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Sediment discharge of the Yellow River, China: past, present and future—A synthesis

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Abstract

The Yellow River cut through Sanmenxia Gorge and discharged into the sea via the North China Plain in 150 ka BP; since then, around 86 000 × 10^8 t sediment has been transported passing Sanmenxia Gorge. Based on land use and land cover changes in Loess Plateau and other available evidence, an estimate of the Yellow River sediment budget is presented here: about 72% of the sedimentary material was trapped in the North China Plain and the remainder (i.e., 26%) escaped to the sea. At the present stage, < 0.2×10^8 t/a suspended sediment of the Yellow River enter the northern Yellow Sea. The transport pattern is determined mainly by the shelf current system. Annually 0.2×10^8–0.3×10^8 t of suspended particles are carried to the East China Sea; the materials are derived mainly from coastal and subaqueous delta erosion associated with the abandoned Yellow River on the Jiangsu coast. Since 1972, the lower Yellow River started to have a situation of continuous no-flow. During 1996–2000, the annual water flow and sediment discharge are only 19%, as compared with normal years (i.e., average for 1950–1979). In response to global warming and increase of water diversion from the Yellow River for industrial and urban use, the sediment flux of the Yellow River to the sea will most likely remain small in the next two to three decades.

Key words: Yellow River, Loess Plateau, sediment budget, transport patterns, sediment retention

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1 Introduction

The Yellow River, China, is characterized by a relatively small water flow (432×10^8 m^3/a) but a very heavy sediment load (16×10^8 t/a). Its mean suspended sediment concentration reaches 37 kg/m^3 and, during a flood season, it could reach up to 911 kg/m^3 (e.g., at Sanmenxia Station, in 1977); this is undoubtedly the highest among the major rivers of the world (Table 1). Because of the importance of the Yellow River sediment discharge, a number of books and papers (in Chinese and in English) have been devoted to the study on this subject. However, up to the present, the long-term sediment budget of the Yellow River and its changing patterns are still poorly understood. This paper is a preliminary attempt to establish a sediment budget on the basis of a synthesis of published data.

2 Origin of the Yellow River

In preparing sediment budget of the Yellow River, a reliable knowledge of the date when the river flows to the sea is of prime importance. A recent study by Wang et al. (2001) shows that in about 150 ka BP the river cut through Sanmenxia Gorge and flowed towards the sea. According to their study, during the late Cenozoic time (about 5 Ma BP), there are a series of enclosed lakes in the middle reaches of the Yellow River, the last and the largest of which is San-Men paleo-lake. It is elongate in shape, extending from Hen-Qu near end of Sanmenxia Gorge in the northeast to Baoji, Shaanxi Province in the west. Very thick lacustrine sediment has been accumulated in this paleo-lake basin. On the left bank of Sanmenxia Reservoir, about 7 km upstream of its large dam, a beautiful section of lacustrine beds 278.3 m thick is exposed which records depositional history of the lake since 5 Ma BP. Near this locality, there are three terraces along the Yellow River valley: the highest terrace, T3 is covered with fluvial deposits which according to TL (thermal luminescence) dating is 148 ka BP. This proves that the Yellow River cuts through Sanmenxia Gorge and flows to the sea in about 150 ka BP (Wang et al., 2001) (Fig. 1).

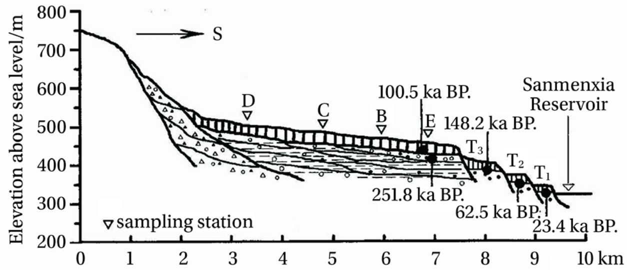

Fig. 1. Thick section of lacustrine deposits and 3 terraces along the Yellow River, 7 km up stream from the dam of the Sanmenxia Reservoir (after Wang et al., 2001).

3 Past sediment discharge

3.1 *Data and methods*

In evaluating past sediment discharge of the Yellow River, the following data were collated.

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Table 1. Hydrologic characteristics of some of the world's major rivers

River	Drainage basin area/km^2	Length/km	Mean annual water discharge/ 10^8 m^3	Mean annual suspended sediment discharge/10^8 t	Sediment concentration/kg·m^{-3}	Station	Year
Yellow River	752 443	5 464	432	11.00	25.6	Lijin	1950–1979
			408	13.40	33.1	Sanmenxia	1958–1979
			426	15.70	36.9	Shaanhsien	1919–1958
Changjiang	1 808 500	6 300	9 113	4.68	0.5	Datong	1951–1979
Mississippi	3 270 000		5 300	2.10			
Amazon	6 150 000		63 000	10.00–13.00			
Ganges Brahmaputra	1 480 000		9 700	9.00–12.00			

Notes: The source is from China Ministry of Water Conservancy, for the Yellow and Yangtze Rivers, and from Meade (1996), for the other rivers.

(1) Hydrologic record of the Yellow River at Shaanhsien–Sanmenxia Station (1919–1985) is used as a basis for comparing sediment discharge in the past. In the present, more than 90% of the sediment discharge of the lower Yellow River comes from Loess Plateau; it is assumed that this is also true in the past (Fig. 2), because general physio-graphical framework of Loess Plateau has been little changed in the last 150 000 years.

(2) There are written historical records about 5 000 years and rich archaeological findings in Loess Plateau. Our Chinese colleagues on historical geography have made detailed study on land use/land cover changes and population changes in different periods.

(3) Study on water and soil conservation in Loess Plateau (incuding experiment using artificial rainfall) has yield large amount of scientific data enabling us to compare soil erosion rate of Loess Plateau between the present and past.

(4) Detailed study on late Quaternary and Holocene loess strata and paleo-soils (pollen analysis and other sophisticated methods) gives clue for comparing environmental changes in Loess Plateau through the last 150 ka.

(5) Tan (1962) found that low frequency of dike breaching and flooding in the lower Yellow River since the East Han dynasty (about 50 AD) is mainly due to smaller sediment load which is triggered by land use change in Loess Plateau from farming to grazing and a large decrease in Han population. Therefore, a casual inter-relationship can be established between frequency of dike breaching and flooding in the lower Yellow River and land use/land cover and population changes in Loess Plateau. This enables us to check the validity of impact of land use/land cover changes in Loess Plateau on sediment load of the lower Yellow River.

These data comes from different disciples, covering both natural and social sciences. The present paper is an interdisciplinary research. All data are carefully compared with each other and checked their validity. From these analyses, more reliable figures of the Yellow River sediment discharge may be arrived. For example, in determining sediment discharge in 8.0–4.0 ka BP, archaeological finding at Qinan Da-Di-Wan site is compared with results of pollen analysis and the Holocene environmental change research. It has been shown that during the climax of the Holocene warm period (7.2–8.0 ka BP), vegetation zone in Loess Plateau was shifted westward about 3–5 degrees longitude, and consequently natural vegetation in Qinan area was mainly forest instead of steppe (in the present). Millet found in Da-Di-Wan site is dated (by ^{14}C) about 8.0 ka BP, and pollen analysis of a sample from this locality (dated (8 155±70) a BP) reveals natural vegetation at this time was mainly temperate deciduous broad-leave forest, indicating a more warm and moist paleo-climate (Shi and Kong, 1992). From this synthesis, it is concluded that although primitive agriculture had begun since 8.0 ka BP, and there may be some destruction of natural vegetation, but owing to very inefficient implements (stone implements) used, the degree of destruction is likely limited. This, coupled with more warm, humid climate and luxuriant vegetation, soil erosion most likely will be small. Therefore, it is assumed that sediment discharge in 8.0–4.0 ka BP is about the same as that of hunting and gathering period (i.e., 0.5×10^8 t/a). Other examples can be found in Table 2.

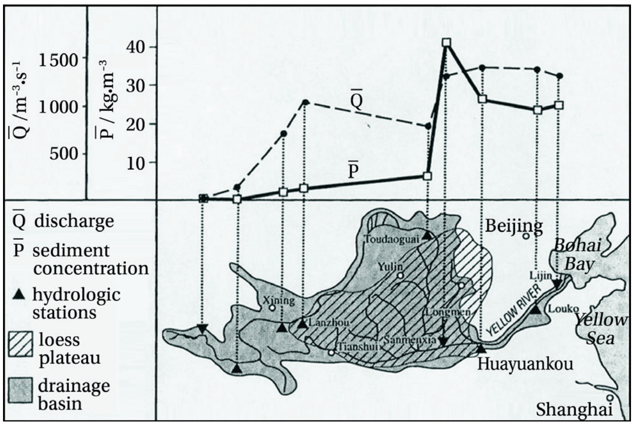

Fig. 2. Water discharge (Q) and sediment concentration (P) at selected stations on the Yellow River (30-year average, 1950–1979) (after Ren and Shi, 1986).

In Loess Plateau, Holocene profile is characterized by a loess-paleosol series in which paleosol is covered by new loess about 30–60 cm thick. There are two kinds of paleosols: chernozem (or black soil) and cinnamon soils, the former is developed under wet steppe or shrub–steppe environment, and the latter under forest–steppe or forest. In Luochuan, central Shaanxi Province, ^{14}C date of chernozem paleosol is (7 650 ± 275) a BP and the overlying new loess (2 760 ± 180) a BP. Therefore, studies on the Holocene loess–paleosols series strongly suggest a warm–humid climate in 10 000–30 000 a BP (Tang et al., 1991). It is interesting to note that Co-Ching Chu's classical paper on climate change in China during the last 5 000 years also points out that climate of the Yellow River basin in 5 000 a BP is similar to that of the present Yangtze (Changjiang) River Basin and in 3 000 a BP, the temperature is about 2°C above the present (Chu, 1973). His conclusion corresponds well with characteristics of loess–paleosol series in

Loess Plateau and gives confidence for comparing erosion rate of Loess Plateau in 10 000–3 000 a BP with that of the present Yangtze (Changjiang) River Basin.

3.2 *Land use/land cover changes in Loess Plateau and changes of sediment discharge of the lower Yellow River from 150 ka BP to 1970 AD*

The land use/land cover changes in Loess Plateau and changes of sediment discharge of the lower Yellow River may be divided into several periods, as listed in Table 2.

3.3 *The fate of sediments*

The sediment delivered by the Yellow River is partly accumulated over the North China Plain (this sediment retention is responsible for the growth of the plain), and the remainderescapes towards the sea.

(1) 75–150 ka BP, the sediments were essentially deposited in the North China Plain.

(2) 5–75 ka BP, in the last glacial period in Quaternary, with the continental shelf being exposed, about 1/2 sediment were deposited on the shelf and a small part probably entered the Okinawa trough (Milliman et al., 1989).

(3) 2 340–5 000 a BP, about 80% of the sediments were deposited in the North China Plain and built old Yellow River Delta near Tianjin, 20% escaped to the sea (Fig. 3).

(4) Since the building of the dikes along the lower Yellow River in 2 340 a BP, 3/4 sediments escaped to the sea, about 1/4 sediment accumulated in the riverbed, making the lower Yellow River a typical "hanging river".

(5) In response to the breaching of dike in 1128, the lower Yellow River did not enter the Bohai Sea but instead flowed towards the south for 726 years during 1128–1854. Between 1128 and the middle 16th century, the sediments were essentially deposited in the Huang-Huai Plain (i.e., the southern part of the North China Plain). From the middle 16th century to 1854, the river flowed into the southern Yellow Sea.

Table 2. Land use /land cover changes in Loess Plateau and changes of sediment discharge ofthe lower Yellow River since 150 ka BP

Land use / cover patterns	Time	Soil erosion and sediment discharge/ 10^8 t·a^{-1}	Sediment discharge/ 10^8 t
Hunting and gathering–natural vegetation cover remains essentially intact. However, after the Yellow River cut through Sanmenxia Gorge in 150 ka BP, regional base level of erosion is lowered which triggers gully cutting in Loess Plateau, and its erosion rate is increased. Therefore, we assume erosion rate 0.5×10^8 t/a between 150 ka BP and 8 ka BP. This is about 100% above the present erosion rate of the Yangtze (Changjiang) River Basin (according to data at Datong station) but is only 3.1% of the present sediment discharge of the Yellow River[1)]	150 – 8 ka BP = 142 ka	very slight, about 0.5	71 000
Primitive agriculture cultivation of millet (Da-Di-Wan archaeological site in Qinan, central Loess Plateau), farming, limited to small area, natural vegetation only slightly destroyed	8 – 4 ka BP = 4 ka	0.5	2 000
Ancient agriculture; bronze and iron tools used in 3 600 and 3 000 a BP, farming developed but still largely limited to the lower Wei-he plain, Loess Plateau remains a grazing area	4 – 2.25 ka BP= 1 750 a	1.0	1 750
Qin and West Han Dynasty: military conquest and forced migration of Han people pushed agriculture to North Loess Plateau. For the first time, natural vegetation seriously destroyed	2 250 – 2 100 a BP = 150 a	2.0	300
Weakening of West Han power, nomadic tribes come to Wei-he valley and North China. Incessant fighting between local warlords	2 100 a BP – 600 AD = 700 a	1.0	700
Tang Dynasty–early period: nomadic tribes retreat northward and westward	600 – 740 AD = 140 a	2.0	280
Late Tang Dynasty–North Song Dynasty: nomadic tribe move southward	740 – 960 AD = 220 a	2.0	440
North Song–Qing–Yuan Dynasty: large area of steep slope opened to farming, serious destruction of vegetation cover, soil erosion accelerated, especially on ⩾ 25° slopes, rate of soil erosion increased 50–100 times after farming	960 – 1370 AD = 410 a	6.0	2 460
Ming Dynasty–first period of Qing Dynasty: cultivation of steep slopes continued	1370 – 1800 AD = 430 a	10.0	4 300
2nd period of Qing Dynasty – present: rapid increase of population, from 1490 to 1840, population nearly increased 4 times. From 1840 to 1990, population almost doubled. Owing to pressure of increasing population, more land opened to farming soil erosion further accelerated	1800 – 1970 AD = 170 a	16.0	2 720
Total			85 950

Notes: [1)] According to a written communication from Wang et al. (2001); the data are compiled on the basis of the following publications: Ren and Zhu (1994); Meng (1997); Shi et al. (1985); Tang (1993); and for the period 1128–1854, Ren (1992).

The fate of Yellow River sediments may be summarized in Table 3.

3.4 *Sediment budgeting*

From the above, the sediment budget of the Yellow River since 150 ka BP may be established (Table 4).

Table 3. Fate of Yellow River sediments since 150 ka BP

Period	Time/a	Sediment discharge or flux/10^8 t·a^{-1}	Fate of sediment	Total amount of sediment deposition/10^8 t
(A) Built North China Plain (and deltas)				
75 –150 ka BP	75 000	0.5		37 500
5 –75 ka BP	70 000	0.5	about 1/2 escaped to the sea	17 500
2 340 –5 000 a BP	2 660	0.5 (1 000 a average) 1.0 (1 660 a average)	about 20% escaped to the sea	1 728
2 340 a BP–1128 AD	1 468	average about 2.0	after building of dike, 10% sediment deposited in the plain	294
1128 –1550 AD	422	6.0 (232 a average) 10.0 (190 a average)		3 292
1550 –1854 AD	304	6.0 (250 a average) 16.0 (54 a average)	build plain 5×10^8 t/a 7 × 10^8 t/a	1 628
1855 –1970 AD	115	16.0	3.5 × 10^8 t/a build plain	402
				total 62 344
(B) Escape to the sea				
(a) To Bohai Sea				
5 –75 ka BP	70 000	0.25		17 500
2 340 –5 000 a BP	2 660	0.1 (1 000 a average) 0.2 (1 660 a average)		432
2 340 a BP –1128 AD	1 468	average 1.5		2 202
1128 –1550 AD	422	0		0
1855 –1970 AD	115	8.0		920
(b) To South Yellow Sea				
1550–1854 AD	304	6.0		1 824
				total 22 878
(C) Accumulated in the lower Yellow River bed about 728 × 10^8 t				

Table 4. Sediment budget of the Yellow River since 150 ka BP (10^8 t)

Source	Sink		Percentage of total
85 950	build North China Plain	62 344	72.5
	flux to the sea	22 878	26.6
	accumulated in the river bed	1 741	2.0

4 Present-day sediment flux to the sea and its transport process

At the present stage, a remarkable feature of the lower Yellow River is long period of no-flow since 1972 when both water flow and sediment discharge were greatly reduced (Fig. 4). At Lijin Station between 1986–1995, mean annual water flow and sediment discharge are only about 40% of those between 1950–1979 (before no-flow or normal time). In 1996–2000, mean annual water flow is only 79.0×10^8 m^3 and sediment discharge only 2.07×10^8 t, about 19% of that in the normal time. Particularly in 1997, when duration of no-flow was the longest, 226 d at Lijin Station, water flow was only 16.81×10^8 m^3 and sediment discharge only 0.164×10^8 t. If the loss of river water to evaporation and filtration and the loss of sediment to deposition in the estuarine river channel (about 100 km long) are taken into account, actual flux of water and sediment to the Bohai Sea is probably less than 15×10^8 m^3 and 0.14×10^8 t. This has triggered a series of serious environmental problems. In addition to problems mentioned in author's 1998 paper (Ren and Walker, 1998), it has been found that reduction of sediment flux to the sea has caused serious coastal erosion of modern Yellow River Delta where 115 km^2 of land were lost during 1976–1999.

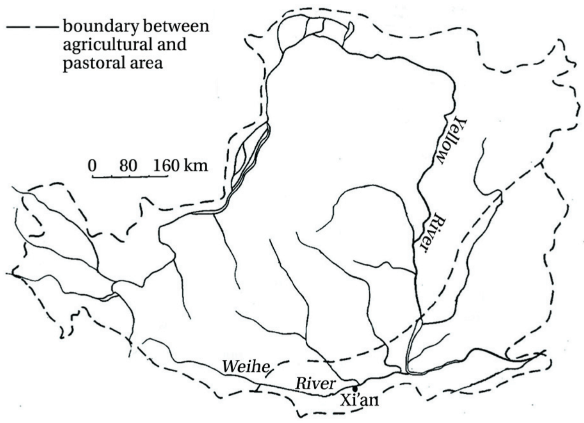

Fig. 3. Main agricultural and pastoral areas in 2 700–2 300 a BP (after Meng, 1997).

In the modern delta, since diversion of the river outlet southward to Qingshuigou in 1976, the direction of the littoral sediment drift of the Yellow River has changed from northward to southward (Fig. 5). A stationary turbidity front is present in the shallow sea near 37°50′N, which divides muddy freshwater of the Yellow River in the south from the clear saline sea water in the north. The former has suspended sediment concentration 300 mg/L and salinity 10% but suspended sediment concentration and salinity in the latter are 50 mg/L and 20% (Fig. 6). On the fate of sediment flux of the Yellow River, it has been estimated that during 1964–1973, 24% of the sediments built sub-aerial delta (above the 0 m isobath), 40% deposited in coastal shallow waters (below the 0 m isobath), 36% diffused to the deeper sea (the Bohai Sea) (Pang and Si, 1980). If 1/3 of the sediment diffused to the Bohai Sea escapes to the North Yellow Sea, this will be about 10% of the annual sediment flux of the Yellow River. As the sediment flux is only 2.07×10^8 t/a between 1996–2000, it is estimated that only about 0.2×10^8 t/a Yellow River sediment enters the North Yellow Sea. After entering the North Yellow Sea, the net transport direction of Yellow River sediment is toward SE (Cheng and Gao, 2000) (Fig. 7).

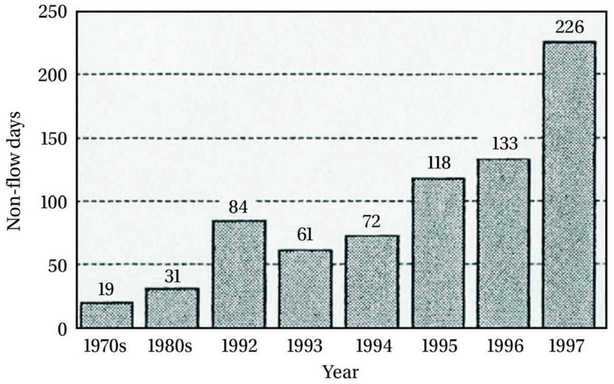

Fig. 4. Duration of no-flow at Lijin (after Ren and Walker, 1998).

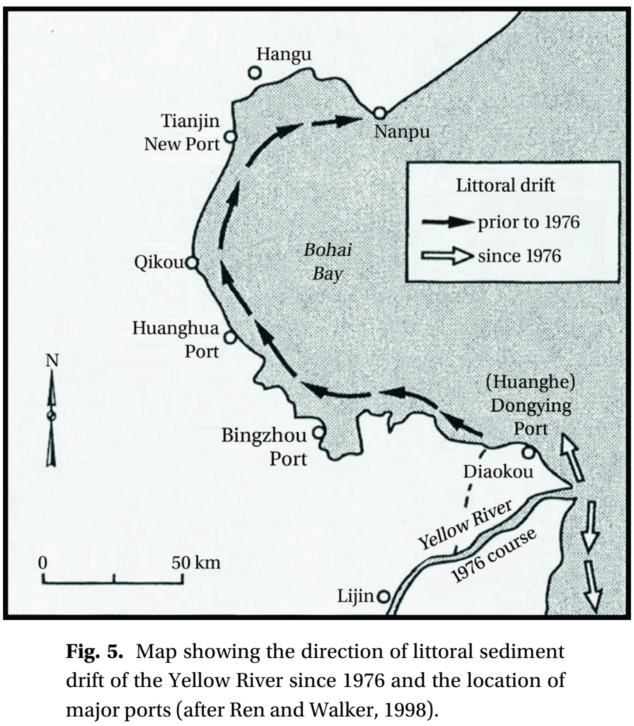

Fig. 5. Map showing the direction of littoral sediment drift of the Yellow River since 1976 and the location of major ports (after Ren and Walker, 1998).

In the Yellow Sea and East China Sea, transport pattern of the suspended materials is largely determined by the current system. The most important currents are the Yellow Sea coastal current, Yellow Sea Warm Current, and Taiwan Warm Current. In winter, owing to strong northerly wind and stormy weather, the Yellow Sea coastal current is especially strong and sediment in the subaqueous delta of the abandoned Yellow River is resuspended. Consequently, suspended particles of the Yellow River can diffuse southeastward to the northern part of the East China Sea in winter. But owing to the obstruction of the Yellow Sea Warm Current, little can reach east of 126°30′E. At the same time, suspended particles in the continental shelf also cannot diffused to the continental margin due to the barrier of the Taiwan Warm Current and upwelling water from the Kuroshio Current (Fig. 8) (Guo et al., 2001).

In the outer shelf of the East China Sea, about SW of Cheju Island, there is an area of fine grain sediment (mud). It is located in the "cold eddy region", formed by upwelling currents. The source of this mud seems mainly come from silt eroded from the mouth of the abandoned Yellow River. It is estimated that the amount is about 20×10^6 t/a. There is also a mud patch in Okinawa Trough, where about 7.3×10^6 t of mud from the abandoned Yellow River Delta is deposited per year (Hu et al., 2001).

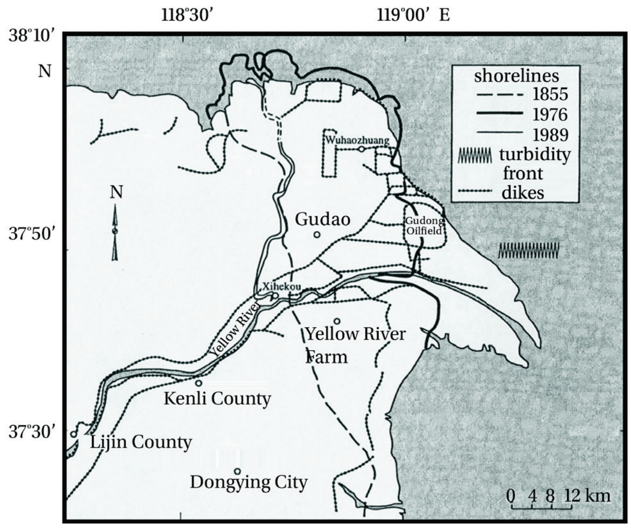

Fig. 6. Progradation and retrogradation of coastlines in the modern Yellow River delta, 1976–1998, showing the location of turbidity front (after Ren and Walker, 1998).

5 Future trends

As sediment flux of the Yellow River is influenced by various natural and socio-economic factors, predicting its change for a longer period (say 100 years) is difficult. But from the present knowledge, the trend for the next 20–30 years may be predicted. We suggest that sediment flux will most likely be small in the next 20–30 years. This is due to:

(1) Amount of water diverted for industrial and urban use will be greatly increased although water for irrigation may not be increased owing to improvement in agricultural practice and irrigation technique.

(2) Because many countries do not want to cut their greenhouse gasses emissions, global warming will be accelerated. For the upper reaches of the Yellow River, climate in next few decades will be hotter and drier, resulting in deterioration of environment

and reduction of water flow. Thus, water discharge of the upper and middle Yellow River in the 1990s is 24.4% less than that of 1950s. It has been predicted that precipitation in North China will be likely small in the next 5–10 years.

(3) Recent plan for great development of western China put emphasis on ecological improvement which, like planting of trees and grass, will consume considerable amount of water. Therefore, water consumption for ecological use will be increased.

(4) During the recent years, 12 large reservoirs have been built on the Yellow River and several ten thousands of smaller reservoirs and dams for holding silt have been constructed on the tributaries and gullies in Loess Plateau. Thus, residence time of the river water in land is increased, causing considerable loss of the river water through evaporation. At present, three large reservoirs are under construction and more large reservoirs are planned. It is likely that in the next few decades, more river water will be lost through evaporation.

(5) In the Yellow River, although relation between water flow and sediment discharge is rather complicated, but according to record at Lijin station in the last 21 years (1980–2000), the relationship is almost linear (Fig. 9). Therefore, in the next few decades, a reduction in water flow will result in a decrease of sediment discharge.

According to the analysis outlined above, without additional water supply from river diversion in Tibetan Plateau, both water flow and sediment flux of the lower-reach Yellow River will decrease in the next few decades.

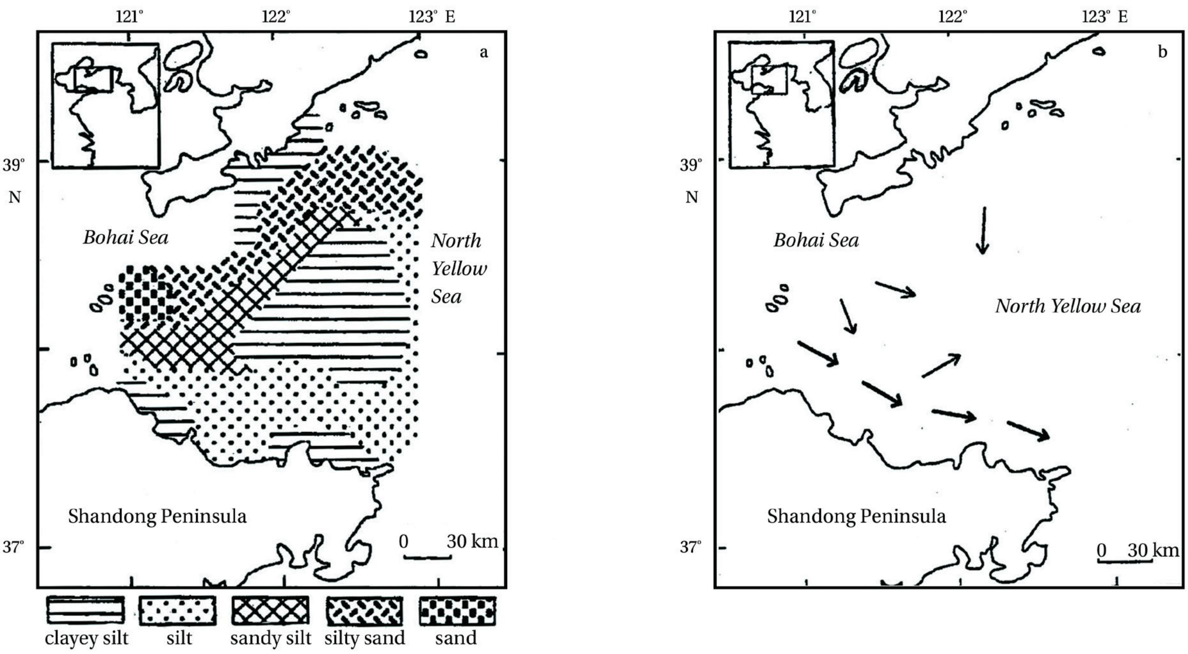

Fig. 7. Classification of surficial sediment and net sediment transport patterns in the northern Yellow Sea: a. spatial distributions of surficial sediment (the Yellow River suspended sediment consist mainly of silt sized materials); and b. net sediment transport patterns, with the arrows showing the direction of net sediment transport, after Chen and Gao (2000).

6 Summary

The general sediment budget patterns of the Yellow River may be summarized as follows.

(1) Although the Yellow River has the largest sediment discharge in the world, but a greater part of the sediment is used for plain and delta building and only a very small part is diffused to the outer shelf and ocean. Milliman et al. (1989) also suggested that "about 90 percent of the Yellow River sediment remains in the proximal environment". Thus, the role of major rivers in global sediment flux to the ocean should be re-evaluated.

(2) Effect of human activity on sediment discharge of the Yellow River is especially great. In addition to land use/land cover changes in Loess Plateau, man's breaching of dike in 1 128 results in shift of its depositional center from north of the present river channel to its south for more than 700 years. Such striking change of sediment depositional pattern by human intervention is unique among world's major rivers. In the last 30 years, owing to irrational use and unwise management of water resources, the lower Yellow River has suffered seasonal desiccation. At the Lijin Station, the duration of no-flow (d/a) has increased consistently. Consequently, the river has changed from perennial to intermittent in flow. This is also extremely rare in world's major rivers.

(3) Since 150 ka BP, there are three periods when soil erosion and sediment discharge are greatly increased. These increases are triggered by different drivers: (a) 3 ka BP, the driver is revolution of agricultural implement from stone to iron; (b) 2 250–2 100 a BP, the driver is the order of individual emperor, notably Qin Shi-Huang (or the first emperor of Qin Dynasty) and Han Wu-Di. Qin Si-Huang is well known for his numerous remarkable accomplishments, the most famous being construction of "terra cotta", the 7th wonder of the world, in Xi'an; and (c) 960 AD, the driver is rapid increase of population. Owing to population pressure, large area of steep slopes is cultivated.

(4) China has many favorable conditions for studying sediment budget of the Yellow River. (a) Written historical records about 5 000 years and rich archaeological findings; (b) large amount of data on soil erosion rate in Loess Plateau and late Quaternary and Holocene loess strata and paleo-soils; and (c) long hydrologic record of the Yellow River, 1919–1986 at Shaanhsien–Sanmenxia station and other key stations along the river.

(5) This paper discusses land use/cover changes in Loess Plateau since 150 ka BP, which may reoresent one of the longest time

series studies on this subject in the world. However, it must be pointed out that the values for the sediment budget (Table 4) are only preliminary, since it is not possible to obtain more accurate information from the existing available data.

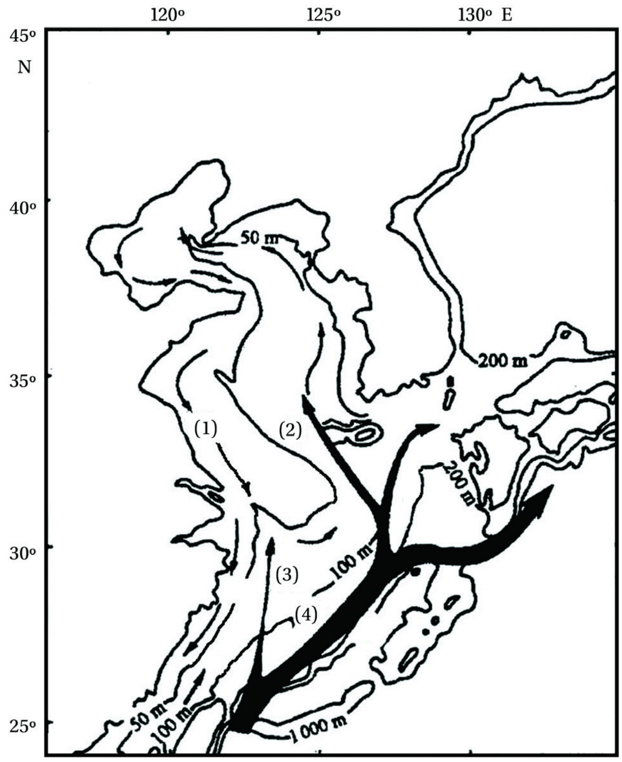

Fig. 8. Shelf circulation patterns in the Yellow Sea and East China Seas: (1) Yellow Sea Coastal Current; (2) Yellow Sea Warm Current; (3) Taiwan Warm Current; (4) Kuroshio Current; and (5) Okinawa Trough (after Guo et al., 2002).

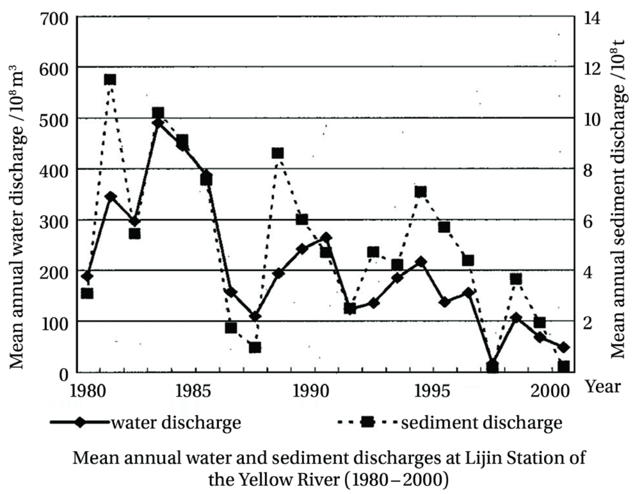

Fig. 9. Mean annual water and sediment discharges at the Lijin Station, the Yellow River, 1980–2000.

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Editorial note: The paper "Sediment discharge of the Yellow River, China: past, present and future — A synthesis" by late Professor Ren Mei'e deals with the river–sea interaction associated with the Yellow River. Although this article was written some six years ago, the ideas expressed by Ren Mei'e are still valuable today; in particular, the analysis of sediment budget in relation to the Yellow River system evolution is of importance for the study of the coastal zone in response to global climate change. On September 13, 2008, Professor Ren asked about the possibility of publishing this manuscript in a scientific journal, but shortly after the discussion about the arrangement for the submission of the article, he passed away in Nanjing on November 4, 2008. As such, the Chief Editor of the journal decides to publish the paper as it was.