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Sedimentary Causes and Management of Two Principal Environmental Problems in the Lower Yellow River

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ABSTRACT / Flood and water shortage are two of the leading environmental problems around the world, and among the causes of the problems is sedimentation. The Yellow River brought disastrous floods in its lower reaches in Chinese history. Today, although floods caused by the river are still a formidable hazard hanging over China, it cannot provide the lower reaches with enough usable water. The ineradicable flood hazard and newly emerged water shortage problems of the river are proved to be closely associated with its immense sediment load. The over loaded flow of the river can quickly fill the reservoirs and unceasingly raise the riverbed, attenuating the capacity of reservoirs to suppress floods and provide more water for dry seasons and of river channels to convey floods. Also, the high sediment content pollutes the water and reduces the volume of usable water. In virtue of the intimate linkage between these problems and the formidable sediment load in the river, the solution to these problems should be based on sedimentation management. After reviewing the defects and merits of management measures implemented and proposed, a management scenario composed of multiple measures are recommended. Beside of persistent soil conservation to reduce the huge sediment load, more reservoirs to check sediment and regulate river flows, approaches to alleviating riverbed accretion, interbasin water transfer to mitigate water deficiency, and so on, an emphasis should be laid on use of muddy flows in order to scatter the sediment in a vast area, which was a natural process but has been interrupted by construction of embankments.

Flood disaster has been a problem of global importance. Statistics shows that flood disasters accounted for 32% of the significant damage, a same percentage of the persons affected and 26% of human life loss caused by the worldwide major disasters during 1963–92 without figuring in the effects associated with tropical storms, which give rise to disasters mainly in the form of flooding (UNDHA 1994). Flood disasters have done immense damages in China also. In the period from 1950–97 the areas inundated by floods in China had an increasing trend and an annual average of 91.06 thousand km^2, leading to immediate loss of over 10 billion Renminbi Yuan annually (ECWCA 1990–98). Now, in the east China about 738 thousand km^2 land area is under the flood level of adjacent rivers and flood hazards shadow the areas that are inhabited by 40% of China's population, yield 60% of national gross output, and have 35% of farmlands of the whole country (NSB, CAC 1995).

Contrasting with the flood problem in the hydrological sense, water shortage has been another principal environmental problem perplexing part of the world. Water scarcity results from limited water resources, which are unevenly distributed in time and over space and are unable to quench the continuously increasing water demands from humans. The world's water withdrawal increased by 5.73 times over the period from 1900 to 1980, and in 1990 the water withdrawals in many regions of the world (including north China) accounted for 20–65% of their annual runoff (Shiklomanov 1993).

The Yellow River has a notorious historical record of flood disasters, which have devitalized more people than any other single event ever recorded on the earth. The astonishing damage to human life made by the river had been widely cited (Gregory 1980, McDonald and Kay 1988, Bryant 1991, Gleick 1993). After the foundation of the People's Republic of China, many endeavors have been made for preventing the river from flooding and, at the same time, exploitation of the water from the river has been carried out on an increasing scale. However, the result is not as good as expected. The actual situation is that the water-scarce problems emerged and became worse quickly in recent years, while the flood problem continues to be one of the most dangerous hazards in China.

The fundamental cause of flood disasters is human

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encroaching on flood-prone areas; water scarcity is the result of human demand outstripping the limited water resources, but there are many other factors playing an important role in exacerbating these problems. One of the factors is sedimentation. Flood prevention achievement can be eroded because sediment deposit steals the flood retention capacity of reservoirs and flood delivery capacity of river channels. Besides, sediment in water contaminates the water by itself and pollutants absorbed on it, leading to the decline of water quality and the amount of water suitable for use. For example, river aggradation is recognized as one of the long-term causes of the recent floods in Bangladesh by Khalequzzaman (1994) and the flood damage and water treatment costs due to sediment account for 41 million Rand annually in South Africa (Braune and Looser 1989). Likewise, reservoir silting, as a worldwide problem, has an enormous influence on economy. The estimation made by Mahmood (1987) of an average loss of worldwide reservoir capacity is 1% per year, giving rise to an annual replacement cost of about $6 billion. In the case of the Yellow River, the above two problems have an intimate relation with sedimentation because the river has an annual sediment load of about 1.6 billion tons, close to the world's largest one (1.67 billion tons) in Ganges/Brahmaputra (Milliman and Meade 1983), but an apparently low annual runoff of 58 billion m^3, which ranks it the fourth largest even in China. The close linkage between sedimentation and the occurrence of the two problems in the river basin deserves to be studied for extending the knowledge of the sediment-related problems.

An attempt of formulating a solution to these problems is made herein. It should be admitted that the Yellow River management in the past 50 years made the great achievement of no dyke-breaching flood occurring. However, flood problems still exist and, in fact, flood control is still recognized by the Chinese government as the first task in the Yellow River management at present. At the same time the water shortage problem emerged and is getting worse. Under this changing situation the strategies implemented and proposed for harnessing the river should be examined and amended.

Current Situation of Two Environmental Problems

Flood

Large-scale cultivation on the lower Yellow River floodplain started with the construction of a system of massive dykes or embankments along the river (Xu, J. X. 1993). Unfortunately, the dykes did not confine the river successfully. It breached or even deserted its channel frequently with a record of about 1500 times flooding out of dykes in the 2500 years before 1949, in which 6 times did the river desert the old channel and flow in a new route down the whole lower reaches.

The nightmare of dyke breaching on the river has been eradicated for 50 years in the reign of Chinese communist government, except for a small flood near the river mouth induced by ice floes in the winter of 1955. The elimination of dyke breaching has been realized both by constructing more concrete flood control projects and by institutional or nonstructural measures, especially a flood prevention team equipped with the advanced technologies. The flood control projects include three components, i.e., a set of giant embankments along the lower reaches, the reservoirs on the main stream and tributaries in the middle reaches, and flood detention areas in the lower reaches (Figure 1). The embankment in the lower reaches had been uplifted three times on a large scale and consolidated incessantly after 1949. Now, the design flood of the embankments has a recurrent interval of 60 years, and it will be enlarged, according to hydrological calculation, to a recurrent interval of about 1000 years by the Xiaolangdi reservoir under construction.

However, the above flood-prevention measures cannot guarantee the elimination of flood problems. There is still the possibility of dyke breaches owing to the incessant bed accretion, the weaknesses of the dykes, and the damages to the dykes caused by burrowing animals and earthquakes (Li and Finlayson 1993, Shi and Ye 1997). With a high perching channel above the surrounding areas, a possible large dyke breach can rampage an area of 33,000 km^2 inducing 48 billion RMB Yuan (at 1991 prices) immediate economic loss (Lin 1993). Because the river flow is so muddy, the consequences of dyke breaches on the natural environment in the inundated areas might be also disastrous, including destroying the inundated river systems, filling up lakes, and turning farmlands to wastelands (Shi and Ye 1997).

Moreover, controlled extreme floods can also result in loss of life and property in flood detention basins and on floodplains between dykes. As a part of the flood control system, the off-river flood detention basins had been set up in the lower reaches for reducing floods of peak discharge over 22,000 m^3/sec at Huayuankou station and 11,000 m^3/sec at Aishan station. Yet the losses can be colossal by using these flood-detention basins to avoid dyke breaching because these basins have been occupied by a large amount of population (about 1.7 million in the largest two basins,

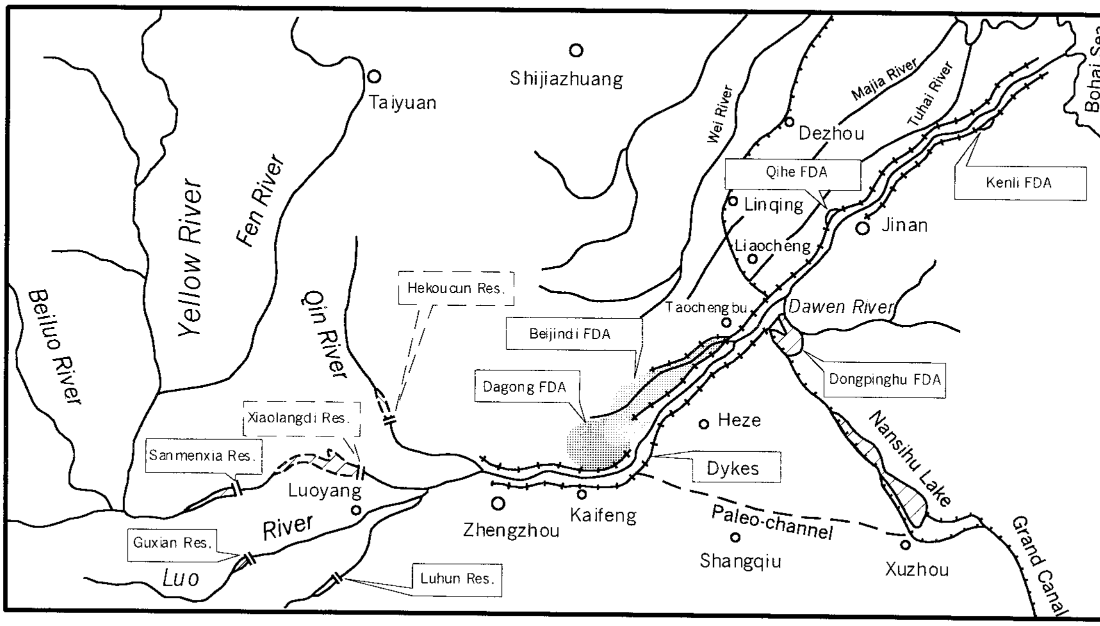

Figure 1. Sketch of the flood control system of the lower Yellow River (after OHYRFC 1988).

Beijindi and Dongping Lake (BRM, YRCC 1997). The estimation shows that the immediate losses may approximate 8.3 and 7.0 billion Yuan (at 1991 prices), respectively, by opening Beijindi and Dongping Lake flood detention basins only one time (Lin 1993). Even if the large floods are confined between the dykes, enormous losses may be created to the 1.72 million people living on the floodplains between the dykes. Between the dykes in the lower Yellow River there is 395.3 thousand ha of floodplains, of which 24.94 thousand ha are cultivated. The floodplains were flooded in about 1 out of every 2 years according to the records after 1949. The flood in 1996 produced the recorded largest inundation damage to the area between the dykes, with immediate economic losses of about 6.46 billion Yuan (BRM, YRCC 1997).

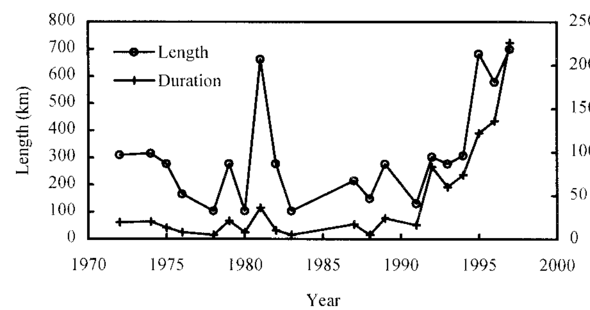

Figure 2. Changes in the annual duration and largest reach length of flow interruption in the lower Yellow River.

Water Shortage

Water shortage problem became very serious in recent decades in the lower Yellow River. The severity of water shortage can be reflected by the steady aggravation of flow interruption of the river. Since 1972, the river has dried out intermittently and the reach length and duration of flow interruption extended as time progressed (Figure 2). The serious case took place in 1997 when the river flow stopped for 226 days at the Lijin station (about 100 km up the river mouth) and the farthest upstream point where flow ever ceased was 700 km up the river mouth.

The consequence of the frequent flow interruption was tremendous economic losses and environmental hazards. According to an investigation (Chang and others 1998), due to shortage of water in the period of flow break from 1972 to 1996, the output of industries and agriculture in the lower reaches was reduced by 26.8 billion Yuan, of which 25.2 billion Yuan was lost during 1990–96. As a result of flow interruption in 1997, over 1.533 million ha farmland in Shandong Province could not be irrigated, leading to a reduction of 2.75 billion kg of grain and 50 thousand tons of cotton, 1.30 million people suffered a shortage of drinking water, and 200 oil wells of the Shengli Oilfield were closed. A partial estimation revealed that the immediate economic loss in Shandong alone was over 13.5 billion Yuan in 1997. Beside the detrimental effects on economy, the environmental impacts of flow break are also immeasurable. These include the probable occurrence of desertification of the lands between and immediate outside of the dykes, damages to the riparian ecosystems in the lower reaches and the estuary, a decline of water quality due to inadequate water discharge to dilute pollutants, etc. (Gao and Cui 1996, Cui 1996, Gao 1998)

Sedimentary Causes for Flood

The incessant and high rate of siltation in the channel has been recognized as the primary cause of the frequent floods in the past and for the difficulty of flood prevention at present in the lower Yellow River. This is why the siltation alleviation was placed in the primary management problems in many proposals for the lower Yellow River in history and at present (Pan 1988, Li 1989, ISP, YRCC 1991).

The sediment accumulation in the lower reaches has been so high and persistent that the river had to constantly change its course. There are many abandoned channels as linear highlands left on the North China plain by the river (Ye 1989). The last abandoned one is the Ming-Qing channel, formed during 1494–1855, and it has the highest relative elevation among the abandoned channels. The floodplains beside of its main channel are 6–8 m maximum 9.5 m high above the floodplains outside of dykes. Up until now, the floodplains between the dykes confining present channel have been raised to a height of 3–7 m maximum 10 m above the surrounding floodplains. Clearly, a perching channel has a high potential of occurrence of inundation, dyke breach, and channel migration.

Recurrent and detailed hydrological records and channel cross-section measurements of the present channel disclosed the intensity and distribution of siltation in the river channel. It was shown that total 10.1 billion tons of sediment was deposited in the lower Yellow River channel over the period of 1950–96. These deposits could raise the bed at an average rate of 3.8 cm a year, a vertical deposition rate with no match in any large river around the world, even if they were laid evenly on the bed between the dykes.

Moreover, the actual sediment accumulation was not evenly distributed between the dykes but concentrated near and in the main channel (Figure 3). This arises from two leading causes, i.e., confinement of the water flow by low inner embankments built by the residents on the floodplains between the dykes and a decrease of water discharge in recent years. Construction of the low inner embankments was carried out on a large scale in the late 1950s. These inner embankments prohibit the floodwater flowing into the floodplains between the inner embankments and the flood-prevention dykes, so deposition can only take place between the inner embankments. Having realized the negative effects of the inner embankments on the sediment accumulation distribution and also on the flood draining, a decree to destroy the inner embankments had been issued later. But it has not been obeyed completely, and some inner embankments that had been felled were even rebuilt in recent years. The situation has become worse when the river suffered from a considerable water discharge decline after the middle 1980s. The average annual runoff flowing into the lower reaches in the period from November of 1985 to October of 1996 was only about 64% of the average in the period of 1919–85. Based on the daily discharge measured at Huayuankou station (730 km up the river mouth), the changes in discharges had a trend of enlargement of duration of discharges smaller than 1000 m^3/sec and decrease of those over 1000 m^3/sec (Figure 4). Consequently, the channel capacity lowered through narrowing or channel bed rising as shown in Figure 3. Based on the measurement of 36 cross-sections along the low reaches the channel lost a flow area of about 773 m^2 on an average from 1986–94, which was about one-quarter of the channel capacity of a mean 2892 m^2 in 1986. The situation was worse at downstream Huayuankou, where the channel lost a mean of 1072 m^2 or a third of its original capacity between 1986–94.

The result of the concentrated sediment accumulation near and in the main channel was a much higher flood stage rising rate than it would be in the case of sediment accumulation distributed evenly. As shown in Figure 5a, along the lower Yellow River the stage of 3000 m^3/sec discharge was uplifted for 2.69–4.13 m at a rate of 5.85–8.98 cm/a during 1950–96. This uplifting rate could also be treated as the rate of stage rising of design flood during 1958–98 because the hydraulic coarseness of the flood lands is much higher than that of the main channel (Figure 5b). Clearly, it is much higher than the presumed rate of 3.8 cm/a in the case of evenly distributed sediment accumulation.

Owing to the rising of the flood level since the last time (1974–83) of dyke uplifting, the channel of the lower reaches does not have the capacity to safely deliver the design flood now. The dykes need to be added up again by about 1 m in the reaches downstream Gaocun (Figure 6).

Sedimentary Causes for Water Shortage

The Yellow River is called the second largest river in China, yet its discharge is smaller than that of the Yangtze, Pearl, and Songhuajiang rivers. Its 58.0 billion m^3 annual runoff accounts only for 2% of the China's

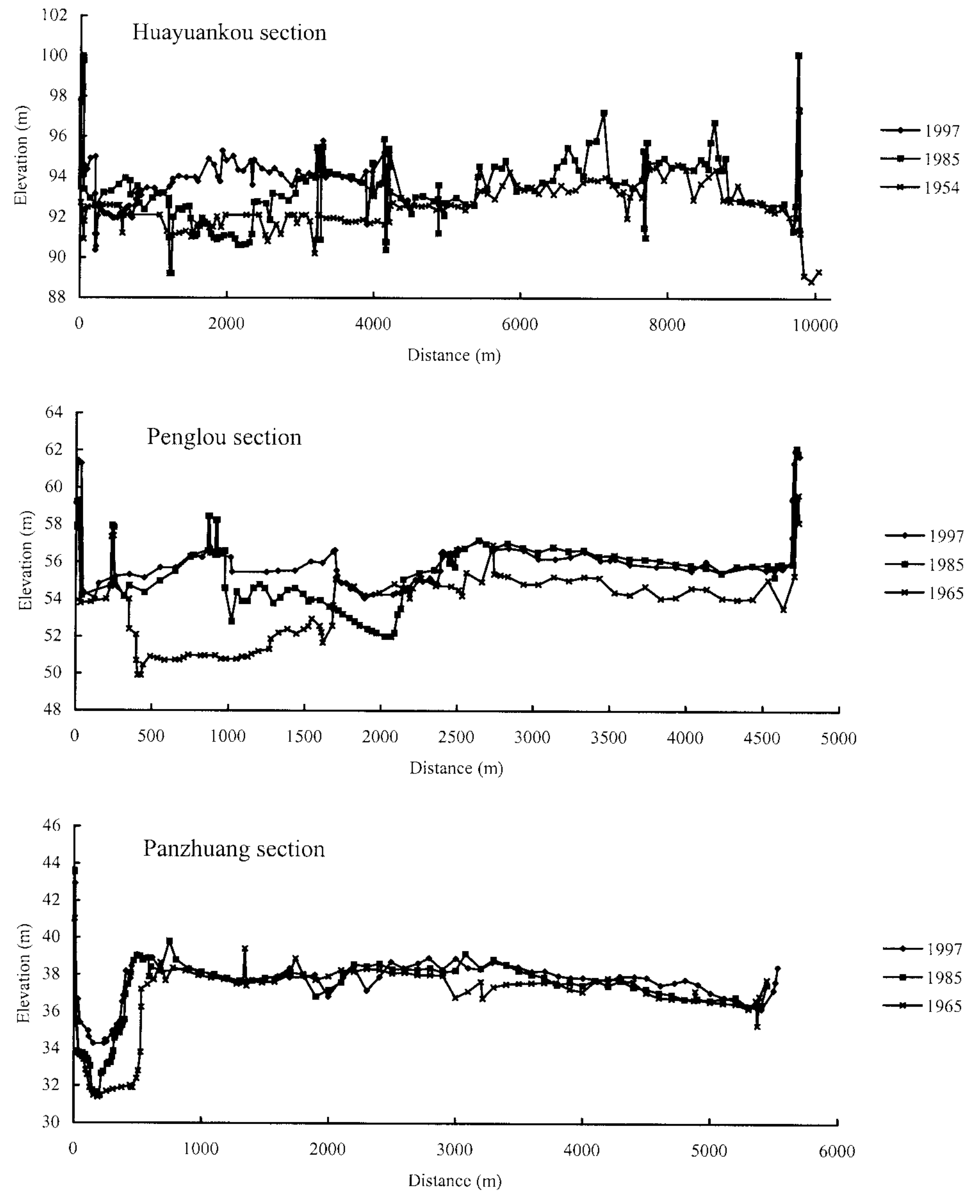

Figure 3. Changes in three typical cross sections showing the characteristics of deposition distribution across the channel (Huayuankou section located in the braided reach; Penglou section, 227 km down from Huayuankou, in transitional reach; Panzhuang section, 394 km down from Huayuankou, in confined and low sinuous meandering reach).

total. On an average of the basin up Huayuankou, the runoff depth is 77 mm, the water volume per head is 593 m^3, and the water volume per ha of farmlands is 4860 m^3. They are just 28%, 25%, and 17% of the China's average, respectively. Thus the water resource is very meager in the basin. Furthermore, the annual natural runoff of the river declined by 16% in 1970–95 and by 26% in 1990–95 than that in the 1950s and 1960s (Figure 7). In addition, the water storage of Longyangxia Reservoir, which is located in the upper reaches and was put into use in October of 1986, reached 16.03 billion m^3 at the end of the flood season of 1989, reducing water flow down the river.

On the other hand, water consumption in the basin has increased steadily over the past decades. As shown in Figure 7, the water consumption in the whole river basin increased from 13.49 billion m^3 in the 1950s to nearly 30 billion m^3 in the 1980s and the first half of the 1990s, which are about 20.2% and 63.1% of the annual natural runoff, respectively. A prediction shows that the water demand in the Yellow River basin will increase considerably, and the total water demand in 2020 may reach about 70 billion m^3 even in the event of a low increase in predicted consumption (Chang and others 1998). This means that the estimated lowest water demand in 2020 is roughly the current total water re-

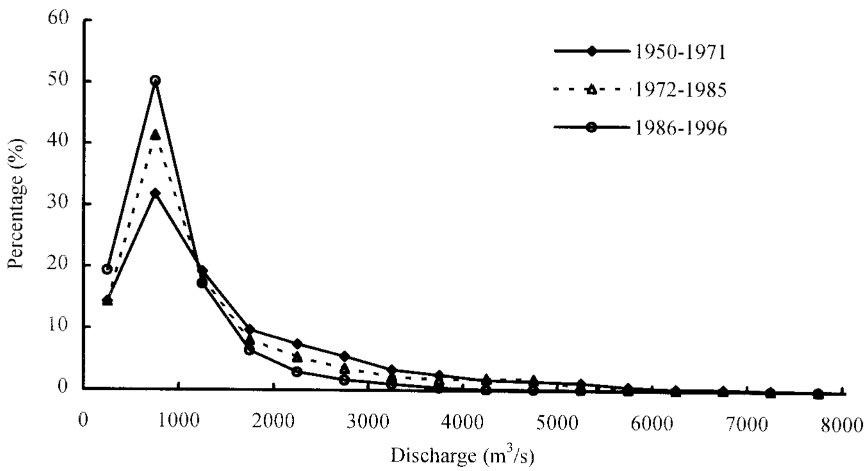

Figure 4. Changes in percentage of different discharge classes.

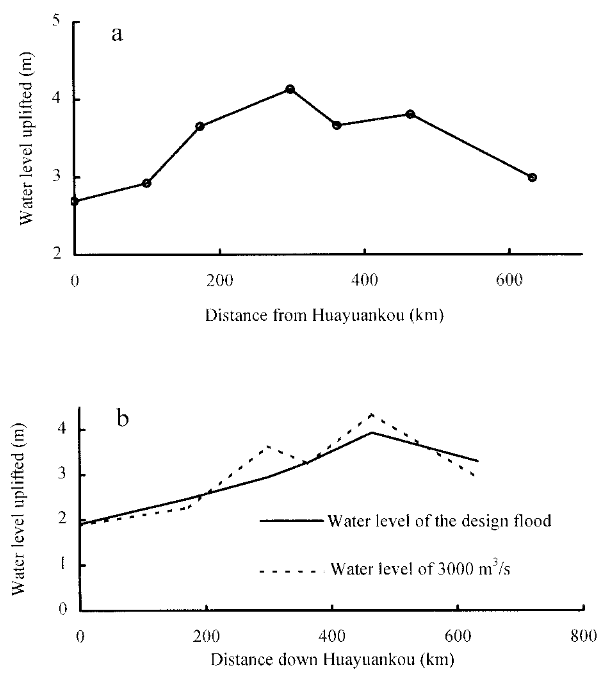

Figure 5. Changes in water level of 3000 m^3/sec discharge from 1950 to 1996 along the lower Yellow River (a) and comparison of water level change of the design flood with that of 3000 m^3/sec discharge from 1958 to 1998 (b).

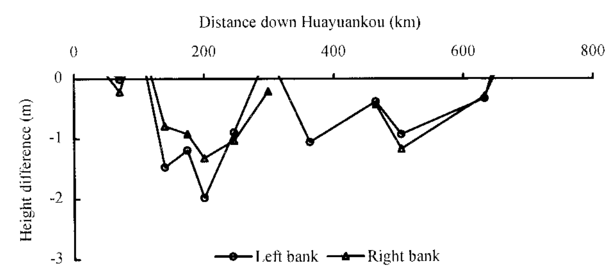

Figure 6. Deficit of current dyke's height for holding the design flood (based on data of BRM, YRCC 1997).

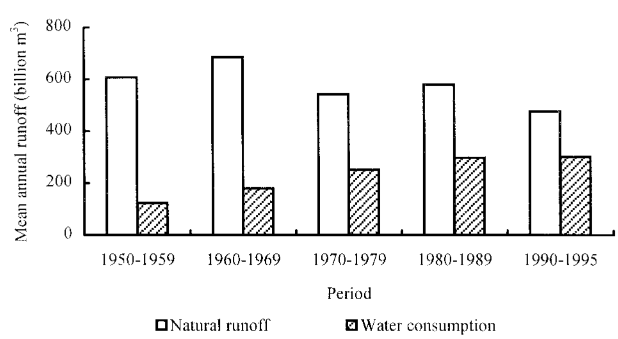

Figure 7. Changes in mean annual natural runoff of the Yellow River and in water consumption in this river basin.

sources in the basin, which include 58 billion m^3 surface runoff and 13.9 billion m^3 shallow fresh ground water. Therefore, the situation of water shortage may become more serious in the years to come.

Besides the aforementioned comparatively high water demand and natural shortage of water, the high sediment load of the river should be another principal cause for the water shortage in the lower reaches. The annual sediment load of 1.6 billion tons carried by the river (the records in 1919–85) can very quickly fill up any large reservoir in the world. Therefore, using reservoirs to control floods and regulate flows on this river has been proved to be very difficult. In 1955, the government approved an ambitious plan of Yellow River management (ISP, YRCC 1991). The aims of the plan were to put the river under control completely, eliminating the flood and drought disasters in the basin, stopping the water and soil losses on the Loess Plateau, and making best use of the water resources for irrigation, electricity generation, and navigation. Yet the soil loss was not alleviated as expected. Up to 1979, control of soil loss was finished on an area of 75.7 thousand km^2, which was only 40% of the planned area. As a result, serious sediment filling problems appeared in some of the reservoirs that had been completed. Two of the reservoirs were built on the lower Yellow River. They had to be destroyed in 1963 when they were in place for only 5 years due to serious sediment filling in them and consequent water level uplifting caused to upstream reaches. Sanmenxia Reservoir had a capacity of 35.4 billion m^3 and was the largest in China when it was finished in 1960. It was a multipurpose project for flood control, irrigation, and electricity generation. Yet the sediment accumulation in the reservoir was so heavy that the total volume of deposits in the section from Tongguan to dam reached 3.65 billion m^3 in the first 4 years. Since the reservoir raised the water level at Tongguan, where the River Wei joins the Yellow River, heavy siltation and flood problems took place in the Wei River, doing colossal harm to people in the tributary's basin. Thus the flow regulation pattern of the reservoir had to be changed from "impounding both water and sediment" during 1960–64, through "deterring flood and discharging sediment" during 1964–73 to "storing clear water and releasing muddy flow" after 1973. The reservoir was modified twice to enlarge its release capacity for the implementation of regulation pattern transform. The design's normal high-level had to be lowered from 350 m to 335 m above sea level, and the storage capacity from 35.4 billion m^3 to 9.64 billion m^3. Even though the average water level of the reservoir was kept in the range of 314–318 m above sea level after 1974, the water level at Tongguan was still kept at around 327.5 m above sea level, 3.8 m higher than that before the dam construction (Ye and Shi 1991). Therefore the huge volume of sediment carried by the river prevents full use of precious capacity of reservoirs to regulate the river as needed.

Disposing the sediment carried in water before the water can be used is another annoying problem. In the period of 1950–90, the annual volume of water drawn from the river down Huayuankou was about 6.43 billion m^3, which carried about 102 million tons sediment, that is, an average sediment concentration of 15.9 kg/m^3. It was much lower than the annual average of 25.8 kg/m^3 at Huayuankou station in that period. Nevertheless, these sediments have caused severe environmental problems. An investigation by Bian and Geng (1993), for example, revealed that about 27,000-ha of pools, which had been used for sediment deposition before the water flows into irrigation canals, were created in the 13 irrigation areas alone in Shandong Province after 1965. The deposits in these pools are mainly composed of sand and silt, which cannot hold water and nutrients necessary for plants. Consequently, about 14,900 ha of the abandoned pools had degenerated to desertified land. Moreover, the existing irrigation canals will be quickly choked by deposits if they divert overloaded muddy flows from the river, so withdrawal of flows with sediment concentration of over 35 kg/m^3 is not permitted in the decree issued by the Ministry of Water Conservancy of China (Dong 1996).

Inasmuch as the over 1 billion tons sediment carried by the river cannot be held by reservoirs and is hard to be consumed, it has to be transported to the sea as much as possible. About 20–24 billion m^3 water has to be left annually for this purpose at present, and it can only prevent the existing serious siltation in the channel from exaggeration (Bai and others 1996). Therefore, although water deficiency has become very serious, there is still a large volume of water wasted for flushing the sediment to the sea every year.

Evaluation of Countermeasures

In view of the foregoing analysis, it seems to be reasonable to argue that the coexistence of both flood hazard and river drying up in the lower Yellow River is the result of particularly high sediment load in the river. It is the sediment that keeps the riverbed incessantly rising, and it is the sediment that inhibits the river to be regulated for eliminating the occurrence of flow interruption. Hence, sediment control should be the essence of good measures for managing the Yellow River. Here, the sediment control means to hold sediment in the upper and middle reaches and alleviate sediment accumulation in the lower Yellow River channel. Many proposals for these purposes had been put forward, and some have been carried out.

Implemented Managing Practices

Soil conservation and reservoir detention had given rise to a considerable reduction of sediment yield in the upper and middle reaches in the past decades. Up to the end of 1991, about 130,000 km^2, which is one-third of the area where 90% of sediment load of the river comes from, had been managed. Considering the effects of changes in precipitation, Xiong and Yu (1996) estimated that sediment reduction by soil conservation was 0.396 billion tons annually in the 1970s and 0.3 billion tons annually in the 1980s. Also, up to 1990 Sanmenxia-Reservoir deterred about 8.078 billion tons of deposits (Long and others 1996), which was about

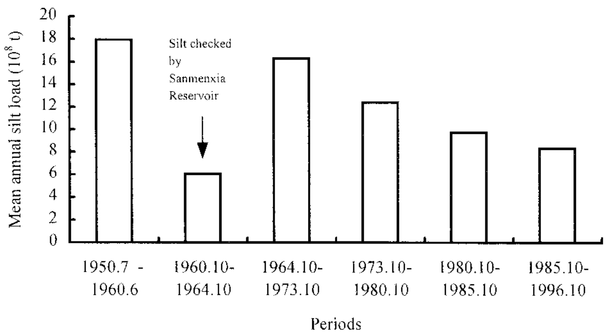

Figure 8. Changes in mean annual sediment load of the lower Yellow River.

0.27 billion tons annually. Consequently, there was an obvious decrease trend in the change of sediment load into the lower reaches as shown in Figure 8.

However, to keep the decrease trend in sediment load or even maintain the current level may be an arduous task given the natural conditions of the Loess Plateau, where about 90% of sediment load of the Yellow River comes. Some scholars had estimated the sediment yield from the Loess Plateau in the near future based on the planned soil conservation projects and the possible changes in natural factors, which have impacts on the soil erosion. The estimation made by Jing and others (1997) is a decrease of about 0.47 to 0.807 billion tons in the middle of the 21st century, so the sediment load to the lower reaches will be in the range of 0.738–1.075 billion tons. J. H. Xu (1993) predicted that sediment yield might be reduced by an annual amount of 0.28–0.884 billion tons in 2020 and that the river would still have an annual sediment load of 0.9–1.5 billion tons. It should be noted that implementation of large-scale soil conservation schemes is the prerequisite of the estimated upper limits of the sediment yield reduction. The annual reduction of 0.807 billion tons given by Jing and others (1997), for example, is fulfilled by an 0.7% pure increase of area of grass and forest lands annually, an annual 0.35-billion-tons-sediment retention by building total 20 thousand key sediment reservoirs in gullies, and no farmlands on slopes over 15°. This is not an easy task and, disclosed by the authors, construction of sediment reservoirs has been obviously behind the plan, finishing only 23% of the plan for the period of 1986–2000 in the first 10 years. Moreover, accounting for about 66.9% of the total 10.655 billion tons of sediment checked by all soil conservation works in the basin during 1949–95 (Yan and others 1998), finished sediment barriers and reservoirs had been the main contributor of sediment yield reduction, but they are losing their capacity to retard sediment. For instance, the sediment barriers and reservoirs built in the 1970s played a key role in sediment yield reduction during the 1970s, and 1980s, yet at the end of the 1970s the capacity of these sediment reservoirs and barriers had decreased by 30–40% and 50%, respectively (Wang and Jiao 1996). Thus, soil loss control on the Loess Plateau alone may not be able to reduce the sediment load in the river to solve the sediment-induced problems in the lower reaches in a relatively long period.

Dissatisfactory progress had been made in preventing the sediment from accumulated in the lower reaches in the past decades. Indeed, the volume of sediment accumulation in the lower reaches was reduced by about 58% in 1973–96 and by 32% in 1985–96 comparing with annual 0.361 billion tons in the 1950s. This reduction of sediment accumulation, however, was mainly the consequence of sediment load reduction mentioned above. Only small portion of reduction in siltation, 25.5 million tons annually in the period of 1973–90 (Zhao and Pan 1996), was achieved through flow regulation using Sanmenxia Reservoir.

It is worth mentioning that the siltation reduction of 32% in 1985–96 was attained while the annual sediment load was lowered to 0.83 billion tons. The annual 0.83 billion tons sediment load was 54% lower than that in the 1950s and close to the lower limits of the aforesaid prediction for the middle of the 21st century. If the water consumption in the future increases as the prediction mentioned, the siltation in the lower reaches may be aggravated and distributed in the channel much more unevenly, leading to a much more unfavorable situation for flood control.

Proposals for the Future

For dealing with the sediment-related problems in the lower reaches in the future many proposals had been put forward (ISP, YRCC 1991, Cheng 1996). Among them are dam construction, storing silts on flood lands, and interbasin water transfer (which may be carried out in the near future) and are worthwhile to be explained here. First, three reservoirs, Longmen and Qikou (in planning) and Xiaolangdi (under construction), are designed to have the function of siltation alleviation in the lower reaches. The anticipated total siltation alleviation in the lower reaches by the three reservoirs is about 20.7 billion tons (Cheng 1996), in which about 7.82 billion tons siltation reduction, a volume accumulated in the lower reaches in 20 years under the natural conditions, is expected to be made by Xiaolangdi Reservoir in 50 years after 2003 when it is put into use (Tu and others 1993). Second, the measure of storing silts on flood lands is to use two sections of the river's flood lands, one in the middle reaches and the other at the upper end of the lower reaches, as sediment retention tanks. A decrease of sediment deposition by 21.22 billion tons in the lower reaches is estimated to be the result of accomplishment of this measure. Third, according to the plan of inter-basin water transfer, about 8.3 billion m^3 of water will be transferred from the Yangtze River basin in the future, and it is predicted to scour 0.128 billion tons of deposits from the lower Yellow River annually (Cheng 1996). In addition, there are many other measures aimed purely at siltation alleviation in the lower reaches, such as sediment transport by hyperconcentrated flows, narrowing the channel, and pumping sea water to scour the bed (Qi 1993, Fei 1998, Mou 1990, Shi and Xu 1997, Lin and others 1999). Nevertheless, further studies and tests on the feasibility of the above proposals in the respective of technology and economy are needed before they are believed to be viable.

The above measures may have effects much lower than expected, like the ambitious plan of harnessing the river proposed in the 1950s, so the sediment-related problems are likely to prevail in the lower reaches and the riverbed to continue to rise. It is clear that confining a river in a perching channel that becomes higher and higher will be very difficult. Therefore, it seems to be reasonable to let the river change its course from time to time, as it did before. A detailed plan of artificially leading the river to abandon the current channel had been worked out by Ye and others (1990). In the plan a long dyke needs to be built to the north of the current channel, forming a new channel with the existing north dyke of the river. Also, from a perspective of hydrology and geomorphology, a proposal of artificially abandoning the current channel was advocated by Li and Finlayson (1993). However, as Ye and others (1990) themselves disclosed, their proposal has many defects, including the need for population migration, impacts on communications and water intake works, as well as on the Tianjian New Harbor, etc.; and the new channel can survive only for about 80 years. The plan of artificial changing channel has not been widely agreed as a solution to the siltation problem now.

A Long-Term Strategy

Most of the above measures are aimed just at getting ride of the adverse effects of the high sediment load in the river. Opposite to these measures in the sense of treatment of sediment load in the river, an alternative is using the sediment to strengthen the dykes and to raise the low floodplains outside of the dykes. This measure will lessen the height difference between the river bed and the surrounding floodplains, which has been enlarged since the practice of using embankments to confine the river about 2000 years ago. It will also increase the availability of the precious surface water in the basin. In the past the lower Yellow River distributed the sediment evenly in the North China Plain through frequent flooding and channel migration. This process was not completely prohibited even after the river was confined by embankments in Chinese history, but it was in the form of severe flood disasters. Artificial diversion of sediment to the surrounding plains may be the way to obey the rule but with less damage to property and life because it is in a gentle manner of flow diversion and under the human's control. Similarly, Khalequzzaman (1994) raised a proposal of diverting the sediment in Ganges and Brahmaputra Rivers to the surrounding low-lying delta plains for flood control in Bangladesh and using sediment to offset subsidence in some areas on Nile and Bengal deltas is a suggestion advanced by Milliman and others (1989). Also, diversion of silt-laden flows to the Barataria and Terrebonne basins of the Mississippi River delta for moderating land loss has proved to be the best among four proposals by Martin and others (2000).

Utilization of the river's silts in the lower reaches started at least about 1000 years ago because they also can be used to fertilize farmlands (ISP, YRCC 1991), and in the reign of Chinese communist government a method to diverting the river's silts to widen the dykes was invented. However, this kind of practice had been carried out only on a small scale in the recent decades. Water intake in the lower reaches carried 0.102 billion tons of sediment out of the river annually on an average in the period of 1950–90 (Wang and others 1996). Another total 0.43 billion tons or an annual mean of 0.011 billion tons of sediment from the river was withdrawn out to widen the dykes, fill the depressions, and uplift the ground surface on the immediate outside of the dykes from 1955 to 1995 (Zhao and Wang 1996). Clearly, the siltation in the river could not be alleviated significantly by taking out only 0.113 billion tons silt; on the contrary, mean annual 11.5 billion m^3 water withdrawal in the lower reaches resulted in additional 0.014 billion tons siltation annually in the period of 1986–93 (Zhao and Pan 1996). This can be ascribed to two principal reasons. One is that the decrease of siltation due to the sediment being taken out cannot make up for the increase of siltation caused by lowered water discharge. The other is that the water taken out has only a sediment concentration of 15.9 kg/m^3, which is about 61.6% and 63.6% of those measured at Huayuankou and Lijin stations, respectively. To better the effects of water use on siltation in the river channel, the amount of water withdrawal should be large enough to ensure that the decrease of siltation due to the sediment being taken out outweighs the increase of siltation in consequence of lowered water discharge.

As in the other measures mentioned, the measure of large-scale sediment diversion to the plains beside the dykes also has drawbacks, including lack of techniques to transport the sediment in canals without siltation for a long distance and present shortage of the means to null the negative effects. Nevertheless, with these problems being solved in the future, this measure should be a good selection for managing the Yellow River on account of its many merits.

Reasonably, diverting sediment to the floodplains outside of embankments need not imply that the other measures of river management should be abandoned. The problems in the Yellow River cannot be solved by any single measure permanently. Rather, a river basin strategy is necessary, as Sundborg and Rapp (1986) suggested in a study of worldwide erosion and sedimentation problems, for avoiding disastrous effects of soil erosion and sedimentation. This river basin strategy should be more comprehensive and reinforced by measures that do not appear in the suggestion of Sundborg and Rapp (1986) for solving the sediment-induced problems in a river with very high sediment load like the Yellow River. We need reservoirs to regulate the evidently unevenly temporary distribution of water flow, soil conservation on the Loess Plateau to reduce the insurmountably huge sediment load in the river, siltation alleviation methods to prevent the riverbed from unceasingly rising, interbasin water transfer to satisfy the increasing water demand in the basin, measures to appropriately distribute the large volume of sediment transported to the lower reaches, and approaches to using the muddy water flows with little adverse effects. Thus in virtue of the flaws and merits of the above proposals, a better strategy of river management may be a combination of the aforesaid measures with emphasis on consuming muddy flows to scatter the sediment in a vast area as the natural processes had done and to promote the usability of the deficient water resources in the basin.

Conclusion

Although the flood hazard still lingers over the lower Yellow River another water problem, water shortage, emerged and became steadily worse in recent decades. Both of the problems have a close association with the very high sediment load of the river. Flood problems were worsened because the flood control function of embankments was diminished by sediment accumulation in river channel and using reservoirs for flood control was hampered by reservoir silting. Water shortage was exacerbated because water quality and usability was lowered due to high sediment content, sediment accumulation reduced the water regulation capacity of reservoirs, and a large volume of precious water had to be wasted to flush the immense sediment load into the sea. Recent water discharge decline in the Yellow River due to water shortage aggravated the existing heavy siltation in channel, eroding the achievement of flood control.

Sedimentation management plays a key role in solving the flood and water shortage problems in the lower Yellow River. Soil conservation on the Loess Plateau is a fundamental measure of sedimentation management, and evident progress had been made in the past 50 years, but further reducing sediment yield by this approach may be difficult according to some estimations. Thus, with continued and enhanced soil conservation, other measures are necessary for both increasing the availability of the precious water resources and eliminating riverbed aggradation in the lower reaches in the coming years. Finishing of Xiaolangdi Reservoir and other planned reservoirs and projects may be the solutions to these problems in the near future, but alleviating siltation in the channel and, especially, diverting sediment to surrounding plains should be the solution to the problems in the long term.

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