Accordingly, the process of variation can be divided into five stages:

- Stage 1 (1950–1958): The river was unregulated and there were no hydraulic engineering works and basically no erosion control measures.
- Stage 2 (1959–1963): The Sanmenxia Dam was completed in 1959, and then the Sanmenxia reservoir was used for water storage, trapping huge quantities of sediment. Hence, the double-mass curve turns to the right, meaning that the sediment into the sea decreased.
- Stage 3 (1964–1968): The reconstruction of Sanmenxia dam was completed, and then the reservoir was operated under the mode of "retaining the flood and releasing the sediment." The sediment deposited in stage 2 was released through the dam, and consequently, the sediment flux to the sea increased. Hence, the double mass curve turns to the left. This indicates that, to some extent, the effect caused by sediment trapping at stage 2 was offset by sediment releasing at this stage.
- Stage 4 (1969–1985): The basinwide erosion and sediment control measures that had been put in practice in the late 1960s become effective, sediment transported into the lower Yellow River and the sea decreased, and thus the double mass curve turns to the right significantly.
- Stage 5 (1985–1997): The erosion and sediment control measures become more effective. In the meantime, water diversion from the Yellow River increased rapidly. The lower Yellow River enters a new period characterized by low discharges and seasonal dry-ups. The river channel has contracted and its sediment-carrying ability becomes much lower. As a result, the sediment flux to the sea decreased further, and the double-mass curve turns to the right once again.

Change of Sediment Flux to the Sea as Shown by Plot of Q_{sf} vs Precipitation

It is generally thought that before 1969, the erosion control measures in the Yellow River drainage basin had not yet become effective (Foundation of Yellow River Water and Sediment Change Research 1993) and thus, the period before 1969 can be re-

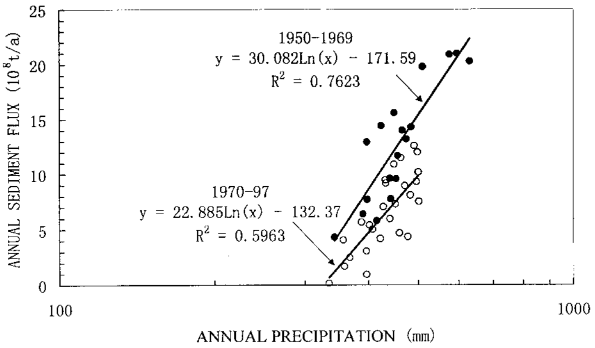

Figure 6. The sediment flux to the sea plotted against the area-averaged annual precipitation P over the whole Yellow River basin.

garded as a baseline period, or the period without measures. This period can be compared with the period afterwards, which is regarded as the period with measures. If a comparison of the Q_{sf}–precipitation relationship is made between the two periods, an assessment could be made of how the erosion and sediment control measures affect the sediment flux to the sea. The sediment flux to the sea Q_{sf} is plotted against the area-averaged annual precipitation P over the whole Yellow River basin in Figure 6, in which the points of the periods 1950–1969 and 1970–1997 are represented by different symbols. The best-fit straight lines are given in the figure by the regression method. It can be seen that, compared with the straight line of 1950–1969, the straight line of 1970–1997 has moved downward. This indicates that, given the precipitation, the sediment flux to the sea declined. The two regression equations are as follows:

For the period without measures (1950–1969):

$$Q_{sf} = 30.082 \ln P - 171.59 \tag{6}$$

For the period with measures (1970–1997):

$$Q_{sf} = 22.885 \ln P - 132.37 \tag{7}$$

It should be pointed out that the points of 1960 and 1961 are omitted, because the Sanmenxia reservoir was used for water storage at that time, and large quantities of sediment were trapped by the dam.

The equation for the period without measures has a rather high correlation coefficient, 0.87, and it can be used to make a rough estimation of the effect of human activities on sediment flux to the sea. Insert the annual precipitation P of the period 1970–1997 into equation 6, and we obtain the Q_{sf} values for each year, assuming that Q_{sf} was affected only by precipitation. Subtracting this Q_{sf} from the measured Q_{sf}, we may obtain the decreased Q_{sf} that was caused only by human activities. The results have been listed in Table 4. It can be seen that, since the 1970s, the reduction in the sediment flux to the sea either by human activities or by decreased precipitation shows a tendency to increase. Of the total reduction, the contribution made by human activities exceeds the contribution by precipitation.

Sediment Flux to the Sea as Influenced by Erosion Control Measures

Land terracing and tree and grass planting may reduce erosion on hillslopes significantly. Checkdams can trap the eroded sediment in gullies and increase sediment storage. Controlled by these measures, the sediment into the Yellow River and into the sea has been considerably reduced. The sediment flux of the Yellow River to the sea is plotted against the areas of three kinds of erosion control measures—land terracing, tree and grass planting, and the land accreted above the checkdams in Figure 7—based on the yearly data. It can be seen that all plots show a negative correlation.

Sediment Flux to the Sea as Influenced by Water Diversion from the Yellow River

Most of the drainage area of the Yellow River is located in a semiarid climate, and the water resources are far from sufficient to meet the water demand, which has been increasing in the past 30 years. As a result, water diversion from the river increased sharply. In the 1990s, the quantity of water diversion amounted to more than 60% of the total "natural" runoff, which is defined as the sum of the measured runoff and water diversion minus the quantity of water returned to the river. Runoff is the force of sediment transport; the reduction in runoff by water diversion would lower the river's ability to transport sediment into the sea. Water diversion in the Yellow River mainly occurs in low-flow seasons and has a relatively small effect on sediment transport in the high-flow seasons during which a majority of sediment is transported into the sea. However, the sediment transported into the sea during low-flow seasons has been significantly reduced, which is attributable to the water diversion during low-flow seasons. After the Sanmenxia Reservoir was operated under the mode of "storing clear water and releasing sediment," the water released during low-flow seasons was clear. It can scour the bed and bank and transport the eroded, relatively coarse sediment into the sea. When large quantities of water are diverted during low-flow seasons, the remaining water discharge of the lower Yellow River becomes very low, and its

Table 4. Reduction in sediment flux (Q_{sf}, ($\times 10^8$ t/yr) to sea by human beings and by precipitation

Period	Q_{sf} ($\times 10^8$ t/yr) by precipitation only	Measured Q_{sf} ($\times 10^8$ t/yr)	Reduction in Q_{sf} ($\times 10^8$ t/yr) by human beings only	Reduction in Q_{sf} ($\times 10^8$ t/yr) by precipitation only[a]	Percentage of total reduction in Q_{sf} ($\times 10^8$ t/yr) By human beings	By precipitation
1970–1979	11.91	8.98	2.94	0.83	78.0	22.0
1980–1989	9.21	6.39	2.83	3.52	44.5	55.5
1990–1997	8.63	4.18	4.45	4.11	52.0	48.0

[a] The reduction in sediment into the sea (Q_{sf}) by precipitation is calculated as the mean annual Q_{sf} in the baseline period (1950–1969): 12.75 × 10^8 t/yr minus the figures in column 2, the Q_{sf} by precipitation only.

scouring and transporting effect is limited. Thus, the increase in water diversion will lead to a decrease in the sediment flux to the sea, especially in the low-flow seasons (Figure 8). The decline in the low-flow season sediment flux would lead to a decrease in annual total suspended sediment flux to the sea, and thus the negative correlation between the annual sediment flux of the Yellow River to the sea and the annual water diversion (Figure 7c). Although the points are scattered, a negative correlation can be seen.

Multiple Regression

As the data for water diversion ($Q_{w,div}$) in the whole Yellow River basin are available only for the period 1952–1996, and for other variables for the period 1950–1997, we choose the period from 1952 to 1996 for multiple regression analysis. As the statistical data for the areas of land terracing, tree- and grass-planting, and land accretion above checkdams are available only on a basis of decades (but for the 1990s, the data are up to 1996), we use a linear interpolating method to extend the data to each year.

The sediment flux to the sea (Q_{sf}) is selected as the dependent variable, and the annual precipitation (P) over the whole Yellow River basin, the total area (A_{tfg}) of hillslope erosion control measures including land terracing, tree planting and grass planting, and the annual water diversion ($Q_{w,div}$) are chosen as influencing variables. The correlation coefficient matrix among these variables is shown in Table 5. The correlation coefficients between Q_{sf} and the influencing variables are all significant at the level better than 0.01. The multiple regression equation is as follows:

$$Q_{sf} = -10.0212 - 0.00190\,A_{tfg} + 0.0556\,P - 0.0072\,A_d - 0.0182\,Q_{w,div} \quad (8)$$

where Q_{sf} is in 10^8 t/yr, A_{tfg} and A_d are in 10^4 ha, $Q_{w,div}$ is in 10^8 m^3/yr. The multiple correlation coefficient is $R = 0.874$, and the value of the F test is $F = 32.354$. The residual standard deviation about the regression line is SE = 2.616. This equation indicates that the sediment flux to the sea decreases with the decreased precipitation, with the increased areas of erosion control measures, and with the increased water diversion.

A comparison between the calculated and measured values is plotted in Figure 9. Equation 8 can be used to estimate the variation in Q_{sf} when the influencing variables are changed. Using the similar procedure as used to Equation (1), we get:

$$\delta Q_{sf}/\delta A_{tfg} = -0.0019 \quad (9)$$

$$\delta Q_{sf}/\delta P = 0.0556 \quad (10)$$

$$\delta Q_{sf}/\delta A_d = -0.0072 \quad (11)$$

$$\delta Q_{sf}/\delta Q_{w,div} = -0.0182 \quad (12)$$

It can be known from the above that, other variables given as constants, when the total area of terrace land and tree- and grass-planting increases by 10^4 ha, the sediment flux to the sea would decrease by 0.19 million t/yr; when the precipitation decreases by 10 mm, the sediment flux to the sea would decrease by 55.6 million t/yr; when the area of land accretion by checkdams increases by 10^4 ha, the sediment flux to the sea would decrease by 0.72 million t/yr; when the water diversion of the whole Yellow River basin increases by 10^8 m^3/yr, the sediment flux to the sea would decreases by 1.82 million t/yr.

Effect of Sedimentation in the Reservoir

Artificial reservoirs trap large quantities of sediment and thereby increase sediment storage in the drainage basin, leading to a reduction in sediment flux to the sea. According to the study by the Yellow River Institute (1999), apart from the Sanmenxia Reservoir, there are seven reservoirs on the main stem of the Yellow River, whose capacity totals 31.412 billion m^3; up to 1969,

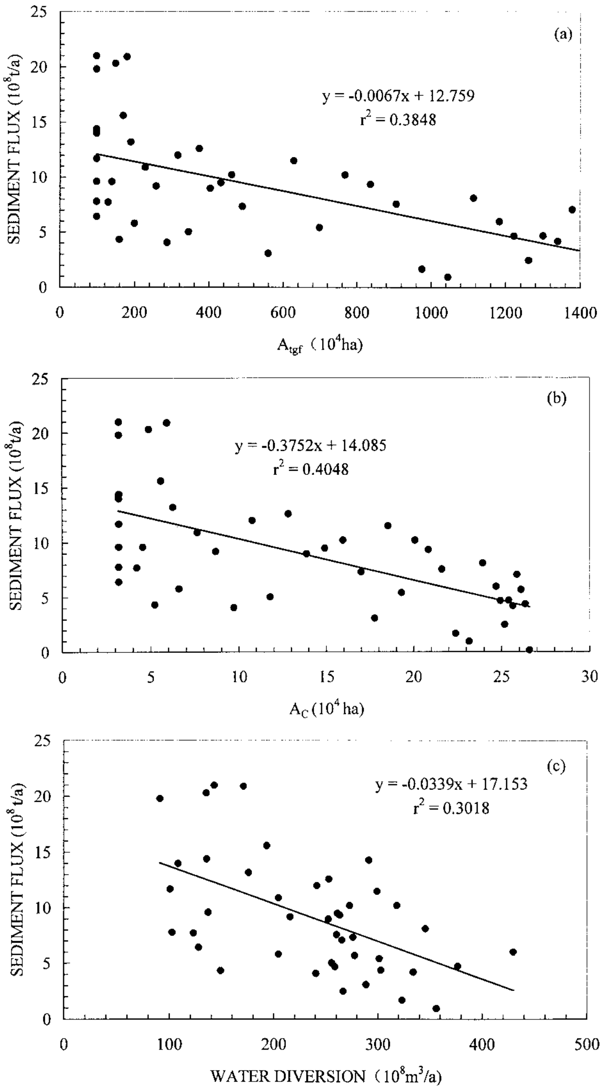

Figure 7. The annual sediment flux of the Yellow River to the sea as plotted in each year against the areas of terrace-land buildingand tree- and grass-planting (A_{tfg}) (a) and the land accreted above the checkdams (A_c) (b) up to that year, and against the annual water diversion (c).

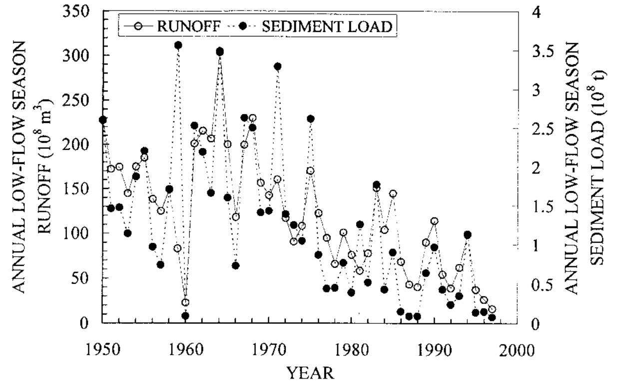

Figure 8. Temporal variations in annual low-flow season (January-May, October-December) runoff and suspended sediment load at Lijin station.

Table 5. Correlation coefficients between independent variable and dependent variables

	A_{tfg}	P	A_d	$Q_{w,div}$	Q_{sf}
A_{tfg}	1.00	−0.22	0.97	0.71	−0.54
P	−0.22	1.00	−0.23	−0.22	0.76
A_d	0.97	−0.23	1.00	0.78	−0.56
$Q_{w,div}$	0.71	−0.22	0.78	1.00	−0.57
Q_{sf}	−0.54	0.76	−0.56	−0.57	1.00

1979, 1989, and 1997, the total cumulative volumes of sediment deposited in these reservoirs were 710, 1309, 2099, and 2546 million m^3, respectively. The total volume of sedimentation for the 1970s, 1980s, and 1990s (up to 1997) were 631, 758, and 447 million m^3, respectively. On the main tributaries, there are 483 reservoirs with a capacity >100,000 m^3, and their capacity totals 7.554 billion m^3. Up to 1969, 1979, 1989, and 1997, the total cumulative volume of sedimentation within these reservoirs were 640, 1651, 2708, and 3343 million m^3, respectively. The total volumes of sedimentation for the 1970s, 1980s, and 1990s (up to 1997) were 1011, 1057, and 634 million m^3, respectively. The volume of sedimentation in the reservoirs on the main stem and tributaries of the upper and middle Yellow River (except Sanmenxia reservoir) totals 1.642, 1.815, and 1.081 billion m^3 for the 1979s, 1980s, and 1990s, respectively.

Sanmenxia Reservoir is the most important reservoir on the Yellow River. In terms of the operation mode, the use of this reservoir can be divided into three stages. From 1960 to 1964, the reservoir was used for water storage, trapping almost all sediment into the reservoir. The total volume of sedimentation was 4.537 billion m^3, but due to clear water scour, 2.312 m^3 of sediment was scoured and transported into the sea, a factor which partly offsets the reduction of sediment flux to the sea by the sediment trapping of the dam. From 1964 to 1973, the reservoir was used for flood retention, but after the flood, sediment can be released through the dam. In this period, sediment deposited in the upper part of the reservoir was 2.094 billion m^3, but 0.923 billion m^3 of sediment was soured in the lower part. Hence, the volume of total sediment deposited in this period was 1.171 billion m^3. After 1973, the reservoir was used under the mode of "storing clear water and releasing sediment," i.e., during high-flow seasons,

Table 6. Some characteristics of the multiple regression

	Sum of squares	Degree of freedom	Mean squares	*F*	*P*
Regression	883.8959	4	220.974	32.04424	5.45×10^{-12}
Residual	275.8362	40	6.895905		
Total	1159.732				

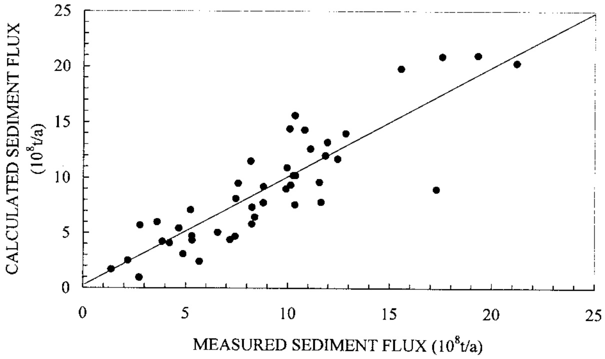

Figure 9. A comparison between the calculated and measured values of Q_{sf}.

all floods can pass the dam freely without retention, but afterwards, the sluice gate is closed to store clear water. Hence, sedimentation in the reservoir is reduced significantly. In the 18-year period from 1973 to 1990, only 0.428 billion m^3 of sediment was trapped in the reservoir. During this period, the volume of sediment deposited for the periods from November of 1973 to October of 1980, from November of 1980 to October of 1985 and from November of 1985 to October of 1990 were 108 million m^3, -103 million m^3 (negative value means that net scour occurred), and 428 million m^3, respectively (Zhao and others 1998).

If considering the whole Yellow River basin including Sanmenxia reservoir, it can be pointed out that the total volume of sediment trapped by all reservoirs for each decade shows a tendency to decrease. The largest quantity of sedimentation occurred in the 1960s, due to the sediment trapping of Sanmenxia Reservoir. The second largest occurred in the 1970s. The sedimentation in the 1980s decreased and that in the 1990s decreased further. Influenced by this tendency, the reduction of sediment flux to the sea might show a tendency to decrease. However, in fact, the reduction of sediment flux to the sea exhibited a tendency to increase since the 1960s. Compared with the sediment flux to the sea in the 1950s, the reductions in the 1960s, 1979s, 1980s, and 1990s (up to 1997) were 2.307, 4.215, 6.810 and 9.019 million t/yr, respectively. This indicates that the sedimentation by the reservoir trapping is not the main cause responsible for the decline of the sediment flux to the sea. Keeping this in mind, the variable of sedimentation by reservoirs was excluded when Equation (8) was established.

Conclusions

1.The Yellow River has the world highest sediment flux to the sea, and it is sensitive to the influence of the changing precipitation and human activities.

2. Since the 1970s, the sediment flux of the Yellow River to the sea has shown a marked tendency of decrease. In the meantime, the area-averaged annual precipitation also decreased, but the areas of all kinds of erosion control measures increased, and so did the quantity of water diversion by man.

3. The sediment flux to the sea responds to the precipitation in different water and sediment source areas in different ways. If other factors are held constant, when the precipitation in the area between Longmen and Sanmenxia decreases by 10 mm, the sediment flux to the sea will decrease by 27.5 million t; when the precipitation in the area between Hekouzhen and Longmen decreases by 10 mm, the sediment flux to the sea will decrease by 14.3 million t; when the precipitation in the area above Lanzhou decreases by 10 mm, the sediment flux to the sea will decrease by 17.4 million t.

4. The periods 1950–1969 and 1970–1997 are considered the baseline period and the period with erosion and sediment control measures, and the regression equations between the sediment flux to the sea and the area-averaged precipitation over the whole drainage basin has been established for these two periods, respectively. By using the equations, the effect of precipitation and human activities on the sediment flux to the sea has been estimated. The result shows that in the 1970s, 1980s, and 1990s, the rate of contribution of precipitation to the reduction of sediment flux to the sea is 22.0%, 44.5%, and 48.0%, respectively, and the rate of contribution of human activities to the reduction of sediment into the sea is 78.0%, 55.5%, and 52.0% respectively.

5. A multiple regression equation has been established between the sediment flux to the sea and the

influencing factors including the area of land terracing and tree- and grass-planting, the area of the land created by the sediment trapped by checkdams, the annual precipitation, and the annual quantity of water diversion. The equation indicates that, given other variables as constants, when the total area of terrace land and tree- and grass-planting increases by 10^4 ha, the sediment flux to the sea decreases by 0.19 million t/yr; when the precipitation decreases by 10 mm, the sediment flux to the sea decreases by 55.6 million t/yr; when the area of land accretion by checkdams increases by 10^4 ha, the sediment flux to the sea decreases by 0.72 million t/yr; and when the water diversion of the whole Yellow River basin increases by 10^8 m^3/yr, the sediment flux to the sea decreases by 1.82 million t/yr. These figures may be used for decision-making in the environmental planning and management of the Yellow River drainage basin and the delta.

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