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Soil erosion in the Yellow River basin and its impacts on reservoir sedimentation and the lower Yellow River

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ABSTRACT The Yellow River has a drainage area of 75×10^4 sq.km with a total length of 5464 km. The river is famous for its enormous amount of sediment load in the world. Although great progresses of harnessing and exploiting of the river have been made during recent tens years, serious soil erosion in the watershed still has not been well controlled. In this paper, the features of soil erosion and its impacts, reservoir sedimentation and channel deposition of the Lower Yellow River are introduced.

CHARACTERISTICS OF RUN-OFF AND SEDIMENT LOAD IN THE YELLOW RIVER

According to the long-term data collected, the annual precipitation for the Yellow River basin amounts to 478 mm, and the measured annual runoff is 46.4×10^9 cu.m with an annual sediment load of 1.56×10^9 tons (at Sanmenxia Station). The characteristics of runoff and sediment load for the Yellow River can be briefly illustrated as follows:

1. Less runoff with more sediment load and quite high sediment concentration.

By comparisions, the incoming runoff of the Yellow River is equivalent to one-twentieth of the Yangtze River, while the sediment load of the Yellow River is three times as high as that of the Yangtze River. The average sediment concentration of the Yellow River is up to 33.6 kg/m^3. The Ganges River of India and Bangladesh has an annual sediment load of 1.45×10^9 tons and yet the average sediment concentration is only 3.92 kg/m^3. The sediment concentration of the Colorado River in the United States is 27.5 kg/m^3, but annual sediment load is only 0.135×10^9 tons. Therefore, the Yellow River plays a leading role so for as the total sediment load and the average sediment concentration.

2. Different sources of runoff and sediment load

Due to the widespread area and the different climatic, geographical, geomorphological, and geological conditions in the drainage basin, the sources of runoff and sediment load are also different. For the Upper Yellow River (upstream of Hekouzhen), the area accounts for 49% of the total watershed area and the incoming runoff is 54% of the total, while the sediment load is only 9%, so that, this region is a main source of runoff in the Yellow River. In the Middle Yellow River, the area from Hekouzhen to Longmen acocunts for 17.5% of the total, the runoff is 14%, but the sediment load reaches 55% of the total incoming sediment load. This region is one of the main sources of sediment load of the Yellow River. Another main source of sediment load is the region between Longmen and Tongguan. In this region, the incoming runoff mades up 22% of the total, and the incoming sediment load makes up 34% of the total. The Yi-Luohe River and the Qinhe River, two main tributaries in the reach downstream of Sanmenxia Reservoir, have a runoff accounting for 11% of the total, yet the incoming sediment load is only 2%. The runoff from the region upstream of Hekouzhen and the Yi-Luohe and Qinhe Rivers has a diluting effect on the high-concentrated flow coming from the region between Hekouzhen and Tongguan.

3. Nonuniform distribution with time

The amount of runoff and sediment load over a long term changes periodically, abundance-low-abundance. The period is about 8-10 years. The annual runoff in abundant water year is 3-4 times as high as that of low water years The maximum annual sediment load is 3.9×10^9 tons (the year 1933). The ratio between the maximum and minimum annual sediment loads reaches 8.

The distributions of runoff and sediment load in one year are also non-uniform. The runoff in flood season (July-October) accounts for 60% of the annual runoff and the corresponding sediment load is over 85%. Moreover, the sediment load is more concentrated in several rainstorm-floods in the flood season. For example, the maximum five-day-runoff accounts only for 4.4% of the annual runoff, while the maximum five-day-sediment load reaches averagely to 31% of the yearly sediment load. The sediment load in the tributaries of the Middle Yellow River is even more concentrated than that in the main stream. Sometimes, floods with the hyper concentrations of 1000-1500 kg/m^3 may occur. The maxium sediment concentrations at Longmen and Sanmenxia Stations of the main stream of the Middle Yellow River are 933 kg/m^3 (July, 1966) and 911 kg/m^3 (August, 1977) respectively.

4. Sharp peak of flood

The floods in the Lower Yellow River come mainly from three regions: (1) the tributaries between Hekouzhen and Longmen; (2) the Jinghe, the Beiluohe and the Weihe Rivers; (3) the Yi-Luohe and the Qinhe Rivers. All of the floods are caused by rainstorms, so that the floods rise and fall rapidly to form sharp peaks of floods.If floods occur simultanuously in above two or three regions, extraordinary large floods in the Lower Yellow River, such as the floods in 1933 and 1958, might happen.

SOIL EROSION AND INCOMING SEDIMENT IN THE YELLOW RIVER BASIN

Soil erosion

The upper and middle reaches of the Yellow River and their tributaries go through a vast loess plateau. The thickness of the loess amounts to tens even hundreds meters. Where the soil is so loose that it can be easily eroded by rainstorms in flood season. The soil erosion with an area of 4.3×10^5 sq.km, 72% of the total area of loess plateau, mainly concentrates in the gullied-hilly loess region between Hekouzhen and Tongguan, but the soil erosion is even more tremendous in an area of 10×10^4 sq.km.

The soil erosion is consisted of slope surface erosion and gully erosion. According to the field data, 60-80% of the eroded soil come form the gully erosion and the others come from the surface erosion.

Ratio of Sediment delivery

The gullied- hilly loess region consists of numerous small gully watersheds. Due to the steep slopes and short stream lengths, the maximum sediment concentrations of various gullies at different dimensions are nearly equal. This implies that all sediment from slope surface may pass through the gullies, ravines. The amount of soil erosion of small gully watersheds is approximately equal to the amount of sediment entering into the tributaries. The observed data also indicate that the average annual modulus of soil erosion of the tributaries with large drainage area is basically close to that of the secondary tributaries with small watershed, and there is no permanent deposition in various tributaries. This also implies that all sediment from these tributaries may enter the main stream of the Yellow River. Therefore, it can be concluded that in the main source regions for the sediment of the Yellow River, the amount of soil erosion is close to that of sediment transported into the main river. The sediment delivery ratio is close to 1 (Gong Shiyang, 1980). This is quite different from what has been found in other countries.

Soil erosion and incoming sediment

According to the field data from 1950 to 1974, the transportation modulus of sediment can be drawn [Fig.1] (YRWCC, 1983). As shown, there are three large rigions, where the transportation modulus of sediment is over 10,000 $t/km^2/yr$: the tributaries between Hekouzhen and Yanshuiguan; the tributaries of the Wudinghe River and the Jinghe River; the northern tributaries of the Weihe River.

The medium sizes of loess particles change from larger than 0.045 mm in the northwest to 0.015 mm in the southeast [Fig.2] (YRWCC, 1983). The coarse sediment (d>0.05 mm) comes mainly from two regions: the middle and lower parts of tributaries of the Huangpuchuan and the Tuweihe Rivers, the middle and lower parts of the Wudinghe River. About three-fourths of the total sediment load of 1.6×10^9 tons and the coarse sediment of 0.73×10^9 tons come from the gullied hilly loess regions between Hekouzhen to Tongguan with an area of 10×10^4 sq.km. The fine sediment comes from the tributaries of the Jinhe, the Fenhe and the Upper Weihe Rivers.

Changes of runoff and sediment load in recent years

According to the field data, the annual incoming runoff and sediment of the Upper and Middle Yellow River in 1970-1984 were obviously decreased as compared with that in 1950-1969. For example, the total runoff and sediment load of Longmen, Huaxian, Hejing and Zhuantou Stations were decreased by 14.8% and 33.7% respectively. The main reasons caused the decreases of runoff and sediment load were the decrease of precipitation and the progresses of water conservancy and soil conservation engineering works.

In recent fifteen years, the annual precipitation in the Upper and Middle Yellow River obviously reduced as compared with that in 1950's. Thus, the soil erosion and the destruction of small water and soil conservation engineering works were also alleviated.

However, great efforts and progresses in the construction of water and soil conservation have been made in the gullied-hilly loess regions. Up to now, a total area of 10×10^4 sq.km has been improved and the annual incoming sediment load in 1970-1984 was decreased by some 0.2×10^9 tons. For some small watersheds, the soil erosion has been better controlled. For example, in the watersheds of the Fenghe

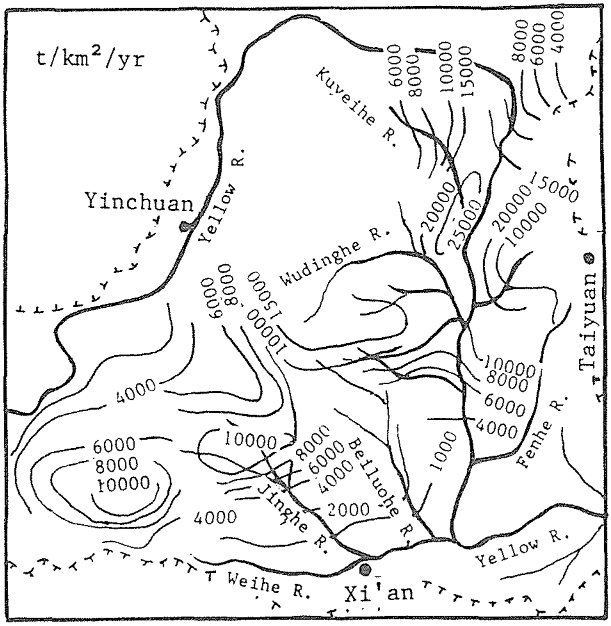

Fig. 1 Transportation modulus of sediment in the Middle Yellow River.

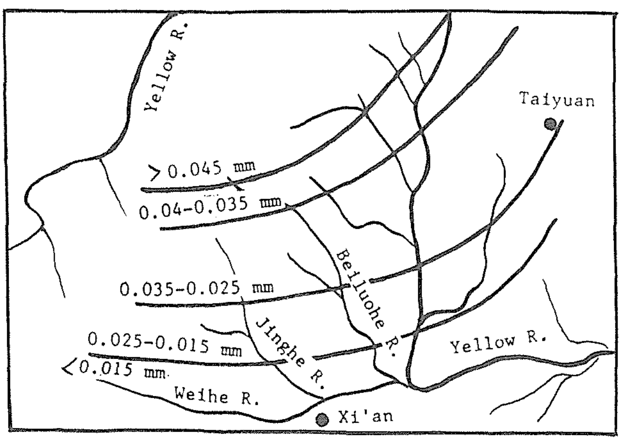

Fig.2 Medium diameter of loess in the Middle Yellow River.

River, the Wudinghe River, etc., the incoming sediment has been decreased by 50%. However, just as the experiences from practice (Xiong Guishu, 1988), the slope surface controlling measures such as the constructions of terrace fields, vegetation planting, etc., can only play a limited role. They are incompetent to stop fully the soil erosion. For engineering measures such as the constructions of small reservoirs, silt arresters and ponds, etc., their trapping efficiency will be decreased with the increasing loss of storage capacity. Therefore, the engineering measures act only a part in postponing the soil erosion, they also can not be able to permanently solve the problems of soil erosion. It seems that it is necessary to continuously construct engineering works of terrace fields, small reservoirs, siltarresters and ponds, and vegetation planting etc., in the gullied-hilly loess regions if we hope to maintain or increase present trapping efficiency of soil.

EFFECTS OF SOIL EROSION ON RESERVOIR SEDIMENTATION

Gravity of reservoir sedimentation

The serious soil erosion affects firstly the sedimentation of reservoir. For some reservoirs on the main stream of the Yellow River such as the Yanguoxia, the Qingtongxia and the TianQiao Reservoirs, 50-87% of their storage capacities were lost to sedimentation in 5-7 years after impounding of these reservoirs. Many reservoirs on tributaries have been even abandoned. According to the preliminary survey in Shaanxi province, there is an increase in reservoir storage of 260 million cu.m per year (counting only those with an original capacity of 1 million cu.m and over), while about 80 million cu.m of storage capacity of the existing reservoirs are lost to sedimentation each year. This is equivalent to one-third of the storage capacity of the reservoir newly built in that year.How to overcome the reservoir sedimentation to meet the needs of flood protection, power generation, irrigation and water supply is a challenging task faced by the Chinese sedimentation researchers.

Effective measures to reduce sedimentation in Sanmenxia Reservoir

Sanmenxia Reservoir is one of the important reservoirs in harnessing of the Yellow River. Due to lack of experiences during planning and inadequate attention being paid to the sediment problems, 1.5×10^9 tons of sediment were accumulated in the lake by March 1962, one and half years after the reservoir was impounded. Until 1964, the deposited sediment was increased to 4.4×10^9 tons and the backwater effect extended rapidly in the upstream direction, endangering the industrial and agricultural developments of Guanzhong plain and the city of Xi'an (Zhou Wenhao et al., 1986). The reservoir was forced to be reconstructed and the original goals had to be given up.

After two reconstructions, the reservoir sedimentation has been controlled [Fig.3]. The annual amount of deposition is decreased to 0.02×10^9 tons. A storage capacity of nearly 1×10^9 cu.m downstream of Tongguan has been regained. A volume of 3×10^9 cu.m below the elevation of 330^m (5.8×10^9 cu.m corresponding to the elevation of 335^m) can been maintained for long term use of rare flood control, benefits of ice-jam control, spring irrigation and hydropower generation.

The main measures to maintain the storage capacity of the Sanmenxia Reservoir are as follows:

1. To enlarge the releasing capability of flow

After reopening eight deep orifices, reconstructing four inlets of turbines and newly constructing two flood tunnels, the releasing capability for the reservoir has been increased form 5460 m^3/s before reconstruction to 13800 m^3/s (both corresponing to the elevation of 330^m). Thus, the water level of the reservoir in flood season may be lowered, the sediment-carrying capacity of flow may be increased and then the deposited material may be flushed out of the reservoir by retrogressive erosion and downward erosion.

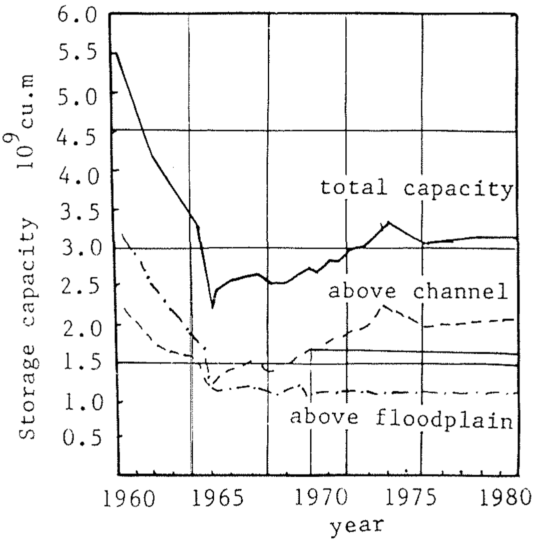

Fig.3 Variation of storage capacity of Sanmenxia Reservoir.

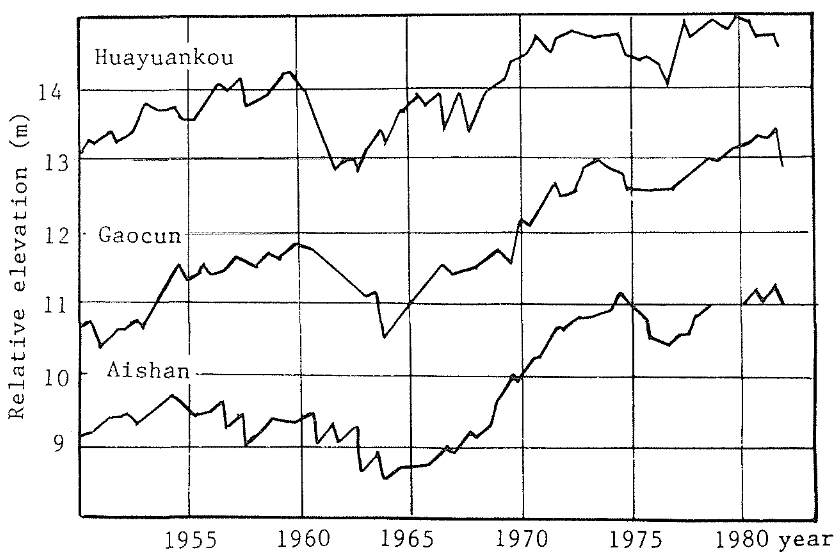

Fig.4 Variation of stages for a discharge of 3000 m^3/s along the Lower Yellow River.

2. To operate the reservoir under the mode so-called "impounding the clear water and releasing the muddy flow"

According to this operating mode, during the flood season when the sediment concentration is high, the reservoir is operated at full discharge capacity. In low-flow season when the sediment concentration is small, the water is stored for irrigation and power generation.

The advantages of this operating mode lie in that: (1) a yearly balance of sediment deposition and erosion may be achieved to keep a certain amount of storage capacity in the reservoir for long term use; (2) the upstream extension of backwater deposition may be controlled by the erosion under lower water level in flood season; and (3) the outflow hydrograph may be regulated to be of benefit to reductions of the accretion in the Lower Yellow River.

The experiences of Sanmenxia Reservoir have been widely used in the planning and design of reservoir constructions on the rivers with heavy sediment concentration in China.

EFFECTS OF SOIL EROSION ON THE LOWER YELLOW RIVER

General description

The Lower Yellow River is an aggradated river. The tremendous sedimentation on flood plain and channel bed results in the river bed raising with a rate of 0.10-0.15m per year. [Fig.4]. The elevations of the bed is 3-5m higher than that of the ground outside the embankments. The maximum superelevation reaches 10m. So the Lower Yellow River is a so-called "up-ground" river or "suspended" river. According to the plan configuration, the river can be divided into three reaches: the wandering (in Henan province), the transition and the meandering (in Shandong province) (Qian Ning et al., 1965) Because of the serious and rapid sedimentation, the main channel of the river often shifts from one side to the other, and the safety of the embankments is threatened. In history, the embankment breach occurred twice every three years. Therefore the flood prevention becomes consistently the most important problem of the Lower Yellow River.

River siltation

A huge amount of sediment from the loess plateau is carried mainly by the floods, so the tremendous sedimentation also occurs in flood season, especially in the floods with hyper-concentration of sediment. According to the field data in 1955-1977, the total amount of incoming runoff was 1267.5×10^9 cu.m, the total incoming sediment load was 40.9×10^9 tons and the amount of total deposition was 9.6×10^9 tons. In the same peroid, there were seventy floods with a total runoff 219.7×10^9 cu.m and a total sediment load of 18.6×10^9 tons, 17%, 45% of the total runoff and sediment load in 1950-1977 respectively, but the amount of accretion reached 8.3×10^9 tons, about 87% of the total siltation from 1950 to 1977. Also in 1950-1977, there were eighteen hyper concentrated floods (sediment concentration greater than 300 kg/m^3). Their total incoming runoff and sediment load only accounted for 2.6% and 18% of those in 1950-1977 respectively, yet the total deposition accounted for 50% of the total in 1950-1977. The material deposited in the Lower Yellow River consists of coarse particles with size larger than 0.05mm. According to the field data in 1950-1960, the bed material load ($d>0.025$mm) and the wash load ($d<$ 0.025mm) for the incoming sediment load accounted for 50% respectively. However, the amount of bed material load deposited accounted for 80% of total amount of deposition. Especially, the amount of accretion for the coarse sediment ($d>0.05$mm) accounted for over 50%. The material deposited in channel were mainly composed of coarse sediment ($d>0.05$mm). In deep part of flood plain, the coarse sediment also accounted for 50%. Obviously, these coarse particles were from the source regions of coarse sediment in the Middle Yellow River. Therefore, from the views of harnessing the Yellow River, it is significant to control the soil erosion in the regions of coarse sediment yeild.

Features of hyperconcentration floods

By analyses of the measured data from the Yellow River, the following characteristics are provided by the hyperconcentrated floods which often happened in the fifties and the seventies (Zhou Wenhao et al., 1983).

1. The hyperconcentrated flow in natural stream behaves as a turbulent flow instead of a Bingham fluid. The vertical distribution of velocity still follows the Law of logarithmic distribution, and the Karmen's coefficient changes with the sediment concentration and has a maximum value when the concentration is 200-300 kg/m^3.

2. The vertical distribution of sediment concentration still follows the law of diffusion and the value of diffusional exponent Z also depends on the sediment concentration.

3. The carrying capacity for bed material load has the same law of the ordinary sediment laden flow, but the grain size in flow is increased with the increasing of sediment concentration. In the Lower Yellow River with a total length of 800 km, the same linear relation of medium size (d_{50}) and sediment concentration are still preserved, all though the hyperconcentrated flow has been regulated along the river course.

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