CASE STUDY ON UTILIZATION OF SEDIMENT RESOURCE IN THE LOWER YELLOW RIVER

IRTCES Report -2010-2-01

INTERNATIONAL RESEARCH AND TRAINING CENTER ON EROSION AND SEDIMENTATION

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Content

1. Sediment Resource in the Yellow River

The Yellow River is a symbol of heavily sediment-laden rivers and “perched river” in the world. Compared with other large rivers worldwide in annual runoff and annual sediment load (as shown in Table 1), the Yellow River is list the highest in terms of sediment load and sediment content, and is well-known as insufficient water amount and excessive sediment load.

Table 1 Water and sediment data of some large rivers

Country	River	Catchment area ($10^3 km^2$)	Annual runoff ($10^9 m^3$)	Annual sediment load ($10^9 t$)	Annual sediment content (kg/m^3)	Sediment load / catchment area ($t/km^2.a$)
China	Yellow	752.4	47.4	1.63	35.0	2126
US	Colorado	637	4.9	0.135	27.5	211.9
India, Bangladesh	Ganges	955	371.0	1.451	3.92	1519
Egypt, Sudan	Nile	2978	89.2	0.111	1.25	37.3
US	Mississippi	3230	564.5	0.312	0.55	96.6

The abundant sediment, which aggrades endlessly along the Yellow River, is the most serious issue on engineering and environment of the River. Sediment yield and deposition make deep influences on the harness and exploitation of the whole Yellow River basin.

1.1 Sediment Sources and Sediment Yield

The Yellow River basin is a widely dimensional area with distinctly different geographies. And more distinguishingly, the source regions of the natural runoff and sediment yield are inconsistent and divided in the Yellow River basin.

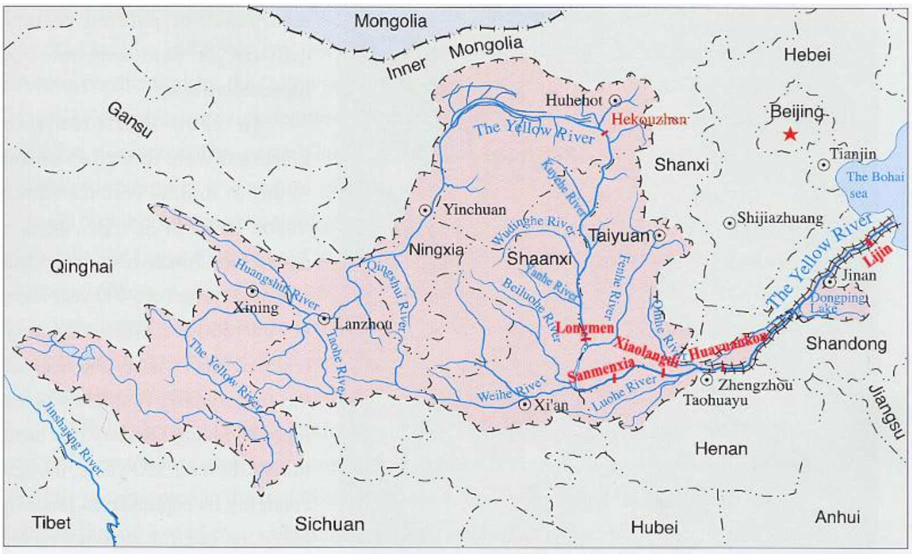

Fig. 1-1 the sketch map of the Yellow River basin

1.1.1 Sediment sources in the Yellow River

Analyzing the statistic data in Sanmenxia station from the year of 1919 to 1960, when the Yellow River was scarcely influenced by human being, the mean annual sediment load of the Yellow River was as high as 1.6 billion t.

Divided the whole Yellow River watershed into four regions, they are Hekouzhen upstream catchments, Hekouzhen~Longmen catchments, Longmen~Sanmenxia catchments and Sanmenxia~Huayuankou catchments, and draw the accounting cake chart for the four regions of watershed area, runoff and sediment load as the Fig. 1-2 shown. It is distinct that the Yellow River runoff coming from the four regions are consistent with the watershed area, while the sediment load yielded from regions is deeply inconsistent with their watershed area. The Yellow River runoff mainly comes from Hekouzhen upstream watershed, accounting for 52.8% of the total basin runoff, while the annual sediment load was only 0.14 billion t equal to 8.6% of the total basin sediment load. The Yellow River sediment mainly comes from Hekouzhen-Longmen-Sanmenxia catchments, located in the loess plateau.

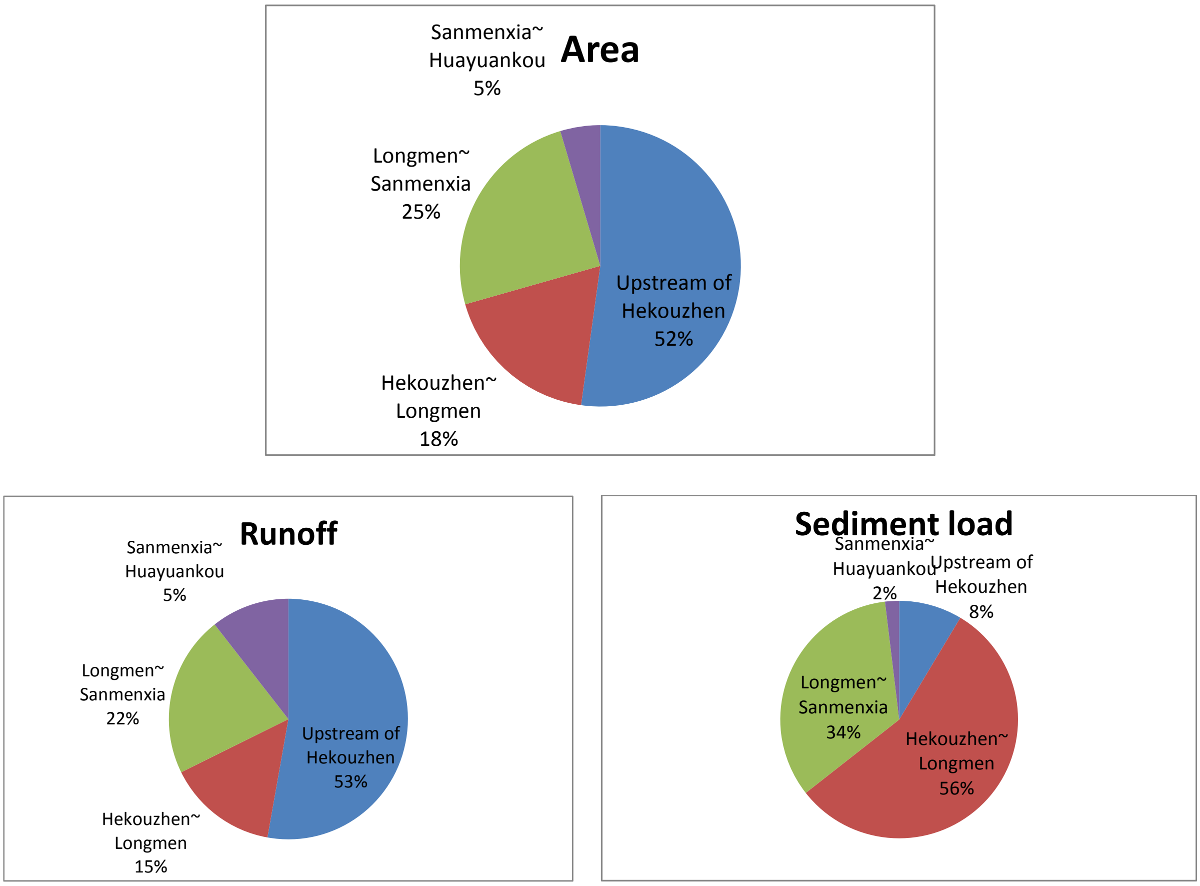

Fig. 1-2 The sources of water and sediment in different catchments compares with their areas in the Yellow River

The Yellow River flowing though the loess plateau, the most serious gullied-hilly soil erosion area, which contribute 90% of the sediment load to the Yellow River (see Photo 1-1) (sediment gazette, 2000).

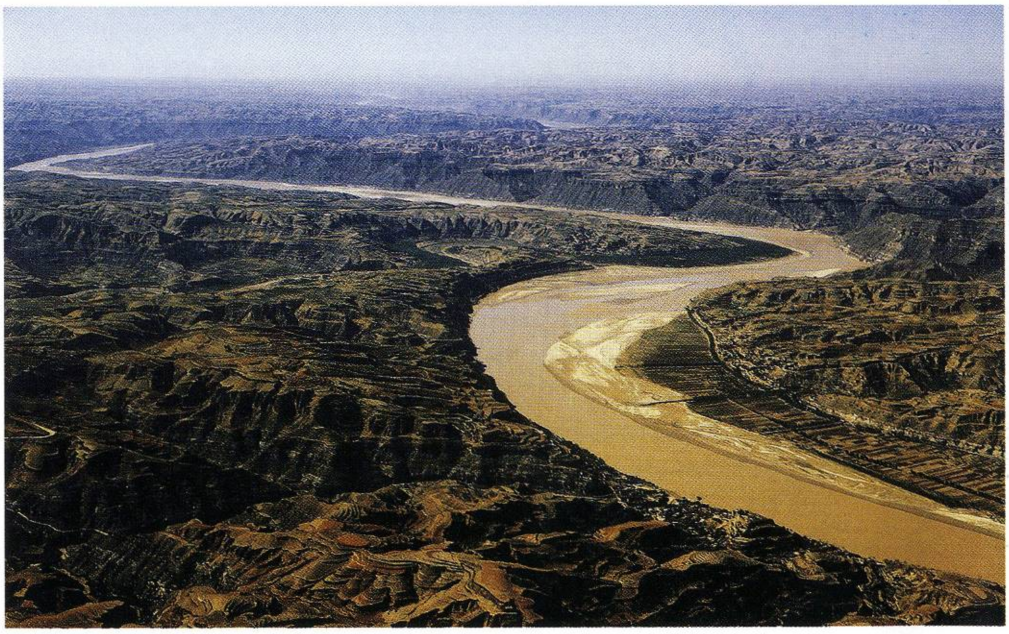

Photo 1-1 The Yellow River running through the Loess Plateau (photo by Yin Hexian)

1.1.2 Soil erosion and zoning of sediment yield

In generally, soil erosion in a watershed is related to the natural environment. The mainly soil erosion area of the Yellow River basin is located in the loess plateau. It belongs to monsoon climate region with density rainfall, which consequently made runoff uneven in the time. The loess plateau consists of loess flatriges, weirs, mounds, gullies and loess hilly, with the character of deep soil layer, loop structure, crashed topography, deficient vegetation, frequent rainstorm and severe soil erosion.

Sediment yield depends closely on different geographies in the Yellow River watershed. The soil and covers in various zones induced different sediment yield, and intensity of soil erosion. The sediment erosion modulus of the upper and middle reaches of the Yellow River can be mapped as Fig. 1-3 shown and the proportions accounts by different erosion grades showed in the Fig. 1-4.

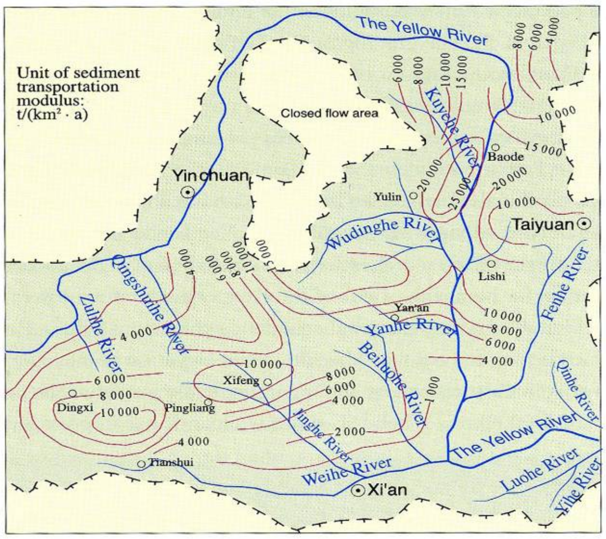

Fig. 1-3 Zoning of Sediment yield

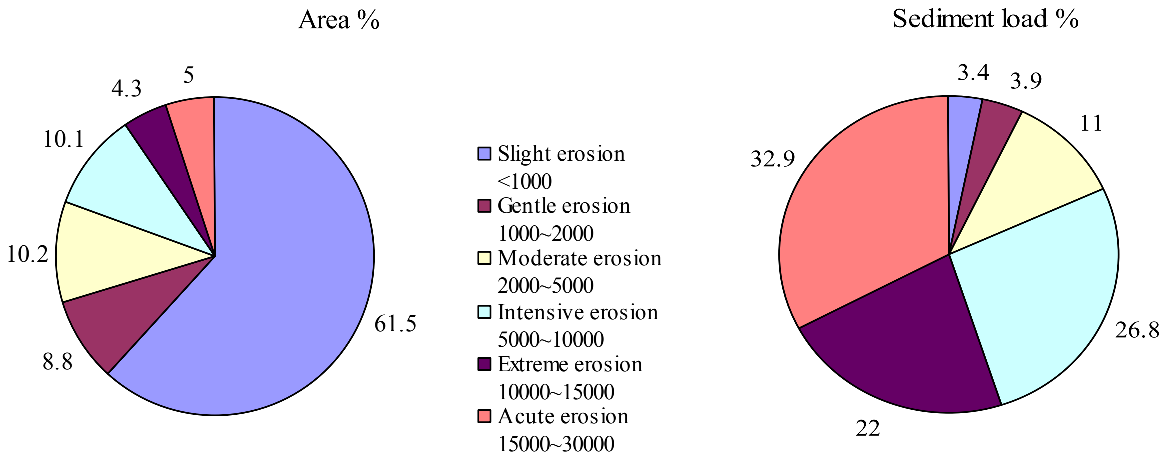

Fig. 1-4 The sediment erosion grades in the upper and middle reaches of the Yellow River

Note:1. Erosion zones classified by the traditional method, the Yellow River Conservancy Commission(YRCC);

2. Slightly deposition zone included by the Slight erosion zone;

3. data origin: from《the Yellow River atlas》(YRCC 1989/12) Calculated data up to 1986

The areas that the sediment yield modulus larger than 5000t/(km^2 • a) are 146×10^{3}km^{2}in sum, which only accounts for 19.4% of the whole basin area, while the sediment yield from these areas is 1.33 billion t accounting for 81.7% of the whole sediment load in the Yellow River, which titles the excessive sediment yield zones for this area.

1.1.3 Distribution of soil particle size

(1) Distribution of Particle Size

As above-mentioned, the sediment load carried by the Yellow River mainly roots in the loess region located in the middle reach catchment. In geography view, the new loess particle size distributes as wide straps. It becomes finer from northwest to southeast in this area (see Fig. 1-5), the loess size in northwest is larger than 0.045mm, and gradually going finer than 0.015mm. This rule can be proved in the distributaries in the middle reach. For example, the sediment size larger than 0.05mm accounts for 58% of the total sediment load in Huangpu river located in north area, while it only accounts for 31.1% and 13.3% in the Yanshui and Weihe river respectively located south area of middle Yellow River.

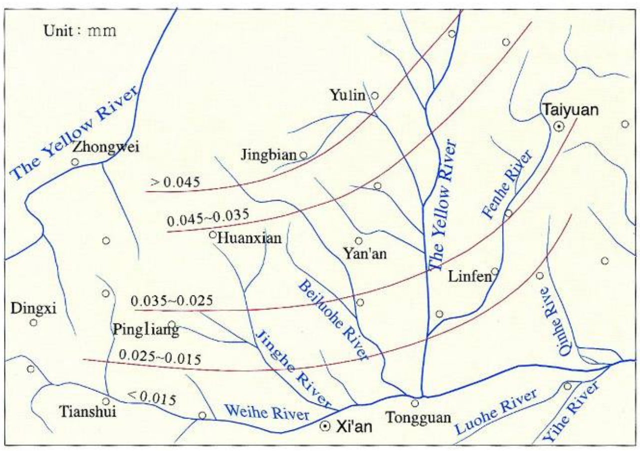

Fig. 1-5 The variation of new loess medium diameter in the middle Yellow River

(2) Zoning of Coarse Sediment

According to the statistics, the total sediment yielded and transported into the middle and lower reaches in forty years of 1950～1989 was 56.4 billion t. The total sediment load can be classified to 3 levels by particle sizes in 6 stream wise districts. As Fig. 1-6 shown, from upper reaches to the lower reaches, the sediment in the channel was becoming coarser. And the sediment with particle size lager than 0.05mm was really big contribute to the sediment components of in Sanmenxia reservoir and the lower reaches main channel.

According to many researches (Qian Ning, Gong Shiyang and Xiong Guishu), it was clear that the sediment, with d⩾0.05mm, was the biggest threat to the silting of Sanmenxia reservoir and the main river channel of the "perched river" in the lower Yellow River. So the sediment with d⩾0.05mm was named as the Coarse Sediment in the case of the Yellow River. Further more, the map of the coarse sediment laden area has been illustrated as the Fig. 1-7 shown.

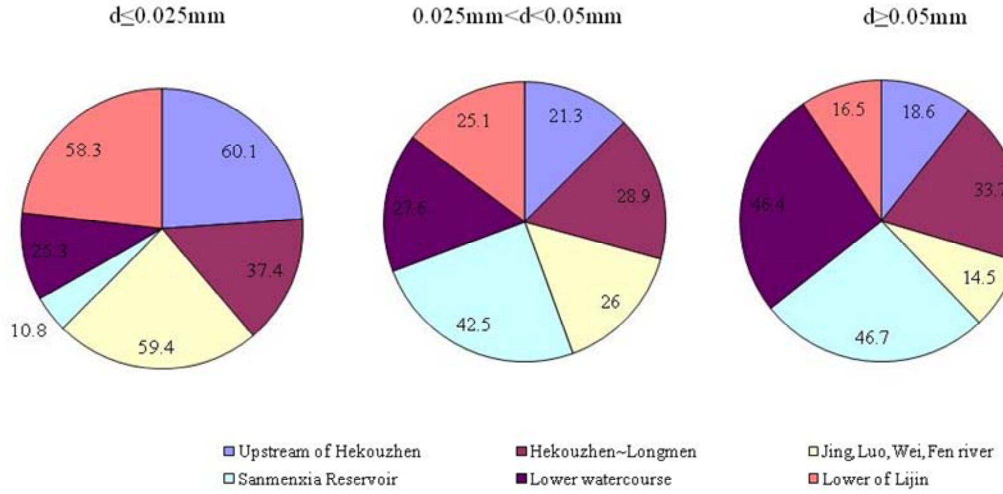

Fig. 1-6 Different sediment sizes change along the Yellow River in the year of 1950~1989

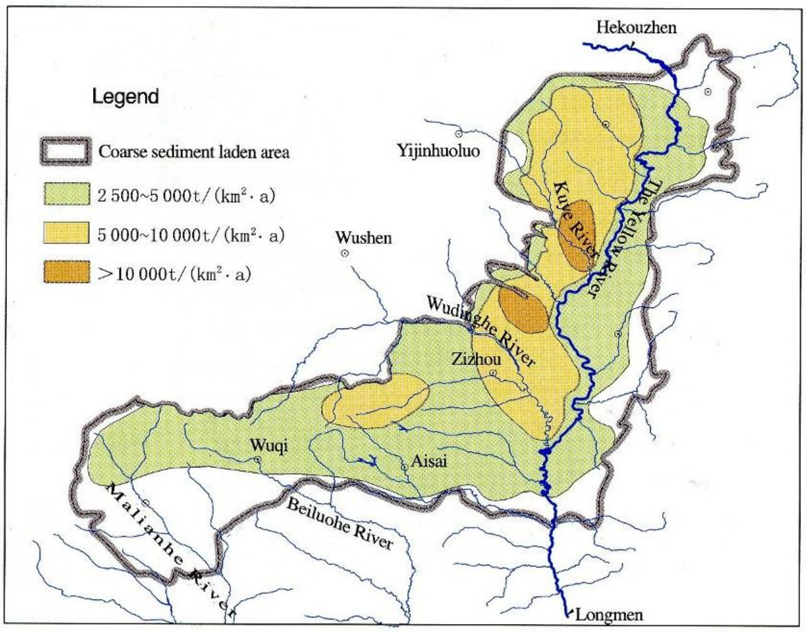

Fig. 1-7 Distribution areas of coarse sediments d>0.05mm in different erosion modulus (YRCC, 2004)

In summary, the sediment sources of the Yellow River can be zoned based on the morphology of upper and middle reaches watershed and the distribution of the Loess. By researches in recent years, the mean annual sediment yield modulus 5000t/(km^2 • a) can be used as a threshold to identify the excessive sediment yield zone or less sediment yield zone; and the mean annual coarse sediment yield modulus 1300t/(km^2 • a) being as a standard between the coarse sediment yield zone and the fine sediment yield zone.

1.2 Changes in Sediment Resources

1.2.1 The trend of the runoff and sediment load of the Yellow River

Though the statistics of runoff and sediment load from 1950~2009, the mean annual runoff in different decades at the main gauge stations along the Yellow River stem is showed in Fig. 1-8, so as the mean annual sediment load in Fig. 1-9. Both the runoff and sediment load have the decrease trend with the decades forward shown in the Fig. 1-10 illustrating by the Tongguan and Lijin station. For example, from 1952~1969, the mean annual runoff of Tongguan station located at the middle reaches, and the Lijin station, the last station of Yellow River stem were 44. 061 billion m^3 and 48. 907 billion m^3 respectively, while both decreased to 21. 043 billion m^3 and 14.094 billion m^3 in the years of 2000~2009. This decrease trend also was reflected in these two stations in the two periods from 1.602 billion t and 12.13 billion t decrease to 0.312 billion t and 0.134 billion t, respectively. It is also implied that the mean annual sediment load decreased sharper than the annual runoff.

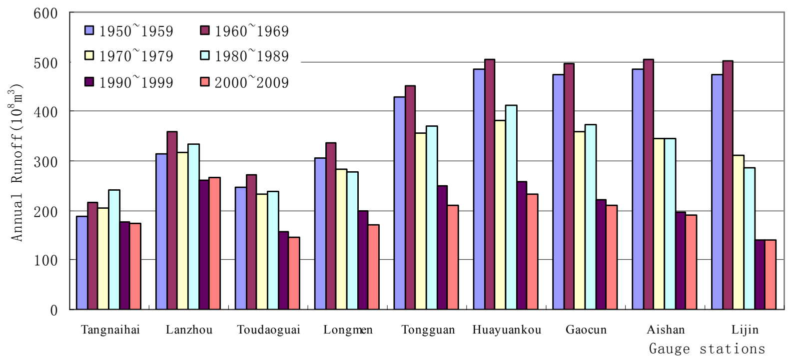

Fig. 1-8 the mean annual runoff in different decades at the main gauge stations along the Yellow River

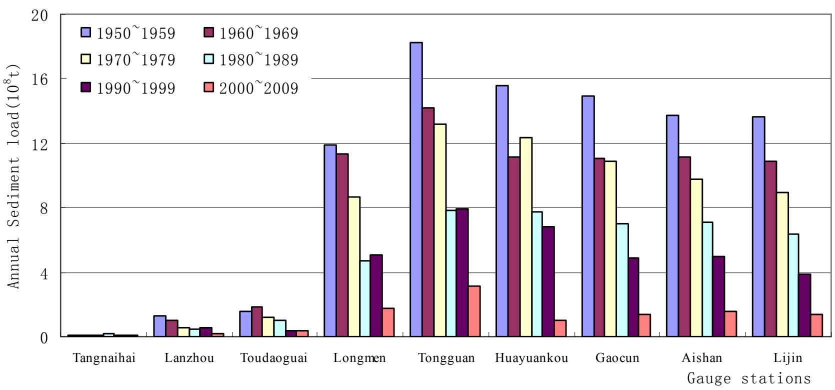

Fig. 1-9 the mean annual sediment load in different decades at the main gauge stations along the Yellow River

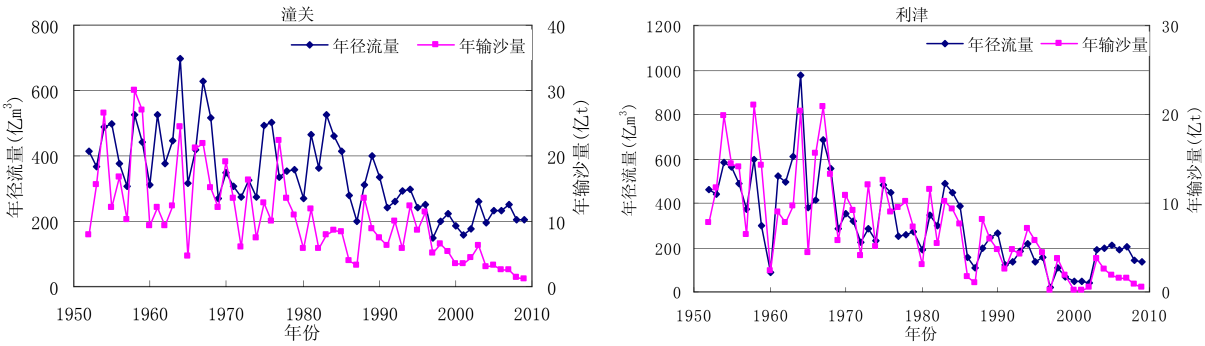

Fig. 1-10 the annual runoff and sediment load of Tongguan and Lijin stations

1.2.2 Sediment Transportation in the Yellow River

The Yellow River is a prominently heavy sediment laden stream in world. It has many abnormal features, such as insufficient water and excessive sediment; highly sediment content; different resources of runoff and sediment yield; runoff and sediment load both are uneven in space of basin and uneven from season to season around a year; multiform matching of discharge and sediment content etc. All the features make the sediment transportation in the Yellow River complexity and particularity.

Firstly, from above-mentioned analysis, the upper reaches of the Yellow River flows in gorge and plain linked reaches with sufficient runoff and deficient sediment load, and low sediment concentration (see Photo 1-2). Through the river auto-adjustment in the upper reaches, the sediment load nearly satisfied with the runoff and keeps in the balance of scouring and deposition.

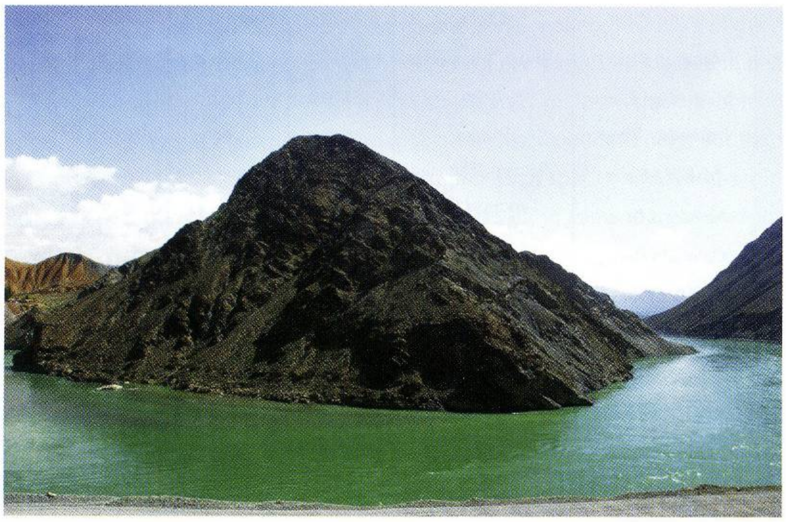

Photo 1-2 Laxiwa Gorge in the upper Yellow River (photo by Dong Baohua)

Secondly, owing to the high of the ratio of sediment yield and sediment delivery in the Loess plateau, the sediment carried by tributaries flow in the middle reaches flushed to stem of the Yellow River normally in the way of the high sediment content flow, sometimes even by the hyper-concentration flow (see Photo 1-3), and lead the Yellow River rank the highest sediment river in the word. While thanks to the gorge segment of Hekouzhen~Longmen (middle-upper reaches of the Yellow River) with steep slop, the sediment came from the tributaries mostly can be transported down, however was deposited in the Sanmenxia Reservoir, the first controlling project located in the middle-lower segment.

Photo 1-3 Wuding River, a tributary of the Yellow River, with a normal annual sediment content of 141kg/m^3 (photo by Chen Baosheng)

Thirdly, along the lower reach, both the runoff and sediment load are sharply decreased. Due to less runoff, more sediment, and the very gentle slop (1.2%% in average) of the lower reaches, the abundant sediment from the upper and middle reaches definitely silting down, which not only divagated several times of the lower Yellow River water way and created the China North alluvial plain in history, but also made the lower reaches “perched river” (see Photo 1-4).

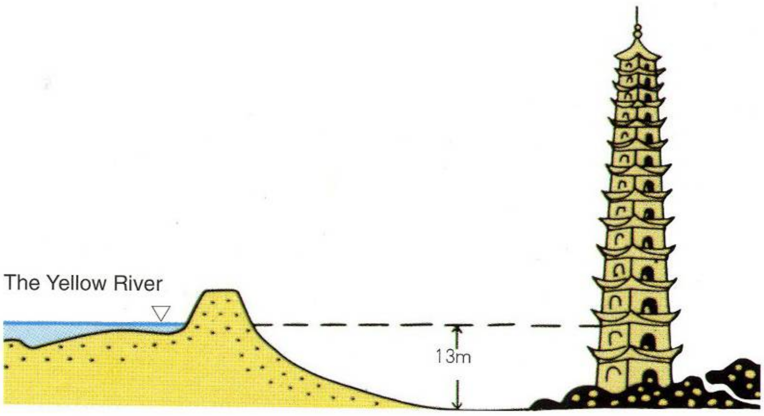

Photo 1-4 Sketch map of the perched river in lower reaches of the Yellow River

1.2.3 Sediment stagnations along the Yellow River

The main sediment stagnations styles in the Yellow River are water and soil conservation, the reservoir deposition, river bed aggradation and irrigation districts chocking up.

Soil and water conservation decreased the quantity of sediment flowing in the tributaries and trunk of the Yellow River, and stagnate the sediment in the watershed. The measures of soil and water conservation are gully control (see Photo 1-5), warping dams, retaining ponds and water-logging polls etc. thanks to the effort of soil control, the mean annual sediment load of the Yellow River has decreased by about 300 million t yearly since the 1970s.

Photo 1-5 Gully-control works in Loess Plateau (photo by Guo Zhi'an)

In the tributaries and trunk Yellow River, the 740 reservoirs have been constructed after the new China founding in 1949, with 54.3 billion m^3 of reservoirs capacity totally. While until 1990(some reservoirs until 1987), the total deposition in reservoirs was about 11.55 billion m^3, accounted the 21% of total reservoirs capacity. For example, the mean annual sediment load of Sanmenxia reservoir (see Photo 1-6) was1.6 billion t, however, there was 1.8 billion m^3 sedimentation for less 2 years operation, which accord for 20% of the total capacity, besides the sedimentation extended upward quickly. The deposition situation could not be alleviated until the project rebuilt two times and changed the operation style as impounding clear water and flushing muddy water.

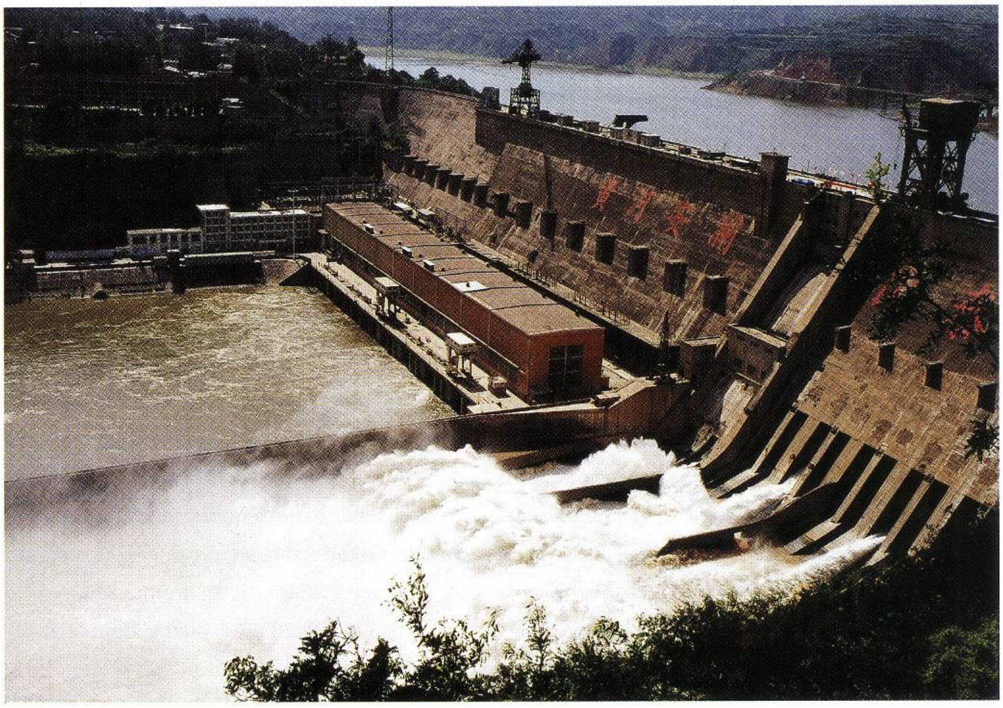

Photo 1-6 Sanmenxia multipurpose hydro-project (photo by Yu Feibiao)

The irrigation area besides the Yellow River basin has increased form 0.8 million hm^2 in 1950 to 61 million hm^2 currently (see Photo 1-7), and the mean annual sediment diversion is 0.171 billion t. Sediment diversion in upper Lanzhou reaches was the least one among the whole reach, because of little water diversion and lowly sediment load. While it was the most in the reach of Huayuankou-Lijin, which locates in the lower Yellow River, owing to more irrigation diversion and highly sediment load, and the mean annual sediment diversion of this reach accounted for 59.6% of the total. Owing to little irrigation diversion in Hekouzhen-Longmen and most diversion from tributaries of Longmen-Huayuankou in non-flood period, the mean annual sediment diversion only 0.0271 billion t which accounted for 15.8% of the total in middle reaches.

Photo 1-7 Bird view of Weishan irrigation district, the largest one of the middle and lower Yellow River

Sediment deposition in the Yellow River channel mainly occurs in the middle and lower reaches especially lower of Longmen station. Among that, Longmen-Tongguan (called mini-North Stem) reach, which admits the tributaries of Fenhe, Weihe and Beiluo rivers, also is conflux area with broadly flood plain and wandering and inconstant regime (see Photo 1-8). By glancing statistics, from 1950s to 1990, after the large scale reservoir constructed, the cumulative siltation was 2.1 billion m^3 in the mini-North Stem and 1.16 billion m^3 in the lower Weihe and Luohe branch of the middle reaches of the Yellow River. For the lower Yellow River, from Oct.1951 to Oct.2000, there was 5.441 billion m^3 siltation in the lower channel in accumulated, equal to 0.11 billon m^3 sediment aggradation yearly.

Photo 1-8 Meandering river in the lower Yellow River (photo by Hui Huaijie)

1.3 Utilization of Sediment Resources

1.3.1 Characteristics of the yellow river sediment

The sediment carried by the Yellow River flow is special and unique. Combining with the Yellow River situation, the sediment characteristics mainly are reflected on the sediment property, sediment yield and sediment transportation.

(1) Sediment physical property

Due to the earth surface erosion in the upper and middle catchment located in the loess plateau, the sediment load of the Yellow River is more nutrient and finer. That is 5000~11000t/(km^2.a) soil erosion in loess, it will lose nutrient more than 1600kg/(km^2.a), among that the organic accounts for 95%, the left 5% comprise some fertility like nitrogen, phosphor, and kalium etc. (based on the data from Suide soil and water conservancy, YRCC). In additional, as the lower Yellow River sediment particles as concerning, except the little coarse sediment, the most sediment is fine (particles diameter less than 0.05 mm accounts for more than 60%) which should increase the soil nutrient and develop the soil structure.

(2) Sediment yield characteristics

- ✓ Sediment yield centralized in space.

Although there are 752 thousand km^2area of the Yellow River basin and will yield 1.63 billon t sediment annually, while in that of 1.5 billon t comes from the same catchment of Hekouzhen-Longmen which only occupies 300 thousand km^2area. And 50% sediment comes from 51thousand km^2 area and 80% sediment comes from110 thousand km^2 area in Hekouzhen-Longmen catchment. Even the coarse sediment, which made most deposition and harmful to the lower reach, mainly comes from this region too.

- ✓ Sediment yield centralized in time.

Sediment load in the Yellow River mostly made by several flood years, while in these several flood years sediment yield mainly comes from only 5~10 days in one year. Based on the natural statistic from 1919 to 1959, the mean annual sediment load in Sanmenxia section was 1.6 billion t, in that 85% occurred in flood season, furthermore the sediment yield focused only on several floods period. In average speaking, the largest five days sediment yield approximately accounts for 19% of the annual sediment load in Sanmenxia gauging section, it even up to 42% and 72% regarding to the tributaries of Wuding River and Kuyie River respectively.

(3) Sediment transport features in lower reach

The rules of Sediment transportation in this reach are unique as following:

- ✓ The more the sediment load the more the sediment transport.

Based on the observed data of this reach, under the same discharge, when the upper high sediment-laden flow is coming, the competence of bed-material load transport is high accordingly, and the sediment load goes higher along this reach; contrarily, when the upper low sediment-laden flow is coming, the competence and the sediment load goes inverse. The differences of these two situations can reach to tens or hundreds times, even through several hundred kilometers adjustment, the flow still maintain this feature.

- ✓ Large discharge transports more, small discharge transports less; watercourse flow transports more, floodplain overflow transports less.

The competence of lower reach increases with the discharge increasing, that is “large discharge transports more, small discharge transports less”. But when overflowing, the more resistance in the flood plain decreases the overflow velocity, moreover, the main course flow velocity also decreased owing to the transverse exchange, so the sediment silts down at the flood plain. Therefore when discharge goes larger than bankfull discharge, the competence of river decrease instead. It should be point out that although the river load ratio is decreased when it overflowed, in generally speaking, it is beneficial to the flood control due to erosion in watercourse and deposition in flood plain, which will aggrandize the height difference of bottom and bank.

- ✓ Sediment transport more in flood season, less in dry season; and the finer the more, the coarser the less.

Before Sanmenxia reservoir construction, the incoming sediment in flood season accounts for 85% of the whole year annually in Lijin station of the lower Yellow River, and the sediment load is in the same proportion. The bed-material load only accounts for 61% of the total incoming sediment, while the wash load accounts for 89%. The runoff of this station in flood season is 1.8 times of that in dry season, but as sediment load as concerns, the ratio is up to 5.7 of different seasons. When Sanmenxia reservoir built up, the lower Yellow River still follow these basic sediment transport rules, and some new features of sediment discharge appeared owing to different operation styles.

In summary, the prominent issues of the Yellow River are less runoff, more sediment and the great aggradation in the lower reaches. On the one side, the sediment issues on projection and environment is so harmful that it does impress on the harness of the Yellow River. On the other side, sediment can be looked as valuable resources. Depending on the soil types and flood control conditions, combining with the sediment features of the Yellow River, the channel deposition can be alleviated by the sediment rational utilities, which change the excessive useless sediment to helpful resources.

1.3.2 The feasibility of sediment resources utilization

In despite of the sediment disaster was always reminded whenever mentioned the Yellow River, it should be restated that sediment is one of natural resources (WANG Yangui). Sediment is absolutely endowed with the natural resources basic properties: the first property is resources validity, meaning of which is good for the society and economy development and environment protection; the second property is resources reconcilability, meaning of which could be assigned or allocated by artificial tools or ways; the third and last property is resources finiteness, meaning of which is the finite in quantity and could be exhausted.

The sediment about the Yellow River is implicated disaster cause of it excessive in amount, while it is definitely endowed with natural resources property. Under the condition of high technology and economic develop support, the redundant sediment in the Yellow River could be change to basic material and to be utilized, which will contribute to produce more social and economic efficiency.

1.3.3 The goal of sediment resources utilization

The goal of sediment resources utilization is, considering of the sediment utility benefits both in current and in the future, considering of the benefits both in different regions and in different trades, considering of sediment utility benefits among social, economy and environment, and also considering of all benefits distribute in all different aspects, to maximize the benefits of sediment utilization and sediment allocation.

In a river basin, through projects construction or non-project management, the sediment, as a kind of natural resources, is allocated reasonably under the given goal to maximize the benefits of the local environment, economy and society, and corresponding to minimize the loss caused by redundant sediment.

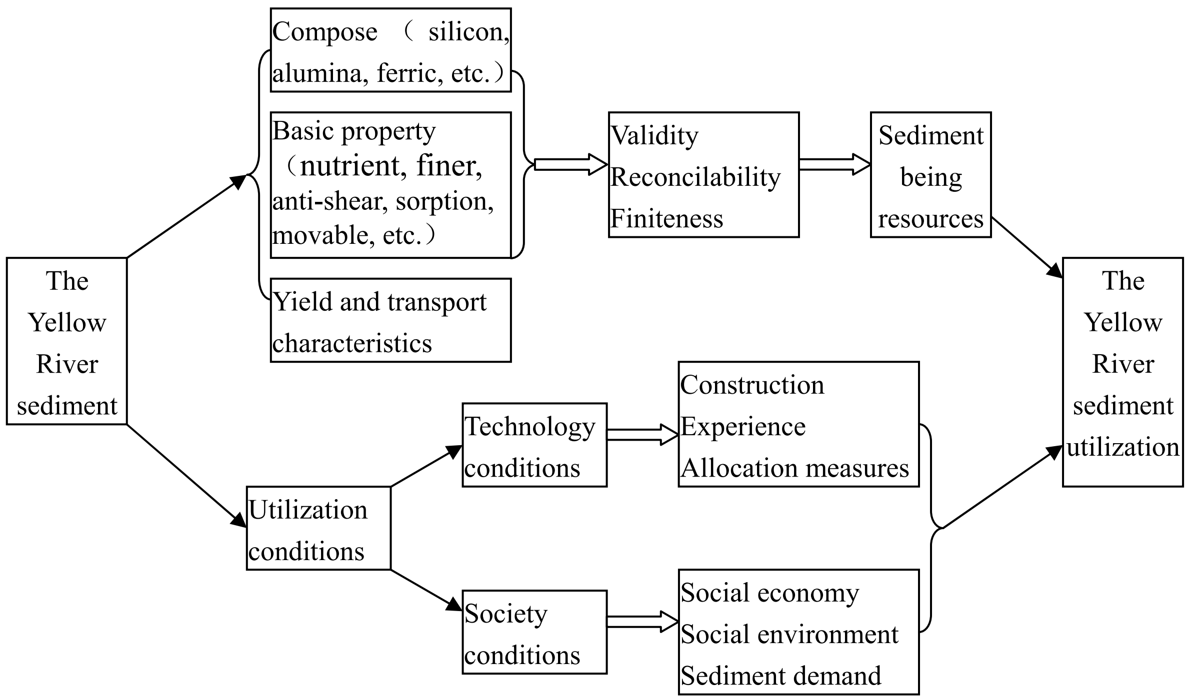

Fig. 1-11 The processes of the Yellow River sediment change to resources

1.3.4 The types of sediment resources utilization

Although the sediment disaster is always very serious in the Yellow River basin, sediment utilization has been developed for a long time. Nowadays, the main types of sediment utility are farmland formation and new continent creation, warping for irrigation, warping for consolidating levees, production constructing martial and wetlands figuration etc.

(1) Farmland formation and new continent creation

Before the human being appearance, sediment had been piled up and made huge area of land under the nature force. The erosion soil or sediment in the high area flow down to the depression area and deposited, to format large scale farmland for agriculture. This process is still going on, such as the eroded soil in the upper and middle Yellow River basin, after conveyed by river flow and depositing, had formatted the Hetao Plain, Fenwei Plain and Huabei Plain. All of these alluvial plains have been the main farmland of local area.

Besides, the huge Yellow River sediment flux still creates the new continent at the speed of 23km^2 annually in the Yellow River mouth. From the last prominent avulsions of 1855 then on, the area of the Yellow River mouth has reached to 2200km^2. Taking advantage of the excessive sediment from the Yellow River, the new continent built up, and agriculture, oil land, fishery and modern cities developed. And it is an economic way to take advantage of sedimentation to fill offshore oil field and change the offshore operation to land extraction, which has been implemented in Shengli oil field, the one of famous oil field in China.

(2) Warping for irrigation

The component of the Yellow River sediment is consistent with its basin erosion soil with rich fertility, especially in flood seasons. For example, the lost soil from Loess plateau contains nitrogen0.8～1.5kg, phosphor1.5 kg and kalium 20 kg, and could be used as a soil improvement material, by taking the inherent property of the Yellow River sediment in account. The main measures of warping to ameliorate the soil structure are warping for soil melioration, warping for paddy planting and sediment-laden flows irrigation.

It is statistics that until 1990, the 2300 km^2 farmland had been ameliorated by warping and more than 1200 km^2 paddy field had been developed. Additionally, the sediment-laden flow in flood season is widely used in irrigation districts along the Lower Yellow River area. It is not only to alleviate the local drought, but also fertilized the crop soil.

(3) Warping for consolidating levees

Warping for consolidating levees not only widens and heightens the levees, made it restrained from piping, seeping and collapsed, but also holds up some sediment from the stem river, alleviating the burden of the lower channel deposition which will improve the situation of flood control, and achieve the purpose of “relative normal river”. Considering the different tools, the warping for consolidating the levees have different operations, such as by gravity, by pumping, or combined with dredging by unloading suction barge. Warping for consolidating levees by pumping begun at 1960’s, while warping combined with the channel excavation started from the 1990’s last century, and become one of the important measures.

It is statistics that until 1994, 400 million m^3 sediment had been dredged up from the Lower Yellow River stem cumulatively, and the yearly most amount excavation was 20 million m^3.

(4) Changes of building material from sediment

In history, the ancient people had found the way to fire the dredged sediment to the building material. The Yellow River sediment, due to the fine particles, is difficult to be use as building material directly instead of changing to building material indirectly. Currently, some successful experiences of changing the Yellow River sediment into building material have been achieved, for example, the sediment mixes with a certain ratio cement and press to building brick in Liuzhuang irrigation district.

(5) Wetlands figuration

Wetlands are unique ecosystems, with the multi-functions of flood control, runoff adjustment, climate improvement, pollutants assimilation, biodiversity maintenanceetc. Wetlands are regarded as the “kidney of global”, which play important roles in keeping the balance of nature ecology. The wetland is one of the highest productive and most biodiversity environmental systems.

Sedimentation builds new continent and inevitably derives new wetland. The forming and vanishing of coastal wetlands are related closely in sedimentation. At estuary, the sediment carried by the river runoff will be suspended by tidal wave and re-deposit along coastwise by diffusion effect, and finally forms new wetlands periodically submerged by tidal waves. Thanks to abundant incoming sediment load deposited in the Yellow River estuary, the YRD is one of the quickest continent-building deltas. The continually increasing new land supplies a wide space for wetlands development.

The nature preserve of the YRD is located at the new continent-building belt near the both sides of the Yellow River mouth, with the total area of 153,000 ha. It is one of the thirteen priority preserved wetlands zone appraised by the United Nations Environment Programme [UNEP], it also was approved as the State Nature Preserve by the State Council of China in 1997 for protecting the wetland ecosystem of newly-formed land, rare and imminent-endangered birds. There are 393 vegetable planting and 1542 wildlife inhabiting in the China newest, widest and youngest wetland ecosystem zone.

For the sake of controlling the Yellow River, the sediment must be utilized, whether the Yellow River controlling successfully or not decided by the sediment treating well or not. The warping has so many virtues (more sediment diversion and widely distribution, warping time limited, simple projects demand, diversion dam available and economic investment etc.) that it is widely used in both sides of the lower Yellow River basin.

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2. Sediment utilization in the main channel of the Lower Yellow River

2.1 Features of the main channel formation

The Lower Yellow River is from Tiexie to Lijin, with a total length of 800km and an area of about 4000km^2 (Fig. 2-1.), belonging to an alluvial channel. The Lower Yellow River can be classified as three river channel patterns, i.e, the wandering reach from Tiexie to Gaocun, with a width-depth ratio ($\sqrt{B}/H$) of 20 to 40, where B is the channel width corresponding to the bankful discharge, and H is the mean water depth corresponding to the channel width; the transitional reach from Gaocun to Taochengbu, with a width-depth ratio of 8.6 to 12.4; and the meandering reach from Taochengbu to Lijin, with a width-depth ratio of 2 to 6。

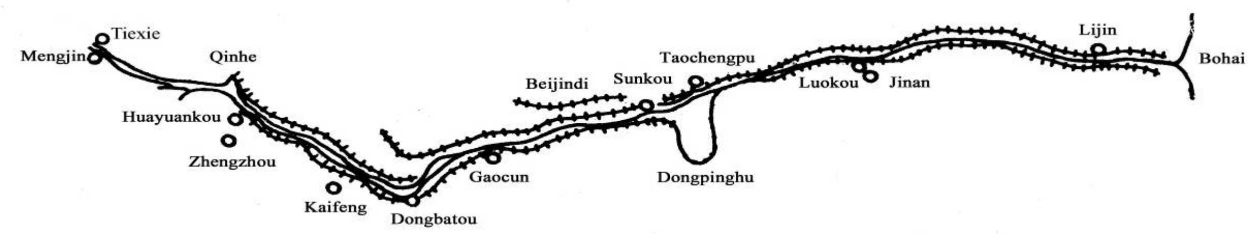

Fig. 2-1 Plan view of Lower Yellow River

2.1.1 Longitudinal Profile of the Lower Yellow River

The longtitudinal profile of the Lower Yellow River is a concave downward curve, as shown in Fig. 2-2. Since the longitudinal distribution of deposition was uneven, being small at both ends of the reach and large in the middle reach after 1955, the downward degrees of longtitudinal profile reduced gradually, the slope difference between reaches reduced slowly. The channel slope decreased gradually from upstream to downstream as shown in Table 2-1.

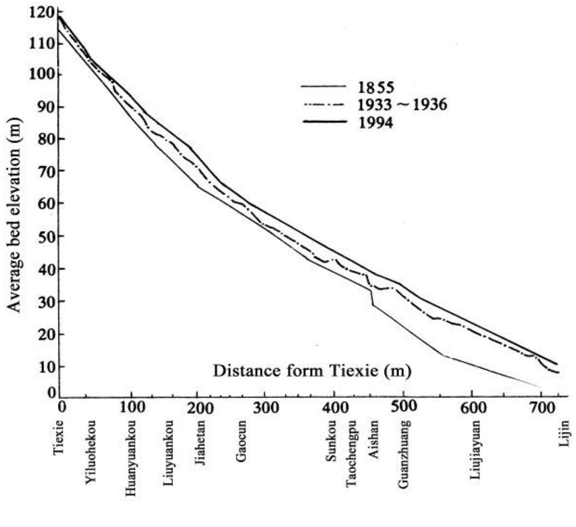

Fig. 2-2 The longitudinal profile of the Lower Yellow River

Table 2-2 lists the channel rising and rising rate during 1960~1999 at main stations in the Lower Yellow River. Table 2-3. shows that rise of water levels and rise rate of water levels in the Lower Yellow River decreased after 1986. In the first period, the rise of water levels above Aishan are larger than 2 m, and the annual average rise of water level at Gaocun and Sunkou stations are 0.259/a m and 0.268 m/a. In the second period, the rise of water levels are also larger than 2 m at stations between Gaocun and Sunkou, and the biggest annual average rise of water level occurred at Sunkou station, which is 0.141m/a.

Table 2-1 Changes in longitudinal profile of the Lower Yellow River (‱)

Reach \ Time	1953	1960	1964	1973	1976	1986
Mengjin~ Huayuankou	2.691	2.728	2.581	2.491	2.480	2.493
Huayuankou~ Jiahetan	1.823	1.856	1.780	1.874	1.836	1.835
Jiahetan~ Gaocun	1.572	1.453	1.499	1.498	1.482	1.453
Gaocun~ Sunkou	1.143	1.454	1.138	1.138	1.137	1.161
Sunkou~ Aishan	1.122	1.385	1.244	1.179	1.156	1.166
Aishan~ Luokou	1.022	1.059	1.030	0.975	0.994	0.995
Luokou~ Lijin	0.879	0.895	0.838	0.915	0.887	0.930

Table 2-2 Channel rising and rising rate during 1960~1999 at main stations in the Lower Yellow River (Unit: m)

Items \ Stations	Huayuankou	Jiahetan	Gaocun	Sunkou	Aishan	Luokou	Lijin
Distance from Tiexie(km)	132	230	309	430	490	592	764
Channel rising(m)	1.10	0.44	1.38	2.15	1.39	3.53	3.33
Channel rising rate(m/a)	0.0282	0.0113	0.0354	0.0550	0.0355	0.0905	0.0853

Table 2-3 Changes of water levels at 3000m^3/s at stations in the Lower Yellow River

Station	Period	Rise of level(m)	Annual average rise of level(m/a)
Huayuankou	1962~1973	2.12	0.193
	1986~1998	1.6	0.133
Gaocun	1964~1974	2.59	0.259
	1984~2002	2.25	0.125
Sunkou	19671975	2.14	0.268
	1986~2002	2.25	0.141
Aishan	1963~1975	2.55	0.213
	1984~2002	2.35	0.131
Luokou	1964~1975	3.03	0.275
	1984~2002	2.30	0.128
Lijin	1964~1975	1.98	0.180
	1984~1996	0.71	0.059

2.1.2 Cross-section of the Lower Yellow River

The condition of inflow water and sediment load determines the form and extent of adjustment of cross sections, and the boundary condition influences the variation scope of river morphology and cross sections.

(1) Cross-sections in the wandering reach above Gaocun

The reach of Tiexie to Gaocun, with a length of 283km and a distance of 4.1km to 20km between levees，has wide and shallow channel cross-sections, and its channel width is commonly 1.5 to 3.5km，somewhere over 4km. Photo 2-1 shows wide and shallow channel of the Lower Yellow River. The elevation difference between floodplain and channel is less than 2m, exceptionally less than 1m, the water depth is very small, and the morphology relationship $\sqrt{B}/H$ at bankfull discharge is 20 to 40 . The reach of Tiexie to Gaocun is relatively straight as a whole, with an average sinuous ratio about 1.15. The location of the main flow is extremely unstable, and the annual average transverse shifting amplitude of main current was from 206 to 1242m in the years of 1955 to 1994.

Photo 2-1 The wide and shallow channel of the Lower Yellow River

(2) Cross-sections in the transitional reach of Gaocun to Taochengbu

The reach of Gaocun to Taochengbu has a length of 165km and a distance of 1.4km to 8.5km between levees, and a main channel width of 0.5km to 1.6km. The morphology relationship $\sqrt{B}/H$ at the bankful discharge is commonly 8.6 to 12.4. The elevation difference between the floodplain and channel increases gradually along the river course, 3.5 to 4 m at the cross-section Sunkou.The reach has an average sinuousity ratio of 1.33. Through regulation in the years 1966 to 1974, the river regime has basically been controlled, and the condition of frequent changes in main current has been changed. The average shifting amplitudes of main current in the reach decreased to 160m in the years of 1975~1990.

(3) Cross-sections in the Meandering Reach of Taochengbu to Lijin

Cross-sections of meandering reach of Taochengbu to Lijin are still mainly composed of a main channel and floodplains, i.e., compound cross-sections. The meandering reach has a distance of 0.4 to 5.0 km between levees, a main channel width of 0.3 to 1.5km, and a floodplain width of 0.4km to 3.7km. The floodplain width in the reach is much smaller than that in the wandering reach and in the transitional reach. The elevation difference between the floodplain and channel is around 5 to 6m. The morphology relationship $\sqrt{B}/H$ at the bankful discharge is commonly 2 to 6. The channel in the reach is relatively stable, and its shifting amplitude is small. The channel sinuous ratio is only 1.21. Changes in cross-section give priority to longitudinal variation in the reach.

2.1.3 Distribution of scouring and silting in the Lower Yellow River

a. Channel fluvial processes of the Lower Yellow River

(a) Channel fluvial processes of the Lower Yellow River under natural condition

For the years 1950 to 1960, the river channel was in a natural state, with an average annual runoff of 48 billion m3，an average annual sediment load of 1.795 billion ton, and an average sediment concentration of 37.4kg/m3. Sixth times of large overbank floods with a discharge larger than 10000 m3/s occurred at Huayuankou gauging station. During this ten years, 3.61 billion tons of sediment was silted in the Lower Yellow River, of which 2.79 billion ton on the floodplain, accounting for 77.3％of the total sedimentation, 0.82 billion ton on the main channel, accounting for 22.7％of the total sedimentation. Deposition in the reach of Jiahetan to Aishan accounted for 54.6％of the total sedimentation in the Lower Yellow River, 33％ in the reach of Tiexie to Jiahetan, and only 12.4％in the reach of Aishan to Lijin.

For the wandering reach from Tiexie to Gaocun, the floodplain was deposited and the channel was scoured, the river channel became narrower and deeper during the big flow, and the river channel became wider and shallower during the low flow. The variation of channel geography was most acute during the falling period of flood peak. For the transitional reach from Gaocun to Taochengbu, there existed a smaller and slower channel shifting than the wandering reach, and only one or two channel bend shifted remarkably. For the meandering reach from Taochengbu to Lijin, there existed no big change in channel geography, and the flow attack apexes lifted up and moved down.

(b) Channel fluvial processes of the Lower Yellow River during the sediment detention period of Sanmenxia Project from Oct.1960 to Oct.1964

For the sediment detention period of Sanmenxia Project from Oct.1960 to Oct.1964, a small amount of sediment was released by the Sanmenxia Reservoir, and the river channel was eroded. The average annual amount of inflow water in the period was 57.3 billion m3, the average annual amount of inflow sediment load was 0.603 billion ton, and the annual average sediment concentration was 10.5 kg/m3. Due to almost no occurrence of overbank flows, the floodplain collapsed, the collapsed floodplain area in the reach of Tiexie to Aishan was about 330km2，and the amount of erosion was about 0.8 billion ton. During this period, the total amount of erosion in the Lower Yellow River amounted to 2.3 billion ton, of which 58.3％ in the reach upstream of Jiahetan, 32％ in the reach of Jiahetan to Sunkou, 5.4％ in the reach of Aishan to Lijin. The longitudinal profile of the Lower Yellow River was flattened by erosion, and the longitudinal slope upstream of Huayuankou maximally reduced by 5.4％.

During this period, for the wandering reach from Tiexie to Gaocun, cross sections was mainly scoured and the current was smooth, currents of some sections even became more scattered. The reach below the Gaocun was scoured and kept single and smooth current with narrow and deep cross sections.

(c) Channel fluvial processes of the Lower Yellow River during flood detention and discharging sediment of Sanmenxia Project from Oct.1964 to Oct.1973

In the period of flood detention and discharging sediment of Sanmenxia Project from Oct.1964 to Oct.1973, a lot of sediment was released from the reservoir. The average amount of water inflow was 42.6 billion m3, the amount of sediment inflow was 1.63 billion ton, and the annual average sediment concentration was 38.3kg/m3, which belongs to a medium flow and high sediment. The Lower Yellow River was seriously deposited, and the total deposition reached 3.7 billion ton. The amount of deposition on the floodplain accounted for 33％ of the total, 67％ on the main channel. Deposition proportion in the reach upstream of Jiahetan increased to 46.3％ of the total deposition, 15.5％in the reach of Aishan to Lijin, and decreased to 38.2％ in the reach of Jiahetan to Aishan. Due to serious deposition, the water stage at discharge of 3000m3/s at each station along the river course rose remarkably. Due to the operation rule of flood detention and discharging sediment of Sanmenxia Project as well as the effect of production dikes, a perched river that the elevation of channel bed is higher than that of the floodplain outside production dikes has been formed between levees, being called a secondary perched river, as shown in Photo.2.2 and Photo.2.3.

Photo 2-2 The left bank of the perched Lower Yellow River

Photo 2-3 The right bank of the perched Lower Yellow River

During this period, due to serious deposition in the main channel, the bed elevation between the floodplain and the main channel reduced, the channel became wider and shallower and more scattered, and the main current shifted frequently. For the reach from Tiexie to Gaocun, the average shifting amplitude was 3360m, greater than that in the years of 1950 to 1959. For the reach from Gaocun to Taochengbu , despite many regulation works constructed after 1964, the average shifting amplitude reached over 1000m, greater than that during the sediment detention period. For the reach from Gaocun to Taochengbu, due to good control of the two banks, the main current was relatively stable.

(d) Channel fluvial processes of the Lower Yellow River during storing clear water and releasing muddy flow of Sanmenxia Project from Oct.1973 to Oct.1999

For the operation mode of storing clear water and releasing muddy flow of Sanmenxia Project from Oct.1973 to Oct.1980, discharges larger than 5000m3/s was whittling down, sediment was discharged in flood seasons and nearly clear water was released in non-flood seasons. The annual average runoff was 39.5 billion m3， the annual average sediment load was 12.4 billion ton， and the annual average sediment concentration was 31.3kg/m3. The annual average deposition in the Lower Yellow River was 0.181 billion ton, most of which took place on the floodplain, even a small amount of scour in the main channel upstream of Huayuankou. The longitudinal slope in 1976 changed little.

From Oct.1981 to Oct.1985, the water inflow was high and sediment inflow was low, the duration of medium flow discharge was long, a peak discharge of 15300m3/s occurred at Huayuankou gauging station in August 1982. The amount of erosion in the river channel amounted to 0.485 billion ton. The stage fall at discharge of 3000m3/s in the reach of Tiexie to Yangji was about 0.5m, 0.3m in the reach of Sunkou to Aishan, 0.4 to 0.5m in the reach of Guanzhuang to Liujiayuan, 0.7 to 0.8m downstream of Zhangxiaotang owing to the influence of retrogressive erosion of the river mouth. The longitudinal slope in 1986 changed little compared with that in 1976. The channel width and flow area of the Lower Yellow River in 1985 increased remarkably compared with that in 1981, among which 42％ and 78％ increase in the reach from Tiexie to Huayuankou respectively, 40％ and 75％ increase in the reach from Jiahetan to Gaocun, as shown in Table 2-4.

Table 2-4 Variation of cross section in the Lower Yellow River

Reach	Main channel width/m			Flow area of main channel /m^2		
	1980	1985	1997	1980	1985	1997
Tiexie~Huayuankou	1115	1586	921	1529	2717	1937
Huayuankou ~Jiahetan	1238	1432	923	1491	2449	1408
Jiahetan~Gaocun	860	1208	727	1404	2453	1190
Gaocun ~Aishan	750	879	695	1695	2860	1336

From Oct.1986 to Oct.1999, the water and sediment inflows of the Yellow River were continuously low. The average annual runoff was 30.9 billion m^3， the average annual sediment load was 0.762 billion ton, the average sediment concentration was 24.2kg/m^3. The annual average deposition in the river channel was 0.223 billion ton, which mainly concentrated in the upper reach, the amount of deposition in the reach of Tiexie to Jiahetan amounted to 58％ of the total deposition, and 16.6％ in the reach of Aishan to Lijin. The water stage at discharge of 3000m^3/s had an annual rise of 0.11m at Huayuankou gauging station, 0.13 to 0.15m in the reach from Jiahetan to Liujiayuan, 0.15 to 0.18m downstream of Zhangxiaotang. The amount of deposition in the main channel was 0.161 billion ton, accounting for 72％ of the total deposition, which was 2 times of that in mid-1950's.

Since 1986, the channel shrank, and the channel width and flow area of the Lower Yellow River decreased remarkably due to continuous low water and low sediment load. The channel width reduced 42％ in the reach from Tiexie to Huayuankou and 40％ in the reach from Jiahetan to Gaocun, and the reduction of flow area reached 51％ in the reach from Jiahetan to Gaocun and 53％ in the reach from Gaocun to Sunkou. Since 1986 the shifting amplitude of the main current reduced, the number of branches and centre bars decreased, and the degree of sinuosity and the number of bends increased.

(e) Channel fluvial processes of the Lower Yellow River after the commisioning of Xiaolangdi Project

Experiments of regulating water flow and sediment load and its applications have been successfully carried out seven times since the Xiaolangdi Project started to impound water on 28 Oct.1999. Photo.2.4 and Photo.2.5 show the scene of Regulation of water flow and sediment load at the Xiaolangdi Project.

Photo 2-4 Regulation of water flow and sediment load at the Xiaolangdi Project

Photo 2-5 Releasing water flow and sediment from the the Xiaolangdi Project

According to measured data from 2000～2006, as shown in Table 2-5, the total amount of erosion in the Lower Yellow River was 0.8895 billion m^3, among which the amount of erosion in flood season accounted for 67%. Scour and deposition mainly occurred in the channel, except in 2002. The erosion distribution along the channel was uneven, big in the two ends and small in the middle. The total amount of erosion in the reach above Gaocun accounted for 78%, 9% in the reach from Luokou to Lijin, 3%～4% in the reach from Sunkou to Luokou. The average erosion amount per unit length during 2000-2009, as shown in Fig. 2-3, was 0.353 million m^3 in the wandering reach from Xiaolangdi to Gaocun, 0.108 million m3 in the transitional reach from Gaocun to Aishan, 0.079 million m^3 in the meandering reach from Aishan to Lijin, which reveals that the impact of the Xiaolangdi Project on the Lower Yellow River gradually weakens as the distance from the Xiaolangdi Project increases.

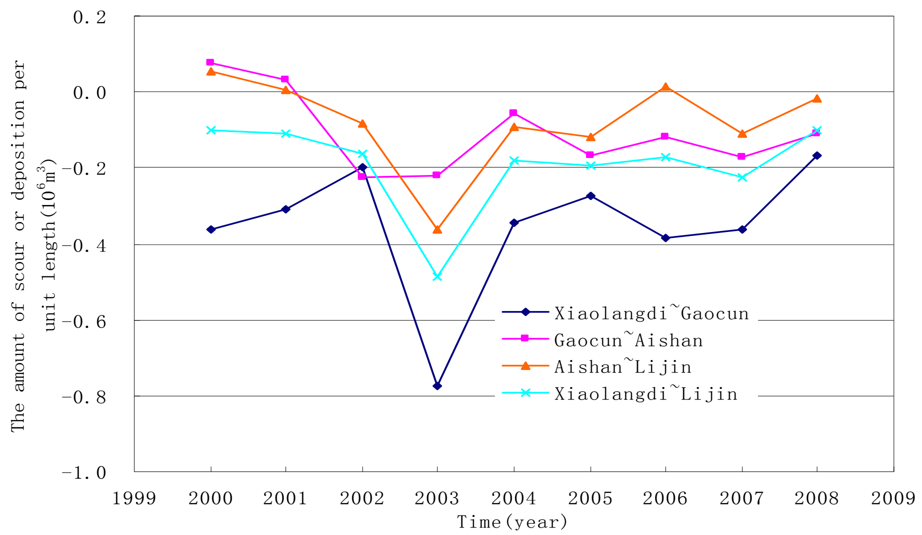

Fig. 2-3 Change in the amount of erosion or deposition per unit length in Lower Yellow River

Table 2-5 The amount of erosion or deposition in the Lower Yellow River from 2000～2006

Reach / Time	Baihe~Gaocun	Gaocun~Aishan	Aishan~Lijin	Baihe~Lijin
2000	-0.104	0.0139	0.0148	-0.0753
2001	-0.0888	0.0054	0.0018	-0.0816
2002	-0.0568	0.0045	-0.0225	-0.0748
2003	-0.1665	-0.0408	-0.0547	-0.262
2004	-0.0859	-0.0094	-0.0235	-0.1188
2005	-0.0772	-0.0322	-0.0358	-0.1452
2006	-0.114	-0.0215	0.0036	-0.1319
Total in non-flood season	-0.3478	-0.0066	0.0641	-0.2903
Total in flood season	-0.3453	-0.0736	-0.1805	-0.5994
Total	-0.6932	-0.0801	-0.1163	-0.8896

The longitudinal profile and cross section of the Lower Yellow River changed after the commissioning of the Xiaolangdi Project. Cross sections in the reach above Gaocun were both widened and incised, and mainly incised in the reach below Gaocun. The increase in width above Jiahetan reached 420～450m. The average incision depth above Huayuankou was 1.49m, and only 1.05m between Sunkou to Aishan, as shown in Table 2-6. The width-depth ratio $\sqrt{B}/H$ of the entire Lower Yellow River decreased in 2006 compared to that in 1999, which shows that the cross section of the Lower Yellow River was improved after the commissioning of the Xiaolangdi Project.

Table 2-6 Variation of cross section in the Lower Yellow River after the commisioning of Xiaolangdi Project

Reach	Channel width in Oct.1999 (m)	Channel width in Oct.2006 (m)	Variation of channel width (m)	Thicknesses of scour & siltation (m)	$\sqrt{B}/H$ (in Oct.1999)	$\sqrt{B}/H$ (in Oct.2006)
Baihe~ Huayuankou	1040	1492	452	-1.49	17.9	12
Huayuankou ~ Jiahetan	1072	1494	422	-1.32	24.5	19.8
Jiahetan~Gaocun	725	773	48	-1.17	15.6	10.8
Gaocun~Sunkou	518	527	9	-1.33	12.1	8.1
Sunkou~ Aishan	505	497	-8	-1.05	8.8	6.3
Aishan ~ Luokou	446	429	-17	-1.33	6.0	4.2
Luokou ~ Lijin	405	410	5	-1.18	6.5	5.3

b. Distribution of Scouring and Silting

The longitudinal distribution of scouring and silting in the river channel is extremely uneven and changed during different periods, and the transversal distribution of scouring and silting is also uneven in the Lower Yellow River. For the years of July.1950 to Oct.1993, the amount of scouring and silting in the main channel amounted to 54% of the total deposition, and 46% on the floodplain. After 1985, the deposition in the main channel was serious and the deposition proportion in the main channel increased remarkably, as shown in Photo 2-6.

Photo 2-6 Sediment deposition in the Lower Yellow River near Aishan

In the 1950's, the river channel was in deposition during flood seasons and non-flood seasons, after operation of Sanmenxia Reservoir, the river channel as a whole was still silted in flood seasons, while in non-flood seasons the river channel turned to be eroded. Compared with 1950's, the river channel turned to be soured in non-flood seasons after the commissioning of Sanmenxia Reservoir, due to change in the annual distribution of water and sediment . The percentage of water amount in the flood season decreased from 61.6% to 55.9%, in the non-flood seasons, it increased from 38.4% to 44.1%, and the percentage of sediment inflow reduced from 14.5% to 12.6%.

2.1.4 Channel shrinkage and reduction in flood carrying capacity

The Lower Yellow River kept silting and withering continuously, thus the medium-flow channel has been narrowed seriously. Since 1980's, owing to long-term effect of small discharge and much lower appearing frequency of effective bed-forming discharge, the channel width of medium flow reduced to less than 2km in 1996, which was only 40% to 70% of that in 1950's.

Sedimentation and shrinkage of the channel resulted in continuous reduction in bankful discharge. As the main channel of the Lower Yellow River shrinked, the bankful discharge decreased from 6000～8000m^3/s in the 1950s to 3000～4000m^3/s in 2000, it was even less than 2000m^3/s in some reach.

Sedimentation and shrinkage of the river channel and a sharp reduction in bankful discharges aroused a sharp decrease in flow capacity, severely impacted flood discharging capacity, and caused the condition that low flow overflowed the bank, and the medium- low flow brought about a big flood disaster.

2. 2 Shaping a medium-flow channel through sedimentation distribution

2.2.1 Analyses of scale of medium-flow channel in the near future

According to statistics of measured data, the mean annual runoff at Xiaolangdi hydrologic station during 1986~2003 was 23.6 billion m^3, being remarkably smaller than the mean annual runoff of 35.7 billion m^3 during 1950~2003, and it belonged to a relatively low flow hydrologic series. Compared with the long hydrologic series, the rainfall of the Yellow River Basin during 1986~2003 did not decrease obviously, therefore, it can be concluded that the reduction in the mean annual runoff at Xiaolangdi hydrologic station was not caused by natural factors, but it was a result of human activities, which included sediment trapping by upstream hydro projects, water reduction by soil and water conservation, water use by industry and agriculture and an increase in domestic consumption along the river, etc.. According to analyses, in a quite long period, there will be an increasing trend of the human activities impact. In the future, the mean annual runoff entering into the Lower Yellow River through the regulation of Xiaolangdi Reservoir may maintain the same level as that during 1986~2003 or reduce to some extent. Based on above research results of bankfull discharges and measured data of the amount of inflow, under the present condition of inflow and incoming sediments, the scale of medium-flow channel possibly shaped in the Lower Yellow River is about 4000m^3/s.

The scale of medium-flow channel to be shaped is relevant to the amount of inflow and incoming sediment load and its processes. According to research results by integrated analyses of measured data and calculation results of the mathematical model of sediment transport, it is tentatively considered that adopting operation mode of sediment trapping at the early 5~8 years and controlling proper sluicing efficiency (approximately smaller than 0.3) from the reservoir, then adopting operation mode of sediment regulation for many years and discharging sediment at proper time, appropriately enlarging sluicing efficiency (approximately 0.7) from the reservoir, cooperating with measures such as “regulation of flow and sediment load” and “trapping coarse sediment and discharging fine sediment”, the corresponding bankfull discharges of medium-flow channel to be shaped and maintained under various series of inflow and incoming sediment are as follows:① under the condition that the mean annual runoff is 20~25 billion m^3, and the mean annual incoming sediment load is 0.3~0.5billion t at Xiaolangdi Reservoir, a medium-flow channel with bankfull discharges of 3500~4000m^3/s in the Lower Yellow River can be shaped within 5~8 years, and it can be maintained through proper regulation of sluicing efficiency of the reservoir before the reservoir storage for sediment trapping is full; ②under the condition that the mean annual runoff is 25~35 billion m^3, and the mean annual incoming sediment load is 0.5~0.7 billion t at Xiaolangdi Reservoir, a medium-flow channel with bankfull discharges of 4000~5000m^3/s in the Lower Yellow River can be shaped within 5~8 years, and it can be maintained through proper regulation of sluicing efficiency of the reservoir before the reservoir storage for sediment trapping is completely full; ③under the condition that the mean annual runoff is 35~45 billion m^3, and the annual average incoming sediment load is 0.7~0.9 billion t at Xiaolangdi Reservoir, a medium-flow channel with bankfull discharges of 5000~6000m^3/s in the Lower Yellow River can be shaped within 5~8 years, and it can be maintained through proper regulation of sluicing efficiency of the reservoir before the reservoir storage for sediment trapping is completely full;④ under the conditions that special series of water and sediment load occur(high flow and low sediment load or low flow and high sediment load), the bankfull discharges of medium-flow channel of the Lower Yellow River shaped and maintained may increase or decrease; ⑤under currently real condition of inflow and incoming sediments, a medium-flow channel with bankfull discharge of 4000m^3/ s to be shaped and maintained is appropriate.

2.2.2 Measures for shaping and maintaining a medium-flow channel

According to previous research results, the measures for shaping and maintaining a medium-flow channel of the Lower Yellow River in the near future are: mainly through regulation of processes of water and sediment series released from Xiaolangdi Reservoir and integrated regulation measures, i.e., adopting sediment trapping operation mode at initial stage of operation of Xiaolangdi Reservoir, and coordinating with “regulation of flow and sediment load” during flood seasons, a medium-flow channel with a considerable bankfull discharge is firstly shaped; then shifting to operation mode of long-time regulation of sediment and discharging sediment at appropriate time, proceeding with operation of “regulation of flow and sediment load” during flood seasons and “trapping coarse sediment and discharging fine sediment”, the medium-flow channel that has already shaped will be maintained. For the medium- and long-term through constructing large-scale hydro-projects on the Middle Yellow River and their joint operation with the Xiaolangdi Project, the life-span of reservoir storage for sediment trapping of the Xiaolangdi Reservoir is to be extended, and a medium-flow channel of the Lower Yellow River will be maintained for a long period; increasing the amount of water through inter-basin water transfer, the regulation capacity of the reservoir will be enhanced, the sediment carrying capacity of the channel will be increased, the capability of maintaining a medium-flow channel of the Lower Yellow River will be further enhanced; persisting in soil and water conservation works in excessive and coarse sediment area, to reduce sediment loads entering the Yellow River; pressing on channel regulation works, to manage channel outlook, stabilize the medium-flow channel and enhance capacity of discharging flood and sediment transport, dredging at local reaches, to augment cross-sections, manage abnormal river bend and improve flow capacity at local reaches, realize maintaining of the medium-flow channel of the Lower Yellow River for a long period.

2.3 Warping for reinforcing river dikes

2.3.1 Warping plans for reinforcing river dikes

Warping plans for reinforcing river dikes involves choosing the location of warping and the site of sediment taking, the layout of river reach, the machines, the reasonable time for warping, and engineering designs.

Making use of diverted sediment load to deposit the dike-footings along the levees had been developing in the Lower Yellow River for long time. The total length of deposited dike-footings and the total volume of deposited sediment reached 708km and 400×10^6 m^3, separately.

Since the 1990's, the engineering measures to deposit the dike-footings and consolidate the levees, including raising their height and widening their width, have had a new development. It is called as" building a <Relative Underground Yellow River> in coordination with water diversion from the Yellow River". Its general objective is that the levees of the Lower Yellow River will be step by step raised and widened as two artificial mounds in coordination with water diversion from the Lower Yellow River and arrangement for a great amount of sediment. The Yellow River would be confined-between the two artificial mounds and just like an underground river (relative to the top of artificial mounds on both banks). The top level of the two artificial mounds will be designed according to the designed flood level. The total height of levees in general is about 7-10m and the width of levees is from 100m to 200m, depending on the local condition of flood control. Fig.2.4. is the sketch scheme of cross section of the deposited levees.

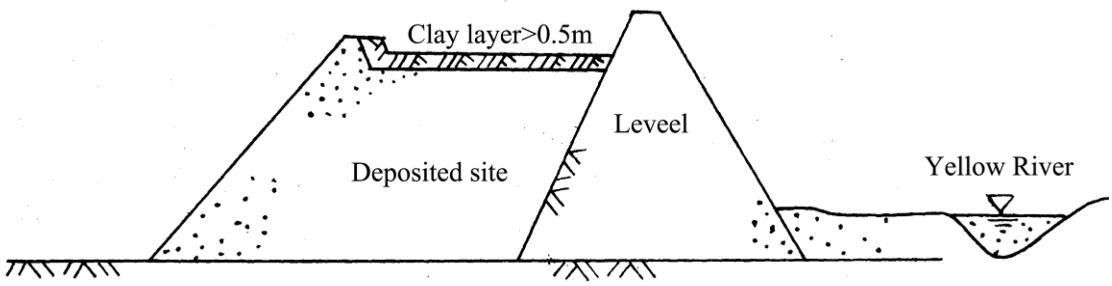

Fig. 2-4 Relationship of flow discharge with sediment discharge at Sunkou Hydrological Station

2.3.2 Techniques for warping for reinforcing river dikes

a. Development of warping for reinforcing river dikes

Depending on different tools of diversion, warping for levee consolidation has three modes: by gravity flow, by pumping and by dredging. No matter which mode in adopted, all of them divert the sediment-laden flow to the back of levees, leave the sediment to consolidate the levee base, and drain the up-layer clear water out for irrigation or town water supply. By this way, on the one hand, the sediment diversion from the Yellow River will alleviate the burden of deposition in the lower reaches; on the other hand, sediment silting for consolidating the levee will diminish the probability of levee break.

Originally, the river management department put forward warping for levees consolidation.

The gravity flow warping started in 1950's, the pumping warping was experimented in 1960's and fully practice in 1970's, while the dredging warping was appeared in 1990's. The practice in the Yellow River in the past several decades proved the prominent effect of warping. Until 1993, warping consolidated 734km levees with a deposition volume of 0.36 billion m^3.

(a)Warping for Consolidation of Levees by Gravity Flow

The gravity flow diverted from the river is usually by culverts or gates. The silting area and junction canal locate parallel with the levees; depending on the slope of the local ground the length of warping area is 1km in minimum and 10km in maximum. The border dike of warping is built from the toe of the levee, and the flow enters the warping area through the diversion gate. If the diversion is carried out by several gates, in order to complete warping in control, each canal should be connected. Limited by the slope of the ground, the height of warping usually is 2m~4m, but for a deep pool it may be large, such as 11m in the Huanyuankou burst pool.

Another type of diversion by gravity flow is by siphon pipeline. The siphon pipeline warping can divert hyperconcentrated floods to depressions or pools. The warping area location of this type is nearly the same with the gravity flow by culverts or gates, except smaller in scale and more flexible in the warping height.

(b)Warping for Consolidation of Levees by Pumping

This mode of warping usually is applied under the local conditions of rich energy sources, city water supply demand and impossibility for gravity flow. Combined with the fixed or movable pump station for water supply, the pumping warping is easily to be implemented. A typical example is the Luojiawuzi pumping station in Dongying, Shandong Province, which pumps water supplying the oil field in the river delta area and executes warping for consolidation of the north levees.

The construction of a pumping station for warping is so simple and flexible that in the Lower Yellow River, many pumping stations were removed after finishing the mission of warping. But this type of warping invests more and per cubic deposition costs higher owing to the demands of large discharge and high water head. It is difficult to be widely applied under recent power condition, except it combines with the city and mine water supply in some localities.

b. Main production processes for warping by machines

Main production processes for warping by machines involves pulping, sediment transporting and sediment depositing.

Pulping refers to mixing the deposited solid sediment with water, forming flowing slurry, to create conditions for sediment transport by hydraulic handling, so as to fetch earth through pumping slurry.

Sediment transporting refers to transporting slurry to the designed location.

Sediment depositing refers to making the sediment deposit at the appointed location according to the design, to reach the effect to reinforce the dike.

c. Design contents of warping for reinforcing river dikes

Design contents of warping for reinforcing river dikes mainly refers to the design of dike cross sections, including the width, the height and the slope of the dike cross sections.

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3. Sediment Utilization in Irrigation Districts along the Lower YR

The area of lower Yellow River is one of the water shortage regions in China, therefore irrigation is significant for this area to protect from drought, guarantee agriculture, promote economy and improve local environment. On the one hand, sediment issues impacts on flood control, hydro-project functions and environment protection so serious that it always associated with disasters in case of the Yellow River basin. On the other hand, sediment is indeed a kind of valuable resources, especially for developing agriculture.

3.1 Introduction of the Diversion Runoff and Sediment Load

3.1.1 The development of Diversion in Irrigation Districts

The ancient Chinese had recognized the sediment and used it rationally in their production practice, which can be proved by the bricks in Qin dynasty and tiles in Han dynasty. Historically, the main styles of sediment utility were warping for irrigation and warping for consolidation the levees. The warping for irrigation means that muddy irrigation to develop the farmland by depositing the fertile sediment (see Photo 3-1). It comprised the farmland-ameliorating, storm flood warping and land-making. The warping for consolidating levees means that stabilization the levees by warping designedly in depression by chance of the heavily sediment load in flood seasons.

Photo3-1 Guanzhong Plain beside the middle reaches of the Yellow River (photo by Zhao Piang'an)

Above-mentioned have been widely used in the Yellow River basin, and get new successful development. After 1949, when the new China established, the irrigation career has been still in flourish developing in the lower Yellow River. The statistics of division runoff and sediment load from 1950~2002, and 2007, 2008, 2009 are showed in Table 3-1.

The table 3-1 showed that from 1950~2002 (except 1962~1965 stop irrigation), the annual division runoff was 7.48 billion m^3, accounted for 19.5% of which at Huayuankou station in the same period. The mean annual division runoff in the 1970's, 1980's, 1990's and 2000~2002 were 6.89 billion m^3, 10.18 billion m^3, 9.58 billion m^3 and 10.97 billion m^3, respectively. While in recent years the annual division runoff was 6.34 billion m^3, 6.27 billion m^3, 8.34 billion m^3 in the year of 2007, 2008 and 2009, respectively. These statistics data illustrate that the annual division runoff began to increase sharply from 1980's but recent years, the annual division runoff were little decreased. Along with the division flow, lots of sediment load diverted into irrigation districts. Also showed in Table 3-2, from 1950~2002, the annual division sediment load was 93.8 million t. The mean annual division sediment load in the 1970's, 1980's, 1990's and 2000~2002 were 131.6 million t, 108.4 million t, 93.8 million t and 61.3 million t, respectively. While in recent years the annual division sediment load were drop down sharply by19.8 million t, 17.6 million t, 19.2 million t in the year of 2007, 2008 and 2009, respectively.

Table 3-1 Annual division runoff and sediment along the lower Yellow River in different decades

Items	Decades or years	Huayuankou ~Gaocun	Gaocun~Aishan	Aishan~Lijin	Huayuankou~Lijin
Division Runoff (10^9m^3)	1950～1959	2.02	1.86	1.05	4.93
	1960～1969	0.89	0.90	0.55	2.34
	1970～1979	2.37	1.90	2.62	6.89
	1980～1989	2.16	3.06	4.96	10.18
	1990～1999	1.94	2.63	5.01	9.58
	2000～2002	1.40	3.64	5.93	10.97
	2007	1.29	1.50	3.55	6.34
	2008	1.64	1.19	3.44	6.27
	2009	2.25	2.66	3.44	8.34
Division Sediment load (10^6t)	1950～1959	47.9	39.5	20.8	108.2
	1960～1969	14.9	17.4	8	40.3
	1970～1979	56	36.7	38.9	131.6
	1980～1989	33.5	34	40.9	108.4
	1990～1999	26.7	24.1	43	93.8
	2000～2002	9.8	20	31.5	61.3
	2007	3.0	4.2	12.6	19.8
	2008	3.9	3.4	10.4	17.6
	2009	3.5	6.9	8.8	19.2

There has been the largest gravity flowing irrigation districts jointed along the both sides of the lower Yellow River. Until the end of 1990, the largest jointed irrigation districts includes 20 cities in Henan and Shandong provinces, with the total ability of division discharge of 3363.5m^3/s (among that 1229.5m^3/s in Henan province, 2134m^3/s in Shandong province) to control the total irrigation area of 30487 km^2 (among that 12440 km^2 in Henan province, 18047 km^2 in Shandong province).

The integrated irrigation and drainage projects have been constructed (as the table 3-2 showed). As irrigation projects as concerns, there are 464 arterial canals with total length of 5288 km, 3198 brunch canals with total length 9233 km, and 8051 lateral canal with total length 7904 km; and for drainage projects, there are 394 arterial canals with total length of 6116 km, 2292 brunch canals with total length 7480 km, and 4380 lateral canal with total length 3455 km.

Besides there are 13 drainage rivers located in the irrigation districts of lower Yellow River, with the total control area of 69267km^2. The irrigation districts in the lower Yellow River have been a comprehensive irrigating and draining system to guarantee the crop fertility nevertheless the drought or waterlog, and have been the important crops yield foundation.

Table 3-2 The statistics of irrigation and drainage projects in the lower Yellow River

Province			Henan		Shandong		Sum
Scale of Irrigation districts			≥200km^2	<200km^2	≥200km^2	<200km^2	
Irrigation project	Arterial canal	Amount	53	52	214	145	464
		Length (km)	747	584	3004	953	5288
	Branch canal	Amount	211	317	1783	887	3198
		Length (km)	1121	890	5489	1725	9233
	Lateral canal	Amount	3395	1615	584	457	8051
		Length (km)	3061	1777	2722	390	7904
Drainage project	Arterial canal	Amount	34	62	189	109	394
		Length (km)	445	817	3899	995	6116
	Branch canal	Amount	90	84	1455	663	2292
		Length (km)	437	549	4813	1681	7480
	Lateral canal	Amount	1477	592	1382	857	4380
		Length (km)	501	904	1551	499	3455

Photo 3-1 The Weishan diversion project at the lower Yellow River

3.1.2 Distribution of diverted water and sediment

(1) Distribution of diverted water

Influenced by the factors such as Yellow River water, level of water management and geographical conditions, etc the annual irrigation water distribution decreasing along the way from upstream to downstream unevenly presents the situation that the water consumption in upstream area is larger and seriously wasted, while the water consumption in downstream area is insufficient or even can not be fulfilled. For example, compared with that of the main trunk canal, the water distribution in unit area of No. 2 trunk canal of Bojili irrigation area, Wuli section and No.1 trunk canal respectively decreases by 15.8%, 23.2% and 52.4%, and water inflow in unit area of No. 2 trunk canal in Wuli section decreases by 8.7% than that of No. 2 trunk canal. The average measured water distribution of Weishan Irrigation District from 1990 to 2001 is mainly concentrated in headwork district, and water distribution of its downstream canal is relatively small. The water yield in headwork of Eastern and Western canals (conveyance canal and sand basin) respectively accounts for 37.43% and 23.85% of their water inflow; unit area water distribution is large in the headwork districts. Annual average water distribution in per square meter of irrigation area in headwork districts of western canal is 0.63 m^3/m^2; average water distribution in per square meter of irrigation area in headwork districts of eastern canal is 0.43 m^3/m^2, both of which are ranked at first in their respective water systems

(2) Distribution of diverted sediment

The diversion sediment in the lower Yellow River irrigation districts from 1958~1990 in accumulation were 3.865 billion t, in which 1.597 billion t diverted in Henan province, accounting for 40.9%, 2.286 billion t diverted into Shandong province accounting for 59.1%; or 1.783 billion t sediment diverted in the north bank of the river, accounting for 46.1%, 2.082 billion t diverted into south bank, accounting for 53.9%.

Table 3-3 Distribution of diversion sediment in the lower Yellow River irrigation districts from 1958~1990

Area	Diversion sediment amount (billion t)	In setting basin		In canal system		In drainage system		In field	
		Amount (billion t)	Accounts (%)	Amount (billion t)	Accounts (%)	Amount (billion t)	Accounts (%)	Amount (billion t)	Accounts (%)
North Bank	1.783	0.491	27.6	0.733	41.1	0.194	10.9	0.364	20.4
South bank	2.082	0.793	38.1	0.632	30.3	0.136	6.51	0.521	25.02
Henan province	1.579	0.227	14.38	0.486	30.78	0.182	11.53	0.684	43.31
Shandong province	2.286	1.057	46.2	0.879	38.5	0.149	6.5	0.201	8.79
Total	3.865	1.284	33.22	1.365	35.32	0.331	8.56	0.885	22.9

The distribution of diversion sediment in Henan was very different from which of in Shandong. In Henan province, the 14.38%, 30.78% and 43.31% of the division sediment deposited in the setting basin, canal system and field, respectively by the statistics from 1958~1990; while in Shandong province, the percent of sediment disperse were 46.2%, 38.5% and 8.8% in the above mentioned area in the same period.

The distribution of Yellow River introducing sediment on the surface of irrigated area is closely related to such factors as natural and geographical environment of irrigated area, sediment treatment methods, water and sand diversion conditions, situations of engineering facilities and crop planting structure, greatly influenced by geographical environment and sediment processing methods in particular. Owing to the muddy water irrigation adopted in Henan Province with larger terrain slope, better conditions of sediment transport of canal system, sediment distribution more obviously tends to spread upward to the surface with generally large distribution proportion in the field, accounting for 43.3 % of the total of sand diversion, furthermore, owing to its location in upstream of irrigated area and advantage of water diversion , sediment entering into drainage system is up to 11.53% and 5% higher than that of downstream of irrigated area in Shandong Province.

From west to east along with downstream of Yellow River, Yellow River introducing sediment distribution in the irrigated area is different, particularly sediment distribution ratios of irrigation canal system and field are quite different. From Huayuankou to Hekou Area, the proportion of sediment distribution of irrigation canal system in irrigated area sand diversion is comprehensively increasing little by little, while volume of the field sediment distribution is decreasing, which results from factors such as natural and geographical conditions along the Yellow River Area and irrigation methods, etc. The ground slope of upstream section in Henan Province is normally 1 / 4000 ~ 1 / 6000, mainly based on gravity irrigation with separate irrigation and drainage systems. While, the ground slope of downstream section in Shandong Province is normally 1 / 6000 ~ 1 / 10000 and adopted with pumping irrigation in consolidated irrigation and drainage system.

3.1.3 Characteristics of the Yellow River diversion

The main features of irrigated area at downstream of Yellow River is less sand and more water, water shortage, sand diversion volume, resulting in serious canal system sediment deposit and causing series of problems.

✓ Water shortage situation is grim, irrigated area water distribution is uneven.

Through long period of governance and sustainable development, the amount of water inflow and sand inflow at downstream of Yellow River basin has changed dramatically, directly impacting on Yellow River introducing and water supply. Usually, actually measured runoff of Yellow River Huayuankou section and suspended sediment discharge represent water inflow and sand inflow situation at downstream of Yellow River. The actually measured water yield of Yellow River Huayuankou Station from 1950 to 2006 in Fig. 3-1 shows that annual changes in Huayuankou Station runoff was large, generally rich from 1950s to 1960s, tended to the normal level from 1970s to 1980s, drier in 1990s, seriously dry after 2000. At the same time, irrigation technique of most irrigated areas is backward and the problems such metered water supply, etc fail to be solved so that the method of broad irrigation is still adopted, which results in serious water waste of irrigated area upstream, water shortage of irrigated area downstream.

In addition, after operation of Xiaolangdi Reservoir of Yellow River in 2001, the discharged water scours and cut the river bed and makes water diversion of irrigated area more difficult. At the same time, along with industrial and agricultural development near the downstream, the water demand is also growing. Therefore, contradiction of water supply and demand at downstream of Yellow River will be further intensified.

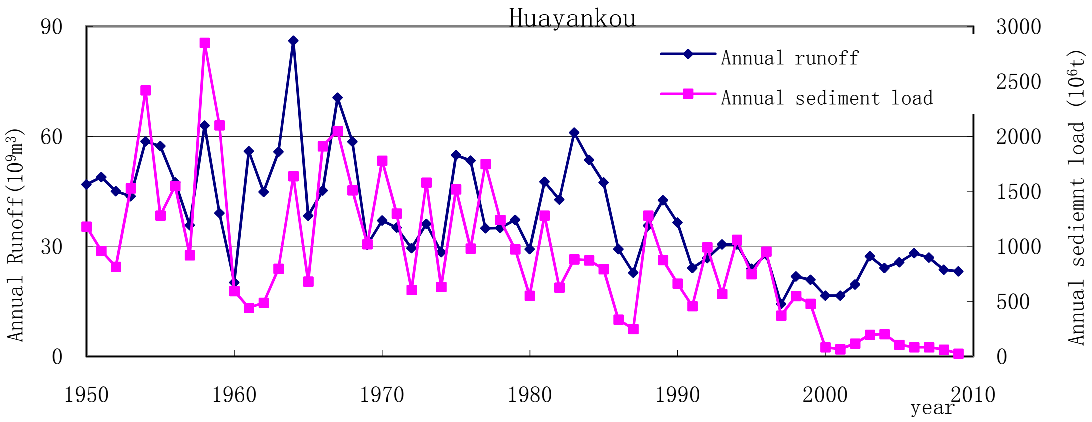

Fig.3-1 the trend of annual runoff and sediment load of Huayuankou station

✓ Sediment problem is still outstanding

Yellow River is with highest sediment concentration all over the world. While introducing Yellow River, the irrigated area helps to bring a lot of sediment into channel and field, with negative impact on irrigated area engineering, irrigation management and natural environment along the Yellow River Area. The biggest problem of Yellow River introducing irrigated area is channel sediment deposit. Owing to restrictions by topographic slope and soil texture, irrigation canals at the Yellow River downstream introducing irrigated area is generally designed to be broad and shallow, in water transport distance and channel levels. Therefore, capacity of channel to discharge sediment is lower, which results in ubiquitous sediment deposit problems almost in every where except for a few of lined channels and channels in larger slope. The main reason is volume of sediment introduced into the irrigated area is large, and terrain slope within the irrigated area is flat, not conducive that flow transports sediment to lower channels and fields.

According to statistics, about 77.1% of the Yellow River introducing sediment deposit mainly stays in the sand base and the irrigation and drainage canal system (see Photo 3-2).

Photo 3-2 Serious sediment deposition at the diversion inlet side by the Yellow River bank

By further analysis, sediment deposited in the sand base, deposit reformation area, core channels occupies more than half the amount of sand diversion, and those areas spread over within 15 km wide range, that is, more than half of Yellow River introducing sediment concentrated and deposited in narrow and long strip in 15 km width. The distribution of irrigated area sediment is uneven. Most of sediment intensively deposits in headwork and core channels, which causes the problems of handling capacity of sediment deposit, headwork desertification, drainage channel deposit and deterioration of ecological environment, etc.

Therefore, sediment problems become the key to constrain sustainable development and long-term benefits of Yellow River introducing irrigation. How to handle and use a lot of sediment entering into the channels become important issues in development and utilization of Yellow River water resources.

3.2 Warping in Flood Period

From the long time practice, Chinese has recognized gradually that the Yellow River sediment load is a potential resource depending on the highly concentration and finer size in floods, which also carried more nutrient favorite to the cropper (see Photo 3-3).

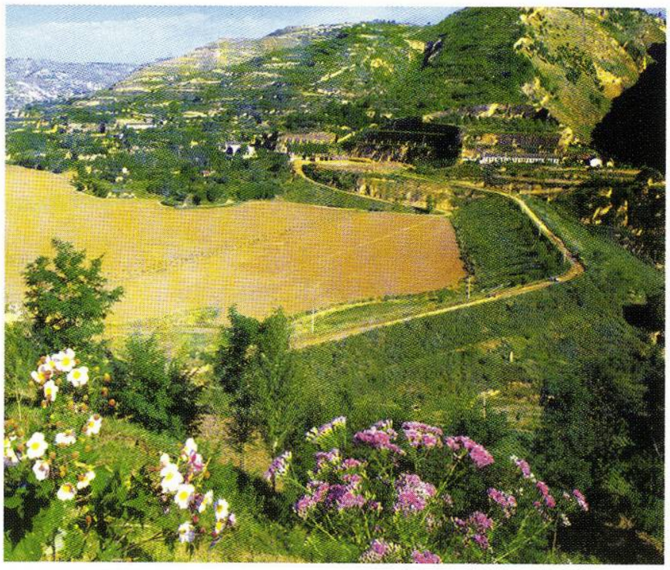

Photo 3-3 Flood diversion for warping farmland (photo by Sun Taimin)

3.2.1 Warping for soil melioration

Based on the sand size observation, the sediment caught by the lower Yellow River flow belongs to silt, with more than 60% particles finer than 0.05 mm. Except some coarse particles, most sediment particle is fine, which is beneficially to increase the soil nutrient and develop the soil structure. According to the nutrition evaluation of the warped soil, it is found that the organic matter and nitrogen increase 0.3% and 0.03% respectively comparing with the soil non-warped in same region. The warped soil also reduces the soil salinity, and makes the desalination ratio up to 50%~80%.

In the process of warping planning and practice, three demands should be considered: (a) the feasibility of warping and minimum canal deposition; (b) the silting area should be warped to “flat, thick and even”. (c) reduction the investment and labor. Standing by these rules, there are some warping techniques as follows:

- ✓ Diverting the concentrated and large discharge in warping area. A large discharge can decrease the deposition in the trunk canal, help the sediment transport to the end of the warping area, keep the entrance from sudden block, and make the deposition in sound delta formation;
- ✓ Diverting muddy flow in warping area in flood season. Based on the data, the flood sediment possesses more nitrogen, phosphor, kalium and other nutrient, especially in the beginning of flood season. The early two times floods in a year are favourable to the optimized warping;
- ✓ The outlets of the warping area should be installed the adjustable underplate. The non-static underplate can be controlled under different conditions of the discharge and sediment concentration. By this way, the discharge and water surface slope in the silt area can be adjusted in time in order to regulate the outlet sediment concentration;
- ✓ Dynamic warping firstly followed by static or backward warping. Warping started from dynamic flow will shorten the flow time, while warping ended by the inundating silt of static water will make the deposition more even;
- ✓ Discharge flowing to and fro by multi-accesses. The multi-accesses make the diversion quickly and smoothly, and form several flows full filling all part of the silt area. Under this condition, several silt deltas move forward and interleave, making the deposition thick and particle size even;
- ✓ Warping ended at low concentration. This measure can reduce the canal deposition as well transport more sediment to the silt tail of the area.
- ✓ The training wall is needed. In order to control or improve the discharge condition, and extend the distance of silt transport, the training wall should be constructed based on the shape of a silt area.

3.2.2 Warping for paddy planting

In some irrigation districts, there are a lot of salina depressions near the river banks. In order to change the salina depressions to arable land, the research of the paddy planting was launched in 1950's successfully. The warping for paddy planting would not only make both paddy and wheat get high yield, but also ameliorate the soil by translating the salinity below. The paddy growth phase prolongs the total flood season. Based on the investigation, the diversion sediment concentration usually is 20～40kg/m^3, and the water demand is 15000～22500m^3/ha, then the diversion sediment load will be 30～45t, and the paddy land will be covered by sediment around 4cm thick annually. It is really a large amount of sediment and efficient for sediment treatment.

Due to limited water resources of the lower Yellow River in recent years, especially in May, June and July of dry years, the paddy planting was not so prevailing after the 1980's. Nowadays paddy planting is only implemented at RenminShengli irrigation district (Dongying city, Shandong provice) located in the Yellow River delta. The techniques of warping for paddy planting are as follows.

- ✓ Integrated plan. Many factors should be taken into account such as the condition of water source, diversion, and the level of farming development, etc. For large planting blocks, the anti-seepage infrastructure should be built at the connection of paddy field and wheat field;
- ✓ Establishing special control shuttles. When the diversion water level is high, warping can

be practiced by gravity; while the water level is low, the pumping warping is needed;

- ✓ Lining branches and ditches, designing cross-sections rationally. Warping flow will carry more sediment in case of smooth canals and appropriate cross-sections. Lining and rational section design will decrease canal deposition and transport more sediment to warping area;
- ✓ Applying alternatively centralized irrigation. Centralized irrigation from one block to another, and from the upper region to the lower can enhance the sediment carrying capacity of the canal.
- ✓ Rationally distributing the irrigation system. There are many quadrate segments in a paddy land. If the segment scale is too large, it will be not good for culture, irrigation and sediment transport, while if the segment scale is too small, the ridge of the segment will occupy more paddy land. Carving up the paddy land and management the irrigation system should under the rule of minimizing the canal counts.
- ✓ Enhancing anti-seepage diversion. Excavating the anti-seepage furrow around the paddy area can make the diversion smoothly and avoid waterlog and secondary salina;
- ✓ Saving water. It includes the saving irrigation and inventing new plant techniques.
- ✓ Canal system and well system combined together. In order to enhance the guaranty of water resources and efficient control the underground water, this measure should be developed in case of the underground water is fresh water or brackish water.

3.2.3 Sediment-laden Flows Irrigation

(1) Sediment-laden Flows Irrigation

Since the 1980's, owing to the limit of the silt condition and the deeply known of the water and sediment resources, the sediment-laden irrigation was developed in area of the lower Yellow River (including the canal system irrigation in Henan province and pipe line irrigation in Shandong province). Especially in part of Henan province, taking most advantage of the big slop of the landform (usually the slop larger than 1/5000), the sediment-laden irrigation flows directly into the farmland (like the Xiangfuzhu irrigation district in Henan province). The sediment-laden irrigation exploits an efficient way to deal with the sediment issue in the irrigation districts. Concerning the techniques of the sediment-laden irrigation, the sediment long distance transportation is very important. Some necessary condition as follows:

- ✓ Setting basin needed. The setting basin is necessary if the condition permits. On the one hand, the setting basin can set down the coarse sediment (particle size larger than 0.05mm), which is easily siltation; on the other hand, the farmland want the fine sediment (particle size smaller than 0.035mm), which will not change the soil structure.
- ✓ Increasing the sediment carrying capacity. There are many measures to meet this requirement, such as adjusting the canal slop, designing the optimized canal section, lining etc.
- ✓ Advanced management. It includes the rational water management and irrigation centralized. Firstly, in order to keeping the canal in the balance, the discharge should not lower than 80% of the designed; secondly, making the order of the different farmland, implementing the alternatively centralized irrigation, which will keep the left discharge enough.
- ✓ Avoiding sediment peak diversion. This is in purpose of lessening the sediment load in

the irrigation area.

(2) Warping by Hyper-concentration Flows

Considering the risk of deposit and block the irrigation canal, the hyper-concentrated warping usually is forbidden in flood seasons when the sediment concentration is lager than a critical level. However, in the case of urgent demand water resources, the Luohui irrigation district (located in the middle reaches of the Yellow River) broke the sediment concentration limit and diverted the flow with a sediment concentration of 165kg/m^3 in 1974. The test took full advantage of the hyper-concentrated flood, and the warping succeeded unexpectedly. Thenceforth, the extensive trials developed in other irrigation districts in the years of 1976～1985, and making a significant progress of the hyper-concentrated warping techniques.

It should be emphasized that the deposition in canals, especially in the ditches, is inevitable and normal during the hyper-concentrated irrigation. But the demand of the balance between aggradation and degradation should be achieved in a definite period, such as a quarter or a year, in order to guarantee the routine irrigation. There are some techniques to make it as follows.

- ✓ Limiting the sediment concentration to prevent the occurrence of the pseudo one-dimensional flow. By controlling, the pseudo one-dimensional flow with high viscosity is prevented from the laminar flow, which is easily stagnated and blocks the canal with high resistance.
- ✓ Guaranteeing the sediment carrying capacity, if the hyper-concentrated sediment flow is a turbulent two-phase flow. The good section should be adopted, typically adopted a narrow and deep section to transport the hyper-concentrated flow further.
- ✓ Enhancing the forecast of water and sediment. Several preparation jobs should be done in detail, such as monitoring the canal scour and deposition, adjusting the diversion runoff and sediment load, dealing with the emergence, etc. to guarantee the smooth transport of the hyper-concentrated flow.

3.3 Changes of Building Material from Sediment

The method to produce construction materials by Yellow River sediment is still relatively common in the Yellow River downstream. Survey of irrigated areas in Shandong, Henan shows that a lot of large brick factories owned by township or villages built up in irrigated area headwork use flood sediment as raw materials. The approach is: firstly low-yielding fields (including saline, low-lying land) are selected to gather earth and bake bricks, use the other lands in the following year.

At the same time, through flood warping of Yellow River introducing river for the pits used for last year, the sediment is deposited, the water is used for irrigation, and land after deposit reformation can not only become high-yield plot but also continue to be used as soil source for the third year; or open up a new earth borrowing pit for the 3rd year, or borrow earth from silt land of the last year while continuing earth borrowing pit for flood silt of Yellow River introducing river for next year. After circulation, sediment transfers into building materials, which not only improves people's living standards but also obtains purposes of sediment disposal and water irrigation. There are seven brick factories nearby Suge irrigated area headwork of Shandong Yuncheng, and l0 brick factories only along with Nanyu channel in irrigated area of Hei Gangkou of Henan.

3.3.1 Use Yellow River introducing silt to produce sand-lime brick

Sand-lime bricks are adopted with sand and lime as raw materials and become masonry materials through burdening, compression molding and autoclaved cure by saturated steam, with decades of production history at home and abroad, and its production materials consist of river sand mostly in particle diameter of 0.15 ~ 1.2mm (70%). But, fine silt particles of Yellow River introducing irrigated area are finer, mostly 0.05 ~ 0.16mm (76.6%). The analysis and experimental results show that silt SiO_2 content in sediment within sand transport canal and sand base of Yellow River introducing irrigated area is averagely above 70%, capable to be made into sand-lime brick through adjusting the ratio with quick lime. The compressive strength and flexural strength of test blocks is up to JC153-75 ministerial standards.

Based on experimental results, Liuzhuang Sand-lime Brick Factory in Weishan irrigated area has been officially put into operation in May 1994. Sand-lime bricks are made by grinding, milling, stirring the raw materials of 88～90％ of Yellow River introducing silt and 10～12％ quick lime with add water and pressing them into blank by high-pressure steam, mainly used for cottage architecture in pool area after put into operation.

3.3.2 Yellow River silt can be produced into high-class decoration glass

Yellow River silt in large amount with good performance can be used to produce decoration glass. Test result by Zhang Xianyu to use Yellow River silt for decoration glass shows that Yellow River silt can help to found various colors of decoration glasses, various technical performance of which can meet performance requirements for finish material, with better appearance performance, and decorative effect, which is a kind of high-class finish material and has good mechanical properties and chemical properties. The production process of decoration glass by Yellow River silt is simple and easy to operate in large demand for silt containing 70% of silt, 30% of auxiliary materials. Through preliminary cost analysis, decoration glass by Yellow River silt is at low cost, with high value-added, contributing to better economic efficiency.

3.3.3 Yellow River introducing silt concrete

Silt concrete is one kind of cement concretes, which is characterized by fine aggregate as original silt, while the Yellow River introducing silt is characterized by high clay content (means that particle size is less than 0.08mm) and fine particles. Weishan Yellow River introducing irrigated area silt clay generally contains 70% silt or more in very small fineness modulus, even finer than commonly known special sand. In accordance with regulations, normally mud content in concrete sand should not be more than 3 to 5%, and its fineness modulus is greater than 0.7. Thus, according to specifications, Yellow River introducing silt is not allowed for the production of concrete. In the principle of close combination of test research and production, a number of applications have been carried out for test results of silt concrete, mainly used to produce channel liner plates, pre-stressed floor and urban road blocks, etc.

3.4 Changing into farmland from highland by dredged sediment in the irrigation system

3.4.1 Problems caused by sediment dredging

Dredging sediment problems of headwork districts exist in many irrigated areas at downstream of Yellow River. Taking Weishan irrigated area into example, Weishan irrigated area is Yellow River introducing irrigated area with the largest water diversion capacity in the middle and lower reaches of the Yellow River, where system gradient of canal system is 1 / 6000 ~ 1 / 10000, sediment transport capability is poor owing to flat terrain, the two operational sand base is exhausted, headwork district sediment is piled into harm, seriously restricting sustainable development of the entire irrigated area. Problems caused by dredging sediment are mainly as follows:

(1) Reduce cultivated land area

According to statistics, since, since Yellow River introducing in 1958, 2100 hm^2 of farmland in Weishan irrigated area have been occupied [2]. Cultivated land per capita in settling land of headwork district is only 0.108 hm^2. Cultivated land per capita in some areas decreases from 0.112 hm^2 per capita originally to 0.069 hm^2 currently, accounting for only 40% of the original farmland (see Photo 3-4).

Photo 3-4 setting basin siltation occupied lots of farmland

(2) Increase of soil desertification

In successive years, dredging of Weishan irrigated area results in 1487hm2 of sandiness highland. Currently, the area to clear silt and sediment on both sides of sand transport area is expanding outward at speed of 27hm^2 newly increased per year[3]. The grain size of deposit sediment in settling areas of Weishan irrigated district is mainly arranging from 0.075 to 0.1mm, mainly composed of fine sand, silt with less viscous particles and poor compactness, floating, spreading, burying vegetation and carrying away most crops, resulting in obvious arable desertification within area of 500m in the sediment embankment zone.

(3) Decrease of soil fertility

Owing to small quantity of soil viscous particles of sand transport area, fine-grained soil on surface is easy to run off with wind and by rain erosion, which results in thicker soil texture, strong permeability, loss of water and fertilizer, lower content of organic matter and lower soil fertility. Crop production level in headwork district is only about 50% of that outside the pool area, resulting in that income level of farmers is low very much.

(4) Deterioration of air quality

According to observations, when wind speed of sand base area ≥ 4 ~ 5m / s, the sandstorm begins, and according to wind speed data statistics by Liaocheng City Weather Bureau, the sandy days in headwork district account for 54% of the whole year. This kind of sandy weather frequently occurred has seriously polluted air, destroyed ecology, brought many diseases, seriously risking the health of local people.

According to actual deposit situation of Weishan irrigated area, we have further carried out research on and application of covering dredging sediment for agricultural land by dredging sediment and highland development technology.

3.4.2 Covering dredging sediment for forestation on both sides sand transport canal

From 1970 to 2002, dredging sediment in accumulated amount of 46.177 million m^3 is piled up on both sides of sand transport canal, forming four 80 ~ 120m wide sand ribbons, 7 m higher from ground in an area of 493 hm^2.

Owing to coarse particles of deposit sediment, all lands on bank with serious desertification can not be farmed. Because of dredging sediment of sand transport channel year after year, height and width of dredging waste bank increase, and the waste bank has been heightened every year with coarse sand uneasy to be dense, causing sandstorm, burying tree and crops in spring, which results in that active sand dune in shape of trip is piled up, difficult to concede the land to farm or forest on both sides of sand transport canal. Since 1994, machineries such as carry-scraper, bulldozers, etc are used to improve area of 218. hm^2 on both side of eastern canal embankment for forest. Land leveling of 195.6 hm^2 of 274.2 hm^2 on both sides of eastern canal embankment is carried out for forests. The current unmanaged desertification area is 78.6 hm^2， accounting for 15.95% of embankment area of the two channels.

3.4.3 Highland is pile up in sand base to cover dredging sediment for agricultural land

Weishan irrigated area has been operated from 1970 to 2002 for 33 years, totally exploring and using 2267 hm^2 of sand base in total deposit sediment of 97.258 million m^3. Sediment particle of sand base is coarse in average particle size of 0.021 ~ 0.023mm or more, which is not suitable for crop growth. Development of highland built up by silt in sand base is the main way to develop and utilize sediment in sand heap. on the basis to summarize past experience, Weishan irrigated area has carried out technology research and demonstration projects to cover dredging sediment for agricultural land [7], experimental study of technical measures and benefit analysis to cover dredging sediment for agricultural land.

Soil optimization scheme to cover dredging sediment for agricultural land through Weishan irrigated area experimental studies is determined that the following three kinds of silt soil structures are best: ① undisturbed soil, 0.7m thick in surface layer; ② undisturbed soil, 0.5m thick surface layer, and silt-falling soil below is 0.2 m,; ③ silt-falling soil is 0.3m, undisturbed soil below is 0.4m

Weishan irrigated area through land leveling is adopted with undisturbed soil roof in thickness not less than 0.5m for cultivated land, divide region to decide square and rectangular pieces of land in field and carry out high-tech agricultural development in sub plots, sub-regions. Highland formed at present is totally managed for covering dredging sediment for agricultural land.

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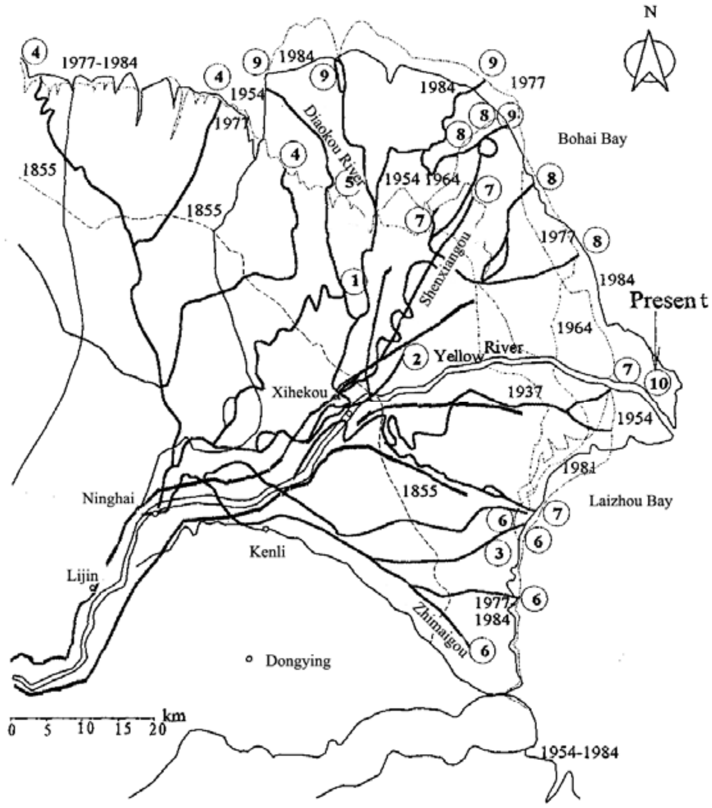
4. Sediment utilization in the Yellow River Delta

4.1 Fluvial Processes of Yellow River Delta

4.1.1 Changes in the tail channel

The Yellow River mouth area, being the main sediment deposit area, is formed during the frequent shifting and diversion of river course. The flow path to the sea has experienced ten great shifting since 1855, as shown in Fig.4.1. The fluvial processes of the Yellow River mouth have been undergone three great artificial diversions and one artificially forking since 1953. Table 4-1 lists its extension and formation of land, indicating the tail channel kept in continuous deposition and extension.



①Aug., 1855,②Apr., 1889③Jun., 1897④Jul., 1904⑤Jul., 1926⑥Sep., 1929⑦Sep., 1934⑧Jul., 1953⑨Jan., 1964⑩May, 1976

Fig. 4-1 The modern Yellow River Delta and shifts of the river channel

The length of tail channel below Ninghai basically had been about 60 km before diversion to Shenxiangou in 1953, it began to increase after 1953, and the coastline of the delta formed during recent diversions in 1953, 1964 and 1976 extended to sea for about an average distance of 20 km. The extension rate of the river mouth to the sea varies with the incoming runoff and sediment load. Since 1986 it has been slowed down and eroded back due to the continuous low runoff and sediment loads. According to measured data, the average annual extension rate of Shenxiangou route was 3.45 km/a，Diaokouhe was 2.68 km/a，Qingshuigou was 2.64 km/a during the period of 1976~1987, 1.14 km/a during the period 1988~1994， it was less than 1 km/a in recent years.

Table 4-1 Extension and land formation of recent river mouth

Flow route	Period	Life-span of the channel (Year)	Sediment load (Billion ton)	Area of land formation (km^2)	Extension length (km)
Shenxiangou	1954~1963	9	11.625	412.0	15.8
Diaokouhe	Jan.1964~Sept.1973	10	11.309	506.9	17.6
Qingshuigou	Jun.1976~Oct.1991	16	10.647	586.9	17.7
Chanhe	Oct.1996~Oct.1998	2	3.94	25	7.0

4.1.2 Changes in the mouth bar

Under the joint action of stream flow and sediment load and ocean dynamics, the plane configuration of the mouth bar appears complicated as shown in Fig. 4-2. When ocean dynamics is stronger than stream flow, the inner mouth shoal and sand bank develop rather quickly as shown in Fig. 4-2 (a). When ocean dynamics is weaker than the stream flow， it develops rather quickly outside the river mouth as shown in Fig. 4-2 (b). When the flow route enters the sea at a relatively stable locality， the shoal and sand bank inside and outside the river mouth connect and change into one single body, form into the mushroom shape as shown in Fig.4.2 (c). The evolution of the mouth bar behaves deposition mode of the old one and the new one overlapping and interlacing with each other, moving back and forward, mainly advancing, which results in transverse and longitudinal extension of the shoal head, and becomes the basic conditions for land formation of the river mouth and coast line extension.

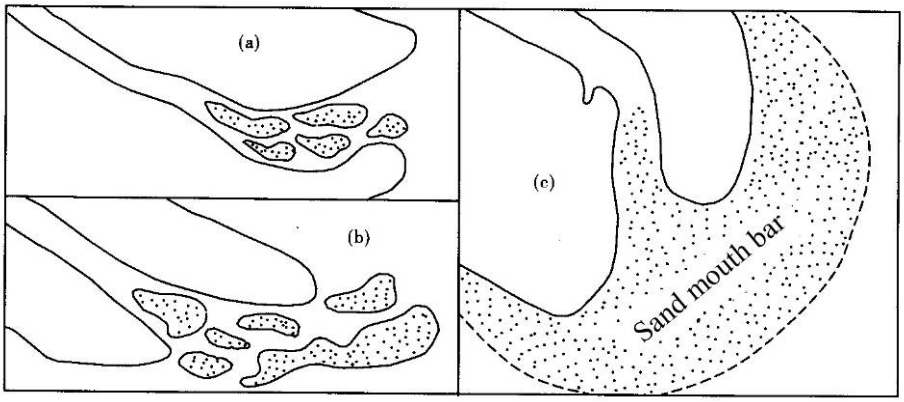


Fig. 4-2 Plane configuration of the mouth bar

Fig. 4-3 shows the longitudinal profiles of the mouth bar in the periods of 1984~1995 and 1996~1999 . The longitudinal profiles of the mouth bar are mainly composed by the reverse slope section of upper reach, the top slope section and the steep slope section. The top slope section forms the erosion datum base of the river channel outlet. The deposition elevation of the top slope section is closely related to the condition of incoming runoff and sediment load, and it aggrades quickly when the incoming runoff and sediment load is large. After 1984, the rise of the mouth bar was rather small; since channel shift to the Fork channel in 1996, due to the low runoff and sediment load, the mouth bar has almost not been developed.

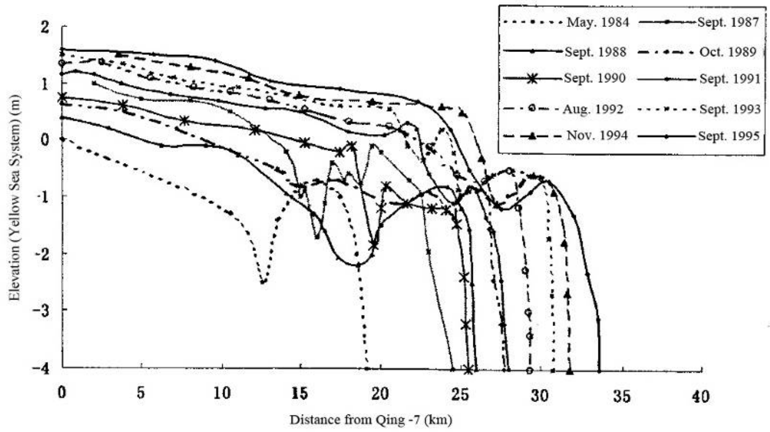


Fig. 4-3(a) Longitudinal profile of the mouth bar before Qing-8 forking

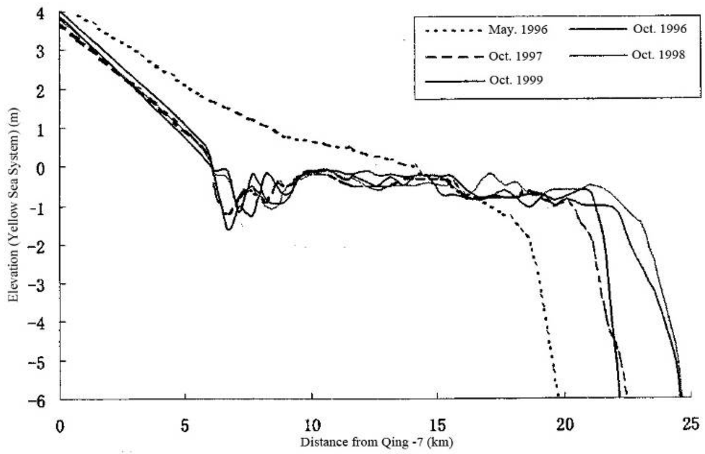


Fig. 4-3(b) Longitudinal profile of the mouth bar after Qing-8 forking

4.2 Land formation with sediment

The Yellow River is well-known for its deficient water flow and abundant sediment load. According to the measured data from 1950~2002, the average annual runoff at the Lijin station is 32.7 billion m^3, the average annual sediment load is 0.821 billion t. The ocean dynamics are relatively weak, the velocity of the tidal current is about 1m/s, the average tidal range is 0.61-1.13 m, and the tidal reach length is only 15-30 km. (Hu, et al., 1996). A great amount of the incoming sediment load deposit in the river mouth, extending the river-mouth bar further offshore. Photo 4-1 shows the scene of heavily sediment-laden flow from the Yellow River entering into the Yellow River mouth. 64 % of the incoming sediment deposit on the delta area, among which 24% deposit on the area above the zero elevation contour, 36% is transported to the deep sea. Photo 4-2 shows sediment deposition on the Yellow River Delta. The Yellow River mouth has a strong function of land creation. Therefore, sediment as resources in the Yellow River Mouth mainly uses to continent-building. It is assessed that the sediment deposited and build new land at a rate of $23km^2/a$. Besides, it is an economic way to take advantage of sedimentation to fill offshore oil field and change the offshore operation to land extraction.

Photo 4-1 Heavily sediment-laden flow from the Yellow River entering into the Yellow River mouth [Yellow River Conservancy Commission]

Photo 4-2 Sediment deposition on the Yellow River Delta

Since 1855, the newly-generated land area is about 2500 km^2, the average annual land formation area is 22.5 km^2/a, it was 23.6 km^2/a during the period of 1855~1954, 24.9 km^2/a during the period of 1954~1976, 14.7 km^2/a during the period of 1976~1992, about 8.6 km^2/a after 1992, as shown in Table.4.2.

Table 4-2 Continent-building after 1855 in YRD (Liu, 2003)

Peroid	Incoming runoff (bil m^3)	Incoming sediment load(bil t)	Net silting area(km^2)	Net silting rate(km^2/a)	Remark
1855~1954			1510.0	23.6	Natural flow way
1954~1976	44.51	1.148	548.3	24.9	Shenxiangou and
1976~1992	27.12	0.657	364.4	22.8	Diaohekou outlets
1992~2001	10.90	0.306	77.3	8.6	Qingshuigou outlet

Along with the reduction of incoming water and sediment load, the extension rate and land formation rate of the Y ellow River mouth have been greatly reduced, and some of the coast area was eroded back.

As shown in Fig.4.4, the Yellow River coast was generally in extension during 1855~2000. Photo.4. 3 shows the change in the Yellow River Mouth in recent years. After the outlet divagated to Qingshuigou outlet in 1976, the average annual extension rate was 2.3km in the years of 1976~1994. The offshore of Qingshuigou outlet extended 11km in 1976, 5km in 1977, but the extension rate reduced sharply in the followed years. Some offshore areas were retrograded evidently. Therefore, sediment can prevent coastal line erosion.

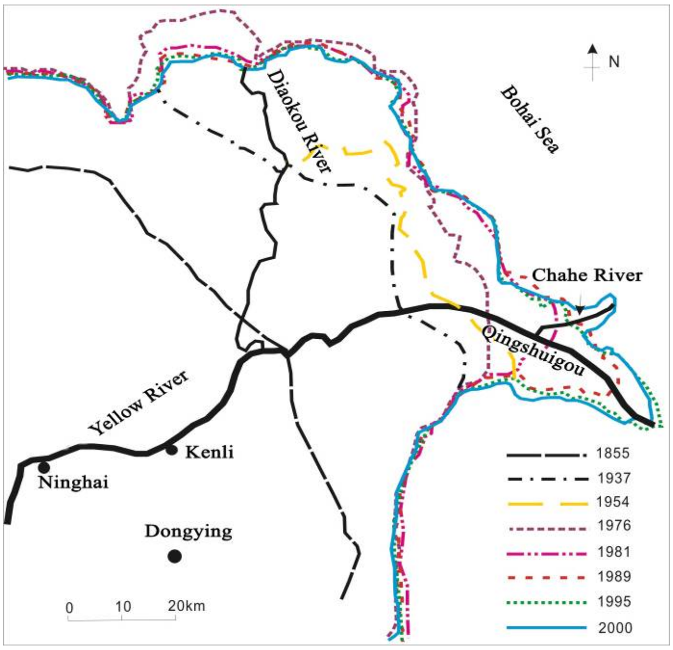


Fig. 4-4 Variation of the Yellow River coastline after 1855

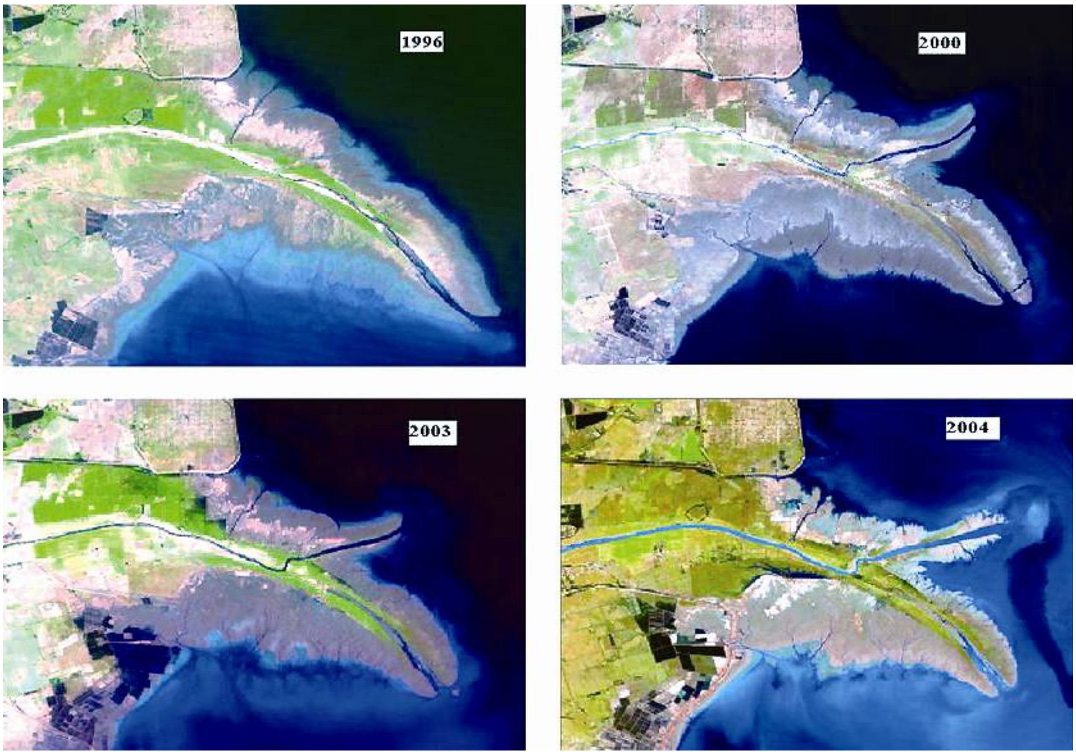


Photo 4-3 Change in the Yellow River Mouth in recent years

The costal area of the Yellow River Delta is in alternations of extending by siltation of river sediment and retrograding by erosion of tidal current. According to expert calculation, the rate of siltation to retrogradation of the coastal line approximately is 4 to 1 (Mao, 2003). As the coast of the Yellow River Delta is concerned, the equilibrium condition should be 0.3 billion t of incoming river sediment load, that is when the incoming sediment load is larger than 0.3 billion t, the coast will be extended, otherwise it will be retrograded.

4.3 Comprehensive utilization of dredged sediment at the estuary

4.3.1 Depositing floodplains

Dredged sediment can be used for several purposes. Dredged sediment can be disposed on floodplains to eliminate big elevation differences among floodplains, which can stabilize floodplains and fix the main channel, prevent floodwater flow along the dike, change the floodplain into fertile land, and reduce the probability of overflow, all of which are beneficial to the production in the floodplain area.

The level of berm on the east and north banks of the Yellow River Mouth is 1.2~2.9 m higher than that of the dike-footing between Xihekou and Qing 7, the transverse slope of the floodplain is large, the probability of levee channel or even rolling current will increase, which threaten the safety of the main embankments, and worsens flood control situation. If dredged sediment can be used to fill the low floodplain area and rise the floodplain 1.5~2.5m, then big elevation differences among floodplains can be eliminated, floodplains and the main channel can become more stable and floodwater flow along the dike can be prevented. In this way, floodplains can be changed into fertile land, reducing the probability of flood water overflowing the floodplain and being beneficial to the production. There are 290 km^2 floodplain area on the north bank and 120 km^2 on the north bank respectively. If the floodplain is to be aggraded by

2.0m in average, 6.58 billion m^3 of sediment will be needed.

4.3.2 Depositing dikes

Dredged sediment can be used to fill the back of dikes to prevent dangerous situations, such as water seepage, piping, leaks and cracks on the levee, thus enhancing the ability of dikes to protect against floods. Dredged sediment can be used to maintain the coastline, aggrading the bottom of the sea dikes; enhancing the resistance of the dike to the influence of wind, waves, and sea current; and stabilizing the coast.

Based on the experience of dredging at home and abroad, warping for levee consolidation combined with dredging was put forward in 1990's. The technique is a combination of desilting the river channel and harnessing the river regime as well as consolidating the levees.

The processes are as follows. Firstly dredges the sediment from channels or point bars by dredgers or pumps, then transports it by pipelines to the warping area located behind the levees. The channel, pipeline, and warping location should be planned focusing on the position of levees, channel or floodplain and dredger (pump) capacity. The warping techniques influence on the environment and are of easy operation owing to one-side river dredging. From 1970's up to now, more than 220 motor boats were used and hundreds km of levees have been consolidated, which is really significant to enhance the levee safety, lessen the levee construction investment, and save farmland, etc.

4.3.3 Land formation

Dredged sediment can be used for land creation to prevent intrusion of seawater, water-logging, serious saline-alkali and degradation, and improve the environment, and thus improve the land so that is can be developed and utilized. Dredged sediment can be used to maintain the coastline, aggrading the bottom of the sea dikes; enhancing the resistance of the dike to the influence of wind, waves, and sea current; and stabilizing the coast. According to Cheng, for the above-mentioned usage of dredged sediment, 1.3 billon m3 of sediment will be needed. Supposing the annual amount of dredged sediment is 0.015 billon m3, 87 years of dredged sediment would be needed.

Dredged sediment can be used to fill the sea and make land. The oil fields within Kendong and Qingdong lie between the inter-tidal zone and –15 m bottom contour; in order to convert offshore oil extraction to land-based oil extraction, over 10 billion m3 of sediment will be needed. It is obvious that the utilization of dredged sediment has many prospects.

4.4 Creating wetlands with sediment

The Yellow River Delta possesses the youngest, widest, best saving and largest wetlands of China. Photo 4-4 ~ Photo 4-6 show beautiful wetlands in the Yellow River Delta. According to measured data as shown in Table 4-3, the total areas of wetlands in the Yellow River delta reached 182376 km^2 in 1998. Since 1980's, the total areas of wetlands in the Yellow River delta have been in increase, and the areas of constructed wetlands, reservoirs and pools also have been in a stable increase, Human activities, the Yellow River drying-up, and water resources shortage are the reasons for the area of wetlands alternation. (Chen, 2003)

Photo 4-4 Flourishing plants on the Wetland of the Yellow River Delta (http://dongying.dzwww.com/)

Photo 4-5 Aquatic plants on the wetland of the Yellow River Delta (http://my.lotour.com/)

Photo 4-6 Lots of birds flying on the Wetlands of the Yellow River Delta (http://wwfchina.org/...)

Table 4-3 Changes in wetland areas of Yellow River Delta (unit:km^2)

Types / Years	Paddy field	Reed marshes	Shoal	Brine pan	Reservoirs	Pools	Total
1981	4763.6	69223.9	80000.4	335.2	1954.1	3000	159277.2
1990	25409	32721	86068	2627.5	12831.6	14410	174067.1
1998	19103	24382	101914	3721	14410	18846	182376.0

In the littoral area in the east and north of the Yellow River Delta especially between the Xiaodao River mouth in south and the Majia River mouth in north, as shown in Fig. 4-5 and Table 4-4, there are large area continuity wetlands, in the forms of coastal shoal wetlands, the present and past channels of the Yellow River estuary wetlands, and riparian wetlands. While in the inland area in the middle and west area of the Yellow River Delta, there are scattered and separated constructed wetlands, such as reservoirs, pools and paddy fields, etc.（Xing, 2005).

Table 4-4 Wetlands area in seven districts of the Yellow River Delta (Cui, 2001) unit:km^2

County	Inundated	Ditches	Reed marshes	Brine pan	Shrimp pool	Shoal
Wuli	47.8	123.44		129.48	84	209.27
Zhanhua	112.28	132.73	1.42	8.95	88.5	100.34
Hekou	73.54	100.15	116.34		72.8	430.49
Lijin	33.46	71.58	17.77			129.74
Kenli	73.6	142.01	79.12		52.84	326.58
Dongying	106.88	156.5	18.96	8.33	55.29	110.55
Guangrao	14.46	60.6	2.94	22.6		21.78
Total	462.02	787.01	236	163.36	353.28	1328.75

I. Natural wetland

I_1. Sublittoral wetland

I_2. Intertidal wetland

II. River mouth wetland

III. River wetland

IV. Marshland

V. Wet meadow

VI. Constructed wetland

VII. Farmland

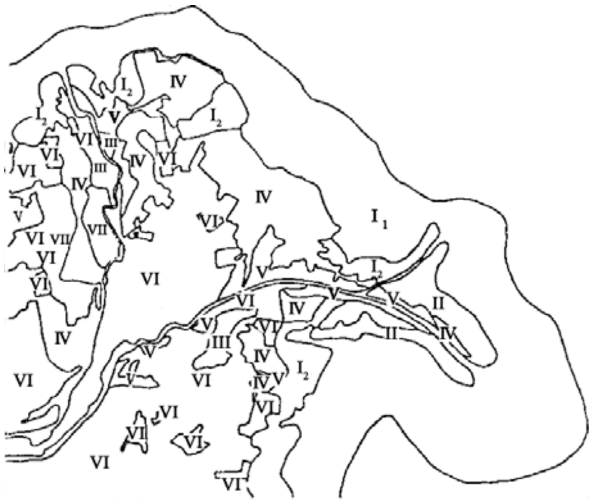


Fig. 4-5 Distribution of wetland in Yellow River Delta in 1996

During the wetlands forming processes in the Yellow River Delta, sediment plays an important role in depositing land and building continent. Without sediment deposition, there would be no so large wetlands in the Yellow River Delta. Photo 4-7 shows the wetlands-building with sediment in the Yellow River Delta. The forming and vanishing of coastal wetlands are related closely in sedimentation. At estuary, the sediment carried by the river runoff will be suspended by tidal wave and re-deposit along coastwise by diffusion effect, and finally forms new wetlands periodically submerged by tidal waves. Photo 4-8 shows wetland along the Yellow River coast.

Photo 4-7 Wetlands-building with sediment [website: www.sdhh.gov.cn]

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