United Nations
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CONTROLLING THE YELLOW RIVER: 2000 Years of Debate on Control Strategies

CONTROLLING THE YELLOW RIVER: 2000 Years of Debate on Control Strategies

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ABSTRACT

Throughout the history of China, the Yellow River has been associated with frequent flood disasters and changes in the course of its lower reaches. The river carries sediment produced by soil erosion from the Loess Plateau and the Qinghai-Tibet plateau and deposits the sediment on the channel bed and in the estuary. The erosion rate accelerated in the past 2000 years due to climate change. The sedimentation rate increased from 1-3 mm per year to 30 mm per year from 00 A.D. to 1855, mainly due to human activities. From 1855-1985 human activities greatly accelerated the sedimentation and the sedimentation rate rose to 50-100 mm per year. Over time, a perched river formed that frequently breached its levees. From 602 B.C. to 1949 the river experienced 1,593 levee bursts, flooding vast areas, in 543 years and claiming millions of human lives. The river shifted its main course (600-700 km long) by avulsion 26 times with the apex around Zhengzhou, resulting in devastating calamities and numerous old channels, including 8 major shifts (5 natural and 3 human-caused) with the river mouth alternating between the Bohai Sea and the Yellow Sea. Because of its wild behavior, the lower Yellow River was dubbed "the sorrow of China". The 700 km long lower reaches have moved across throughout the north China plain leaving numerous old channels.

Controlling the Yellow River has a history of more than 3,000 years. Levee construction was the major strategy of flood control. Two extremely different strategies were proposed and practiced in the past 2000 years, i.e. the wide river and depositing sediment strategy and the narrow river and scouring sediment strategy. Wang Jing implemented a large-scale river training project in 69 A.D.. He completed and enhanced the levees and built many diversion channels and weirs. He constructed many gates about 5 km apart on the grand levees. The river was confined by the enhanced levees tens of kilometers apart, giving enough space for sediment deposition. The riverbed silted up at a low speed of less than 1-cm per year. During great events, water and sediment were diverted through the water gates into diversion basins. In the following 800 years the river was tamed and no big flood disasters occurred.

From 850 A.D. to 1500 A.D. the river woke again and became very active. Sedimentation on the riverbed resulted in high flood stages approaching the crest of the grand levee. The Grand Levee was breached once per 2 years during the period. Closing the breached levee was a hard job for the river training engineers and the technology of levee defence was developed. Because of population growth, the flood diversion strategy was more difficult to implement. Pan Jixun proposed the strategy of narrowing the river and confining the flood within the mainstem channel, in order to raise the velocity and keep

the carrying capacity of the flood high, preventing sediment from depositing and even promoting bed sediment scouring. He regulated the levee system, blocked many branches of the river and made the river flow in a single channel in the lower reaches in the period 1565-1592. After Pan Jixun, sediment deposition in the lower Yellow River channel increased to 5-10 cm per year. The river migrated from south to north and captured the Daqing River in 1855 due to the levee breach at Tongwaxiang.

Since the 1950s the Yellow River Water Conservancy Commission (YRCC) has been the leading body for river training. Wang Huayun, the chief of the YRCC, proposed and implemented his training strategies in this period. The main strategies are to reduce flood discharge with reservoirs, enhance the capacity of the river channel by enhancing and reinforcing the levees, and retaining floodwater in detention basins. These strategies are referred to in short as: build a wide river and reinforce the levees, upper reaches storing, lower reaches discharging and two sides retaining. Wang's strategy is almost the same as that proposed by Wang Jing.

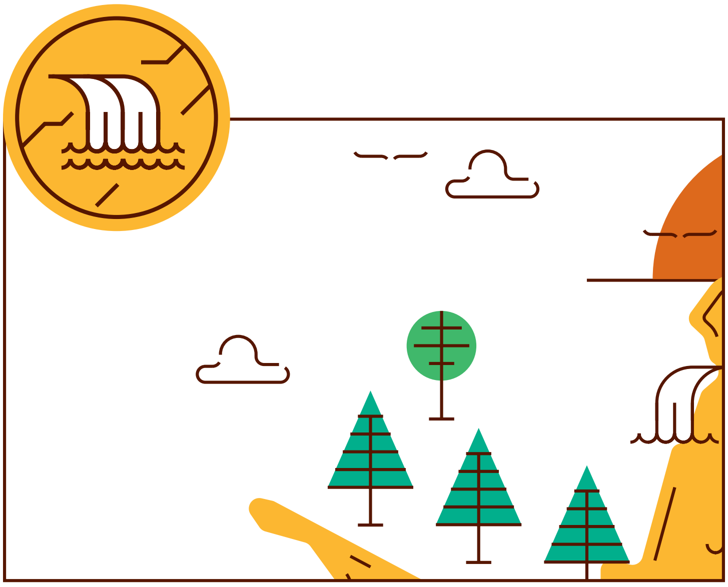
This paper analyzes the levee breaches and flood disasters in the past 2000 years and the compares results of the two extremely different strategies. The narrow river and scouring sediment strategy has only short term effects on levee breach control and flood mitigation. The wide river and depositing sediment strategy can essentially mitigate flood disasters and reduce levee breaches for a long term period of time. The paper also discusses the new challenges and new strategies for Yellow River training and management. The Sanmenxia Project was the first large dam on the Yellow River, and was regarded as a failure of the modern river training, because the extremely high rate of sedimentation caused floods in the Weihe River and the benefit from hydro power generation was reduced to the minimum. The last chapter discusses the merits of the project, its role in the river training strategy and the future fate of the dam.

Key words: Yellow River, Levee breaches, Avulsion, Wide river and depositing sediment strategy, Narrow river and scouring sediment strategy, Sanmenxia Reservoir, Land creation.

CONTENTS

1.

Flood disasters and avulsions of the lower Yellow River



1.1.
The Yellow River Basin

The Yellow River shown in Fig. 1 has a drainage area of 795,000 km^2 and a length of 5,464 km, making it the second longest river in China. The river is divided into its upper reach, middle reach and lower reach for convenience of management and discussion. The upper reach extends from the source to Hekou, which is located at the turning point from flowing east to flowing south in Inner Mongolia. The middle reach extends from Hekou to Taohuayu, which is located between Xiaolangdi and Huayuankou. The lower reach extends from Taohuayu to the river mouth with a total length of about 750 km.

The long-term mean annual sediment load at Sanmenxia Station was 1.6 billion tonnes before 1980, with a maximum annual load of 3.9 billion tonnes. The river ranked first of all the world's rivers in terms of sediment load (Qian and Dai, 1980), but the sediment load has reduced greatly in the past 30 years. The long term (1950-1985) average sediment concentration was 40 kg/m^3 and the maximum sediment concentration was 911 kg/m^3. The ratio of the highest annual runoff to the lowest is 3.4 and the ratio of the highest annual sediment load to the lowest is 10. More than 60% of the water and 85% of the sediment are transported in the flood season from July to October. The Yellow River, recognized as the cradle of Chinese civilization, is arguably the most challenging river in the world. It carries the heaviest sediment load and often experiences erosion and sedimentation that make the river channel extremely unstable. The river watershed is mostly arid and semi-arid with a long-term mean annual runoff depth of only 77 mm and a total annual runoff 58 billion m^3. The water resource per capita of the watershed is only about 500 m^3, one quarter of the average for China.

The sediment load of the lower Yellow River is mainly composed of silt; its mineral composition is quartz, feldspar, calcite, and illite. The sediment is readily suspended and no distinct bed load can be detected. Table 1 lists long term average values of water discharge and sediment load for of the river. They were obtained by averaging the recorded values over 39 years (1950-1989). The long term mean annual sediment load is 1.6 billion tonnes at Sanmenxia and the figure reduces to 1.0 billion tonnes at Lijin. In other words about 60 billion tonnes of sediment are deposited in the 600 km long river section between Sanmenxia and Lijin per 100 years. We may estimate that the river bed was raised by more than 10 m in 100 years. This high rate of sedimentation is the main reason for the frequent levee breaches and flood disasters. The numerous levee breaches have resulted in the spreading of a huge amount of sediment from the river channel outside of the grand levees.

Except for the 0.6 billion tonnes of sediment depositing in the river upstream of the Lijing station the remaining load of 1.0 billion tonnes of sediment is transported to the Yellow River delta. About 90% of the sediments deposited at the river mouth for building the delta and only about 10% is transported beyond the river mouth by sea currents. The sedimentation at the river mouth creates land at a rate of 20-25 km²/yr. In fact the North China plain which covers about 250,000 km² was created by river sedimentation in the Holocene and late Pleistocene.

Table 2 lists the discharge of floods of various recurrence periods for flood control design. The highest peak discharge usually occurs at Huayuankou, which is near Zhengzhou and is the first important hydrological station in the lower reach of the river. The peak discharge with a 100 years recurrence period is 22 times higher than the average discharge, which poses a great flood threat to people in Henan Province.

Fig 1.

The Yellow River and its tributaries (Note: Longmen, Sanmenxia, Xiaolangdi, Huayuankou, Lijin are shown on the map; Important hydrological stations are indicated in the map by numbers as follows: 1 Luokou; 2 Aishan; 3 Gaocun; 4 Jiahetan; 5 Shangyuantou; 6 Chaoyi; 7 Huayin; 8 Lintong; 9 Tongguan; 10 Diaoqiao)

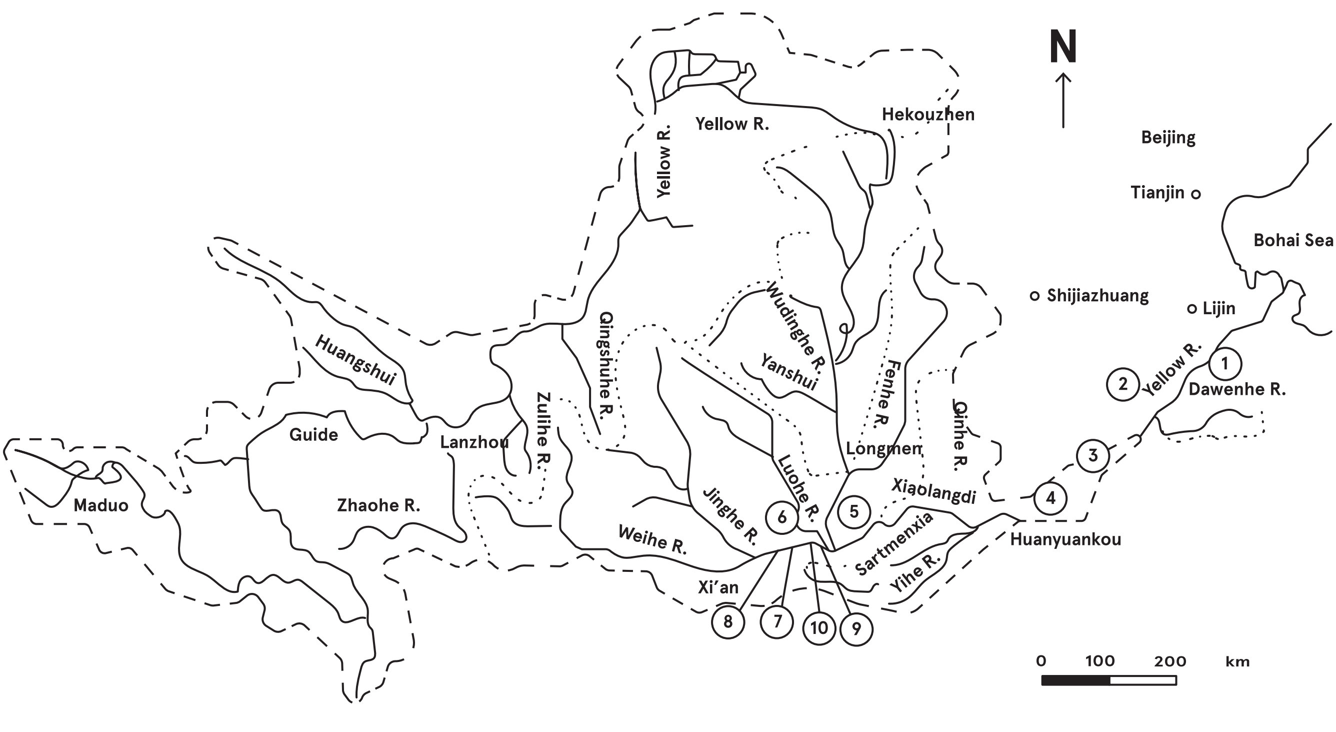


Table 1.

Mean annual flow and sediment load of the Yellow River during the period 1950-1989.

Hydrologic Station	Huayuankou (Zhengzhou)	Lijin (Dongying)
Annual Runoff	43 billion m ^{3}	30 billion m ^{3}
Annual Sediment Load	1.6 billion tonnes	1.0 billion tonnes
Average Sediment concentration	40 kg/m ^{3}	33 kg/m^3
Median diameter of suspended sediment	0.019 mm	0.019mm
Maximum daily mean discharge6	1,860 m^3/s	5,400 m^3/s
Annual mean discharge	1,364 m^3/s	951 m^3/s

Table 2.

Flood features of the lower Yellow River (Chen, 1999)

Hydrological Station	Catchment (km^2)	Peak discharge (m^3/s)		5 days runoff (bm^3)		12 days runoff(bm^3)	
		100 yrs	1000 yrs	100 yrs	1000 yrs	100 yrs	1000 yrs
Huayuankou	730,036	29,200	42,100	7.13	9.84	12.5	16.4
Xiaolangdi	694,155	29,200	42,100	6.24	8.70	10.6	13.9
Sanmenxia	688,421	27,500	40,000	5.91	8.18	10.4	13.6

1.2 Flood Disasters in History

According to historic record, the Lower Yellow River breached its levees 1593 times between 602 B.C. and 1949. On average 2 levee breaches and flood disasters occurred every 3 years. Among them, 543 levee breaches resulted in great flood disasters and death tolls. These levee breaches also caused 26 changes in the course of the lower Yellow River and resulted in several tens of abandoned channels in the North China plain. Table 3 lists the flood disasters in the past 900 years. Data are lacking for several major events with high death tolls. For instance, the levee breaches and flood disasters of 1117 and 1887 killed 2.5 million people, but were reported only very briefly in the "History of the Song Dynasty" and newspapers.

Table 3.

Disasters caused by the Yellow River floods in the past 900 years

Year.Month	Peak discharge (m^3/s)	Flooded counties and villages	Death toll
1117		Yingzhou and Cangzhou	1,000,000
1128			Estimated >200,000
1642.8		Kaifeng city	340,000
1761.8	32,000	24 counties	50,000
1843.8	36,000	27 counties	30,000
1855.8	27,000	53 counties	200,000
1887.9		Kaifeng, Zhongmu, Zhengzhou	>1,500,000
1933.8	22,000	67 counties1	8,293
1938.6		44	890,000
1958.8	23,000	1700	0

Several disastrous floods are briefly summarized as follows (IWHR and WUHEE, 1985):

Flood in 1843 - On August 6-8, 1843 a rainstorm occurred in the middle reaches of the Yellow River, which generated the biggest flood in recorded history (1000 yr reoccurrence). The peak discharge in the reach from Shanxian to Sanmenxia was up to 36,000 m^3/s and the total runoff in 12 days was over 11.9 billion m^3. The flood stage in the reach from Tongguan to Xiaolangdi (see Fig. 1) was the highest in 1000 years of history. Twenty-seven counties and 15,000 villages were flooded and 30,000 people were killed.

Tongwaxiang Avulsion - The Tongwaxiang breach that occurred in 1855 was a very painful event in Yellow River history and resulted in the shift of the lower Yellow River channel from south to east, as shown in Fig. 2. Before the avulsion, the Yellow River flowed from Henan province to Jiangsu Province and discharged into the Yellow Sea for 700 years in the Ming and Qing dynasties. Thus the south course is named Ming-Qing course. The Towaxiang Breach changed the river from discharging into the Yellow Sea to discharging into the Bohai Sea in Shandong Province.

A flood from the upstream magnified by heavy rainfall in the lower reaches breached the grand levee at Tongwaxiang on June 18, 1855. The river poured out and inundated 8 counties, and finally pirated the Daqing River Channel. Consequently, the Yellow River shifted its major course from south to north and flowed into the Bohai Sea. The Daqing River was a small river and the river channel could not accommodate the huge volume of water from the Yellow River. Thus, the flood water broke through the levees at many places along the Daqing River channel before it flowed into the Bohai Sea. Moreover, there was no channel from Tongwaxiang to the Daqing River, a distance of about 100 km. The flood water flowed across the plain and destroyed villages and towns. More than 200,000 people were killed and 7 million people lost their home shelters and farm lands.

In the first 10 years after the breach the central government hesitated and took no action to stabilize the river. The river flowed wildly and flooded frequently because there were no strong levees to accommodate the river water and the government hesitated to move the river back to the south or build a new levee system to stabilize the north channel. The ministers argued for 30 years: Zeng Guofan, Li Hongzhang, Li Hanzhang, Zhang Zhiwan advocated stabilizing the Yellow River on the new course. The Shandong Governors Ding Baozheng and Zhang Yao wanted to bring the river back to the south Ming-Qing course. In this period the river was very unstable because the previous Daqing levee was very weak and there was no channel between Tongwaxiang and the Daqing River channel. Millions of people were killed in Shandong province. The Shandong Governor Ding Baozheng had to construct a levee on the north side of the new course in 1865. The new river course was finally stabilized about 40 years after the Tongwaxiang Breach and since then the river has flowed into the Bohai Sea via Lijin.

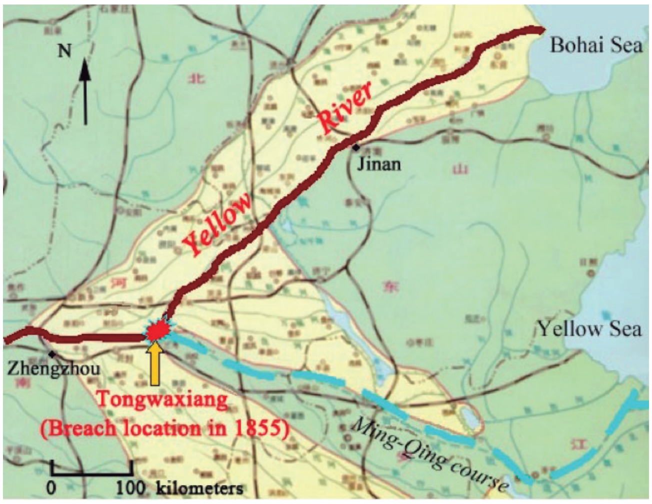


Fig. 2.

The Towangxiang levee breach and the shift of the Yellow River course from south to north

Huayuankou Levee Explosion - In 1938 the Japanese army invaded China moving from the northeast to the southwest. On June 9, 1938 the embankment at Huayuankou (near Zhengzhou) was broken by the Chinese army attempting to halt the invasion by the Japanese army. The government did not evacuate the people but only informed the people near Huayuankou and forced them leaving their homeland.

The army buried explosives on the grand levee and breached the levee. The river water poured out of the levee breach, flooded 44 counties and killed 890,000 people. About 4 million people lost their homes and farmland. They had to leave their homeland and fled for safety, as shown in Fig. 3.

Fig 3 (A)

Water flowing out of the breach one day after the levee explosion at Huayuankou

Fig. 3 (B)

About 4 million people left their homeland and fled for safety (YRCC, 2001).

Fig. 4 shows that the Yellow River water flowed onto the plain to the southeast and captured the Huaihe River. After this, the river flowed on the plain without a fixed channel between Huayuankou and the Huaihe River for 8 years. The river water deposited about 10 billion tonnes of sediment and created the Huangfan flooded area of 54,000 km², which is a desert-like area of land with low productivity and poor vegetation. The fan-shape Huangfan flooded area covered the plain and totally destroyed the drainage system. No action was taken to stabilize the river until the end of the Second World War.

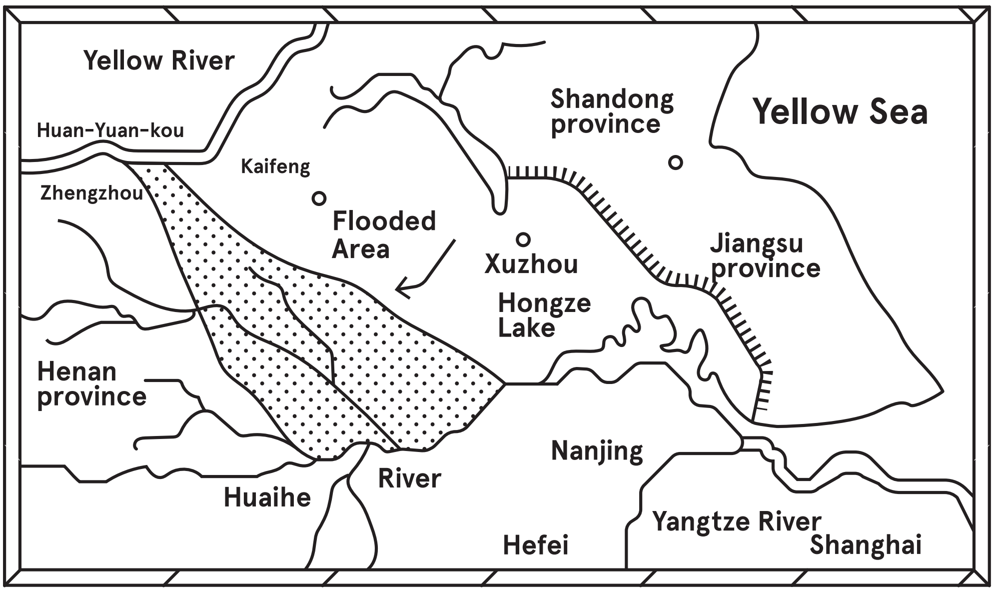


Fig. 4

The man-made flood caused by blowing up the levee at Huayuankou in 1938. The flood water flowed onto the plain and finally flowed into the Huaihe River, creating the 54,000 km² Huangfan desert

After the Second World War the government wanted to move the river back to its original north channel in 1946. The first effort failed because the people could not close the breach. In the low flow season of 1947 hydraulic engineers applied a new method and successfully closed the breach, as shown in Fig. 5.

Fig 5

Closure of the Huayuankou breach finally moved the river back to its north channel

1.3. Avulsions of the Lower Yellow River

Avulsion is a kind of non-continuous channel shifting. Avulsion was defined by Allen (1965) as the abandonment of a part or the whole of a channel belt by a stream in favour of a new course. Avulsion is an inevitable result of river aggradation and is, therefore, closely related to the sediment load the stream carries. Avulsions are classified into nodal and random avulsions (Leeder, 1978). If, over time, more than 2 avulsions occur at approximately the same location this is called nodal avulsion. Random avulsion can occur from any point along the active channel belt. Field (2001) studied the channel avulsion on alluvial fans in southern Arizona. Channel avulsion invariably occurs where bank heights are low and often at channel bends. The action of aggradation during floods is critical in the avulsion process since the greatest amount of overland flow is generated where bank heights are lowest.

Avulsion is perhaps a final aspect of river behavior and concerns the large-scale movement of the river course. The process occurs in meandering, braided, and wandering rivers and is recorded by abandoned channel belts preserved on floodplains. The periodicity of avulsion appears to be on the order of 100-1,000 years. The diversion is actually gradual, but can be considered instantaneous compared with the recurrence time of avulsions. Avulsions are common only where the streams are aggrading relative to their floodplain. In heavy sediment-laden rivers avulsion becomes the dominant mechanism of channel shifting on alluvial fans and river deltas.
Sediment-laden rivers undergo periodic shifts. Avulsion occurred in the Mississippi River Delta along the coast of Louisiana as successive channels searched for gradient advantages over their precursors (Leeder, 1983). The same situation has occurred for the Kosi River in India. From 1730-1960, the Kosi River shifted across the Kosi River fan from east to west at a frequency of one avulsion per 23 years, with the nodal apex around Jogbani (Gole and Chitale, 1966). Major avulsions or changes in channel direction and form occur regularly, particularly in semiarid areas and even in humid regions, during catastrophic, rare floods. A single rainstorm of 3 days duration in California in 1938 produced as much as 189 m^3/km^2 of sediment, primarily from cultivated land, and initiated about 700 new channels on an area of 162 km^2 (Leopold et al., 1964).

Slingerland and Smith (1998) studied the necessary conditions for a meandering river avulsion. They presented a 1-D model and showed that whether a crevasse heals, runs away to an avulsion, or reaches a steady state depends upon the ratio of crevasse to main-channel bed slopes, the height of the crevasse bottom above the bed of the main channel, and the bed grain size. For fine to medium sand, crevasse slopes greater than about eight times the main channel slope are predicted to capture all the main flow.

The Mississippi River, transporting 240 million tonnes of sediment annually, extends into the Mexico Gulf at a rate of 150 m/year, and shifts its course once per 1,000 years (Fisk, 1944). The Danube River, carrying a much smaller sediment load, is quite stable with a frequency of channel shift once per 2,300 years (Panin et al., 1983). The Fraser River in Canada shifted its course in 1827, 1864, 1892, 1896, 1900, and 1912, with a frequency of about once per 17 years (Clague et al., 1983). The Po River in Italy shifted its delta channel 6 times in the past 3,000 years, about once per 500 years (Gandolfi et al., 1982). The Gediz River in Turkey shifted 6 times in the last 10,000 years, with a frequency of about once per 1,600 years. The latest shift of the river occurred in 1980, and since then the river flows in the present channel, the Kirdeniz River (Aksu and Piper, 1983). The frequency of avulsion of the Rhine-Meuse River is very low because the river carries much less sediment. Stouthamer (2001) studied the avulsions in the Holocene Rhine-Meuse Delta. Five avulsions occurred in the Rhine-Meuse Delta from about 6,500 yr BP to 1950 yr BP, when the Rhine-Meuse Delta experienced aggradation. The frequency of avulsion is about 1/800 years.

At present, an avulsion is occurring on the Mississippi River. Since the 1930s, the river gradually began shifting to the Atchafalaya River. Since 1950s the avulsion has been stopped by man-made hydro structures, which control the flow into the Atchafalaya at 1/3 of the discharge with 2/3 of the discharge remaining in the old Mississippi River channel to guarantee sufficient channel depth for navigation.

Compared with the Mississippi and most of the world's rivers, the frequency of avulsions of the Yellow River is much higher. The river carries sediment produced by soil erosion from the Loess Plateau, which deposits on the channel bed and in the estuary. Xu (1998) studied the sedimentation rate of the lower Yellow River applying map comparison, historical literature studies, modern data analysis, and ^{14}C dating. He divided the past 13,000 years into 4 periods, as shown in Fig.6: 1) from 11,000 B.C. to 3,000 B.C. is a period of low sedimentation with an average sedimentation rate of only 0.2 cm per year; 2) from 3,000 B.C. to 600 A.D. is a period with accelerated sedimentation due to climate changes. The sedimentation rate increased to about 0.5 cm per year in this period; 3) from 600 A.D. to 1855 is a period with accelerated sedimentation caused by human activities. The average sedimentation rate increased to 1-3 cm per year; 4) since 1855 human activities have accelerated the sedimentation to an extremely high degree and the sedimentation rate has risen to 5-10 cm per year.

The measured transverse riverbed profile at the Sunkou cross section in Fig. 7 shows that the sedimentation of the lower Yellow River raised the riverbed and floodplain by about 5 m in the past 70 years. Sunkou is a typical cross section in the lower Yellow River, which is not very wide and not narrow and is located in the middle of the lower reaches of the river.

Over time, a perched river formed that frequently breached its levees. From 602 B.C. to 1949 A.D. the river experienced 1,593 levee bursts, flooding vast areas in 543 years and claiming millions of human lives. The river shifted its major course (600-700 km long) by avulsion 26 times with the apex around Zhengzhou resulting in devastating calamities and numerous abandoned channels, including 8 major shifts (5 natural and 3 human-caused) with the river mouth alternating between the Bohai Sea and the Yellow Sea. Because of its wild behavior, the lower Yellow River was dubbed "the sorrow of China". The 600 km long lower reaches have swept across the North China plain leaving numerous old channels. Fig. 8 shows the major avulsions of the river from 602 B.C. to 1855 A.D. and the old channels and the land created by the river.

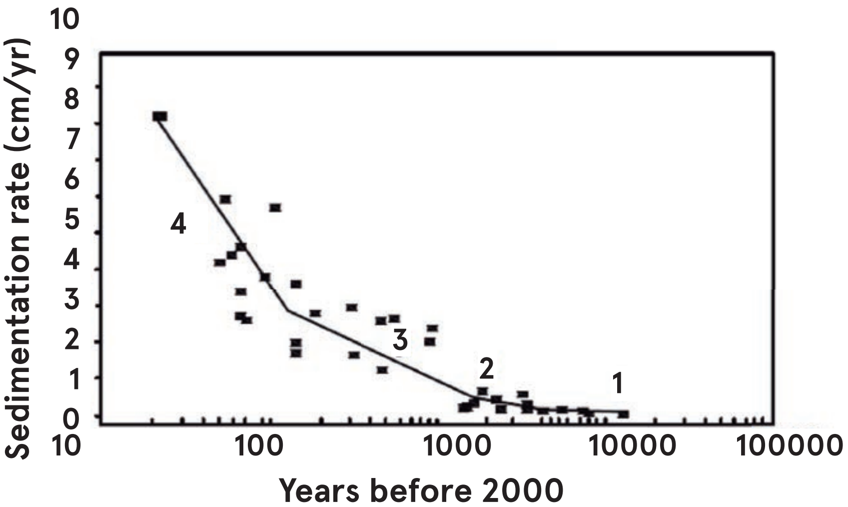


Fig. 6

Sedimentation rate in the lower Yellow River during the 4 historical periods: 1) geological sedimentation; 2) sedimentation due to climate change; 3) sedimentation due to human activities; 4) accelerated sedimentation due to human activities (after Xu 1998)

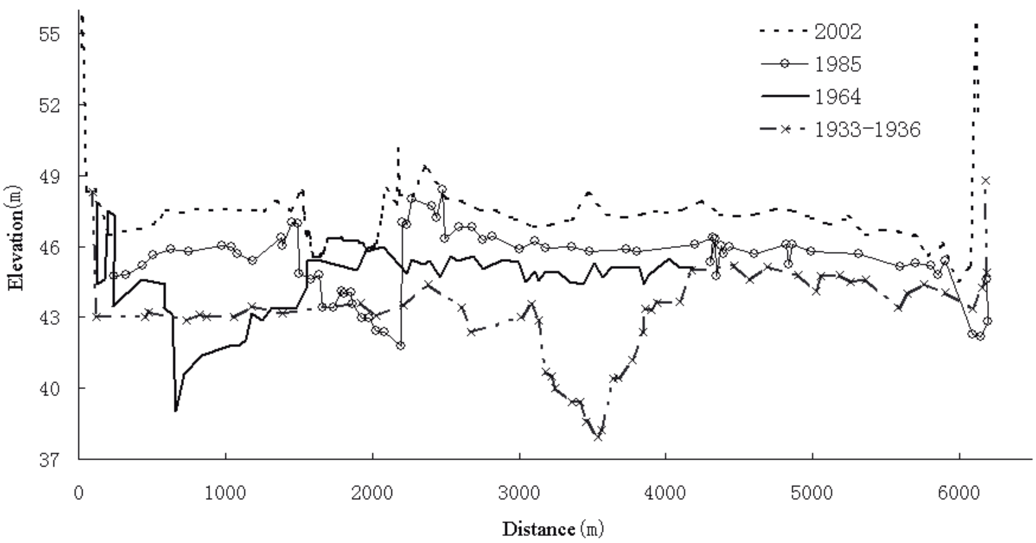


Fig. 7

Sedimentation caused changes in the riverbed at the Sunkou cross section during the period 1933-2002 (Sunkou is 300 km downstream from Zhengzhou and 440 km upstream from the river mouth)

In the Yellow River delta, minor avulsions occur at high frequency, which involves a length of about 60 km of delta channel. The Yellow River carries sediment from the Loess Plateau in central China to the delta and caused the delta to expand by 2,000-3,000 ha per year. The extension of the river channel reduces the gradient and capacity of the channel resulting in avulsions. The length of the new channel is about 1/3-1/2 of the previous one and the gradient is 2-3 times higher. Therefore, nodal avulsions occurred around Ninghai (40-100 km from the mouth as shown in Fig. 9) and the river changed its delta channel 11 times between 1855 and 1976. The river channel swept over a fan-shape area with a radius of about 50 km. The present delta was created by rapid sediment deposition in the past 150 years, accompanied by frequent shifts of the channel in the area. The 12 old river channels are shown in Fig. 9 (Wang and Liang, 2000), and each has its own name. The present channel- Qing-Shui-Gou Channel- has been in use since 1976. A recent minor shift of the mouth channel (about 20 km from the mouth) to Chahe occurred in 1996, which is also shown in the figure. More detailed data on the channel shift and location of avulsions are presented in Table 4 (Yin and Chen, 1993, Zhang et al., 1997).

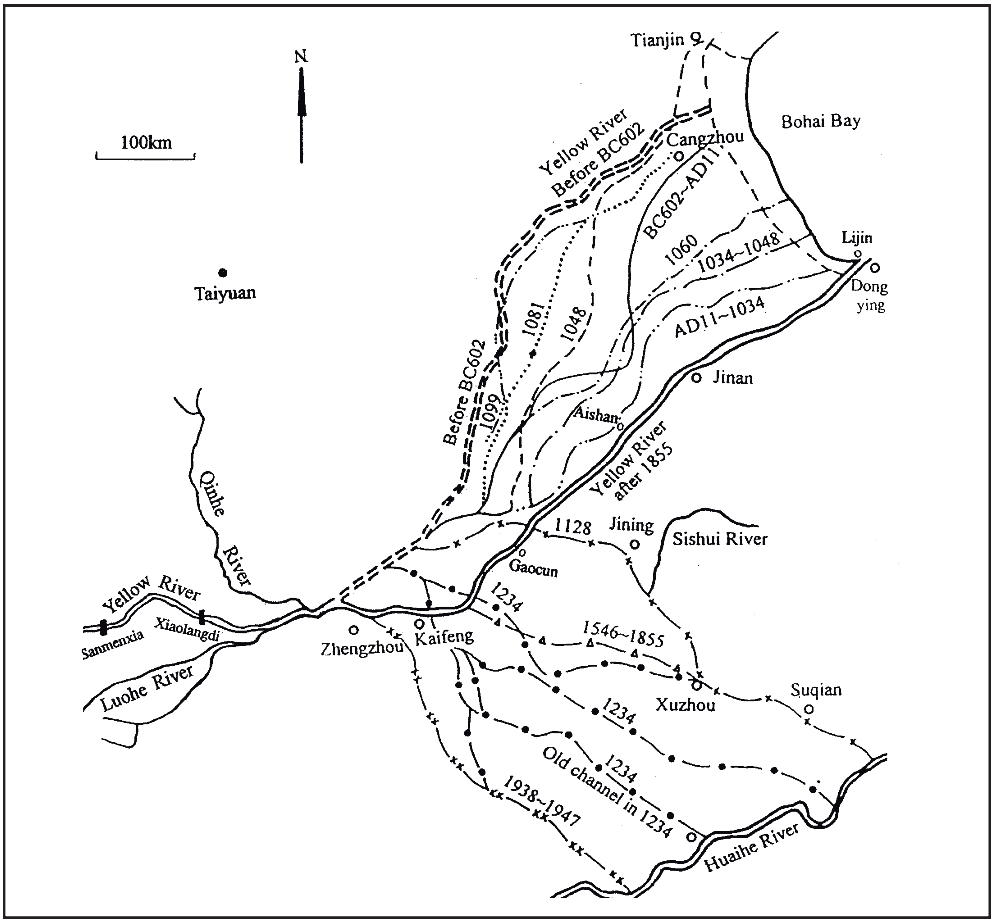


Fig. 8

Migration of the Yellow River and the abandoned channels (major avulsions)

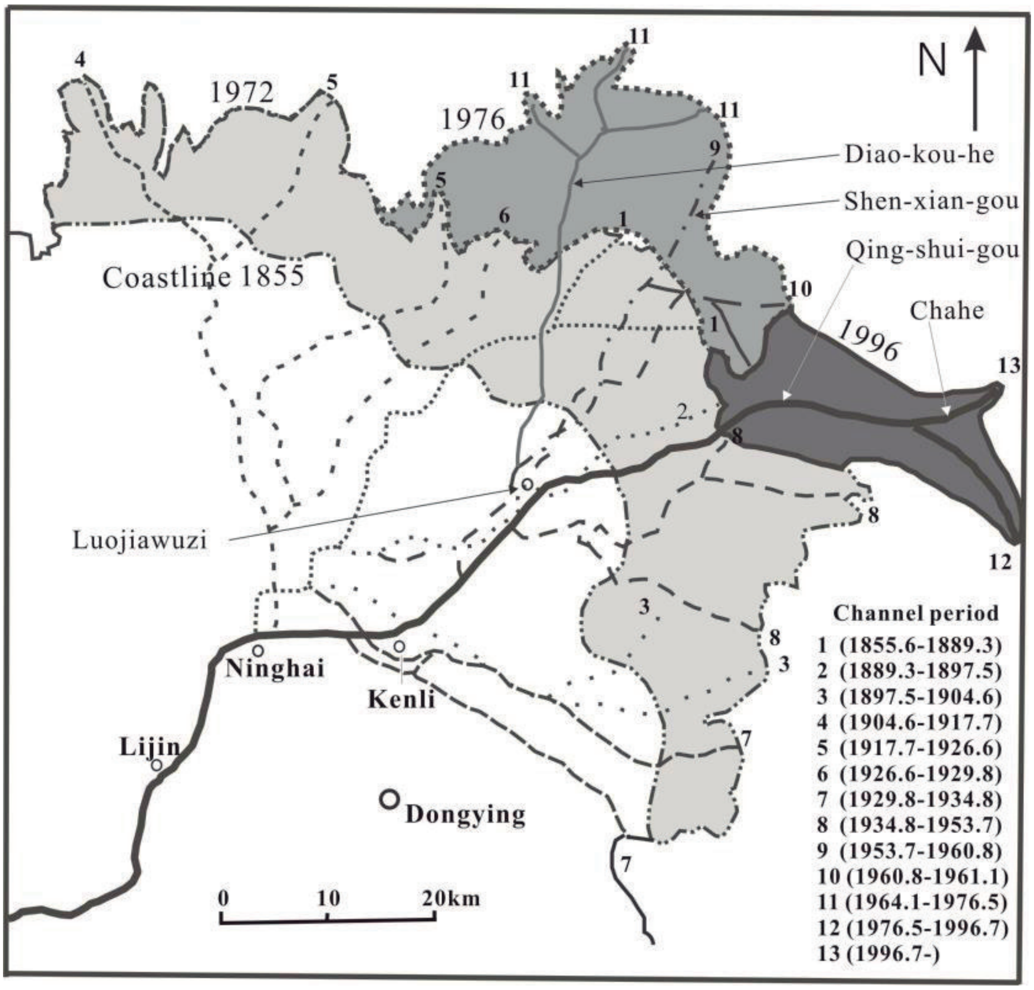


Fig. 9

Nodal avulsions and the abandoned Yellow River channels on the delta. The coastlines show the land created by the river in the periods between 1855-1972, 1972-1976, and 1976-1996

No.	Year	Used time* (years)	Length** (km)	Diversion point	Name of the channel
0	1855	49		Tong-wa-xiang	
0	1881	71			
0	1889.4	32.5***	75		
1	1889.4	61		Xie-jia-yuan	
1	1897.6	5.10	71		
2	1897.6		59	Ling-zi-zhuang	
2	1904.7	5.9	65		
3	1904.7		57	Yan-wo	
3	1917.8	11	63		
4	1917.8		57	Tai-ping-ling	
4	1926.7	6.11	67		
5	1926.7			Ba-li-zhuang	
5	1929.9	2.11	65		
6	1929.9		73	Ji-jia-zhuang	
6	1934.1	3.4	65	Channel changed many times	
7	1934.1			Yi-Hao-Ba	
7	1950		75	Tian-shui-gou	
7	1953.7	9.6	85	Tian-shui-gou	
8	1953.7		75		Shen-xian-gou
8	1964.1	10.6	102		Shen-xian-gou
9	1964.1		70	Luo-jia-wu-zi	Diao-kou-he
9	1976.5	12.4	103		Diao-kou-he
10	1976.5		66	Xi-he-kou	Qing-shui-gou
10	1987		106		Qing-shui-gou
10	1996.7	20.2	112		Qing-shui-gou
11	1996.7		94	Cha-he	Qingshuigou-Chahe
11	1997.12	1.5	102		Qingshuigou-Chahe
11	1999.11	3.5	105		Qingshuigou-Chahe

Table 4

Shifting of the river course on the delta and the 11 river channels

* Used time = the time period the river flowed in a channel. Because the river often breaches the levees and water flowed outside of a channel sometimes, the used time of a channel is less than the time period from when the river began to flow in the channel to its shifting to another channel
** Length = distance from the Lijin Hydrological Station to the mouth of the river
*** 32.5 = 32 years and 5 months

1.4.
Soil Erosion caused Frequent Levee Breaches

On average the delta channel changed once per 10 years. Before the 1950s, the change in the river course was triggered by overflow and levee breaching at the diversion point. Since 1953, the river course has been artificially shifted 4 times. In the spring of 1964, an ice jam occurred and the safety of the Shengli Oil Field in the delta was threatened. The levee at Luo-jia-wu-zi was deliberately breached, and the river shifted from the Shen-xian-gou channel to the Diao-kou-he channel. Before the recent diversion in 1976, people dug the Qing-shui-gou channel at a cost of $1 million. In May 1976, the river course was artificially shifted to the Qing-shui-gou and since then this river channel was safely used for more than 30 years (plus the Qing-shui-gou Channel period). During this period the river created land at a rate of 20-40 km^2/year. It follows the routine of “channel siltation - high flood - breached levee - avulsion.”

The Yellow River has been characterized by a relatively small annual runoff (43 billion m^3/yr) but a very heavy sediment load (1.6 billion t/yr), as listed in Table 1. Its mean suspended sediment concentration was 40 kg/m^3 and, during a flood season, it could reach up to 911 kg/m^3. Fig. 10 shows hyperconcentrated flood at the Kittle Fall, which is located in the middle reaches of the river. The high sediment load of the river was due to extremely high rate of soil erosion in the loess plateau and Qinghai-Tibet plateau.

About 5 million years ago, there were a series of enclosed lakes in the middle reaches of the Yellow River, the last and the largest of which is San-Men paleo-lake. It is elongated in shape, extending from the Sanmenxia Gorge in the northeast to Baoji, Shaanxi Province in the west. Very thick deposits of lacustrine sediment have accumulated in this paleo-lake basin. On the left bank of Sanmenxia Reservoir, about 7 km upstream of the dam, a beautiful section of lacustrine beds 278.3 m thick is exposed which records the depositional history of the lake since 5 Ma BP. In about 150 ka BP the river cut through the Sanmenxia Gorge and flowed east towards the sea (Wang et al., 2002). Since the Yellow River cut through the Sanmenxia Gorge, about 8.6 trillion tonnes of sediment have been transported pass Sanmenxia Gorge (Ren, 2015). Although the Yellow River transported the a very large sediment load to the lower reaches and the estuary, most of the sediment was used for plain and delta building and only a very small part was diffused to the

Fig. 10

Hyperconcentrated flood at the Kittle Fall in the middle reaches of the Yellow River

outer shelf and ocean.

The Yellow River gains most of its sediment from the Loess Plateau in north China, which is underlain by 400 m thick wind-blown mineral dust deposits. About 80% of the sediment transported to the lower Yellow River originates from the loess plateau. The Qinghai-Tibet plateau is another source of the Yellow River sediment. Scientists found that the composition of sediment from the Yellow River underwent radical change after passing through the Loess Plateau. They concluded that the Loess Plateau acted as a sink for Yellow River material eroded from the uplifting Qinghai-Tibet plateau. A major change in the monsoon around 3.6 million years ago caused the onset of the Yellow River drainage system, accelerated erosion of the Qinghai-Tibet plateau and drove loess deposition. At present erosion from the Qignhai-Tibet plateau contributes 20% of sediment to the Yellow River. Fig. 11 shows the high concentration of sediment in a tributary of the Baqu River, which flows

Fig. 11

A high concentration of sediment in a tributary of the Baqu River, which is a tributary of the Yellow River

into the Yellow River upstream of the Longyang Gorge.
According to the British Geological Survey, the Indian Plate moves northward at a rate of 50 mm/yr and collides with the Eurasian Plate, resulting in the uplift of the Himalaya Mountains and the Qinghai–Tibet Plateau (Zhang et al., 2004; Royden et al., 2008). The Chinese Earthquake Bureau measured the current average rate of rise of the Himalaya Mountains at about 21 mm/yr. Fig. 12 shows the rising speed of the plateau in the past four stages:

I Early Stage (60-25 million years ago) slow uplift rate of around 0.012 - 0.31 mm/yr;
II Mid Stage (25-2 million years ago) medium uplift rate of around 0.3 - 1.6 mm/yr;
III Late Stage (2-0.5 million years ago) rapid uplift rate of around 1.6 - 5.35 mm/yr;
IV Present Stage (since 0.5 million years ago) extremely rapid uplift of 4.5-14 mm/yr.

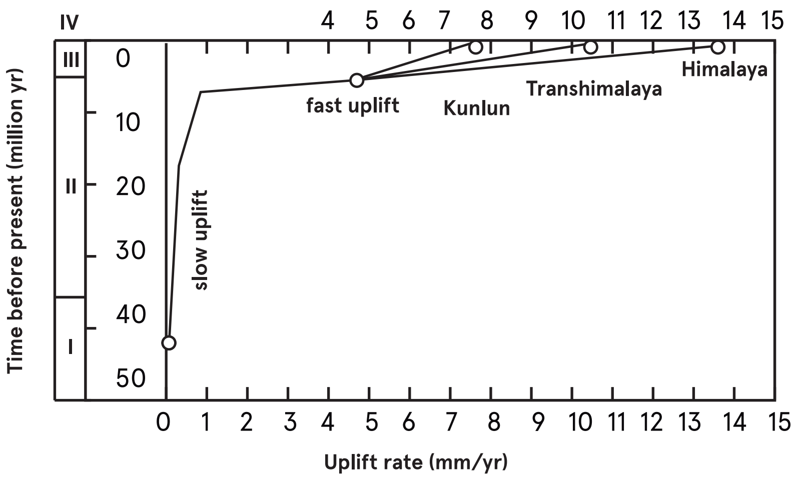


Fig. 12

Rate of uplift of the Qinghai Tibet plateau (modified from Li et al., 2010)

The uplift of the Qinghai-Tibet plateau has affected the fluvial process and reshaped the river morphology. On the margin of the plateau, many rivers have experienced a long period of continuous bed incision because the uplift of the plateau has increased the stream bed gradient (Lavé and Avouac, 2001). The riverbed incision propagated retrogressively to the tributaries and gullies. In recent years the riverbed incision was as high as 200 mm/yr at some locations. The rates of headcut erosion and riverbed incision in the Yellow River source area were estimated by comparing the Google Earth images from September 20, 2010 and the images from June 15, 2013. Although accurate estimates of the incision rate are not available, due to the lack of historical incision depth data, estimates were still made by measuring the channel bed relative to the level of bridge piers and culverts along Highway S301 in Qinghai where the highway construction was completed on October 15, 2010 (Wang et al., 2016). Table 5 lists the incision rates determined for locations at 13 bridges and culverts over the last 3 years. The estimated average channel incision rate at these locations was 0.24 m/yr.

NO.	Latitude/Longitude	Net height (m)	Width (m)	Incised depth (m)	Water depth (m)	Incision rate (myr^{-1})
B-1	N32°57.143′ E103° 02.588′	2.65	3.5	0.75	0	0.25
B-2	N32° 57.143′ E103°02.589′	2.4	5.5	0.65	0.59	0.22
B-3	N33° 05.766′ E102°39.059′	2.55	2	0.2	0.05	0.07
B-4	N33° 05.906′ E102°43.291′	3	8	0.2	0.48	0.07
B-5	N33° 05.607′ E102°46.599′	1.2	2	0.85	0.1	0.28
B-6	N33° 05.348′ E102°48.272′	1.5	1.5	1.3	0.04	0.43
B-7	N33° 05.309′ E102°49.443′	1.2	1.4	0.8	0.05	0.27
B-8	N33° 04.659′ E102°50.210′	3	2	2.7	0.03	0.9
B-9	N33° 04.753′ E102°50.574′	5	2	0.1	0.26	0.03
B-10	N33° 04.129′ E102°52.205′	1	2	0.8	0.05	0.27
B-11	N33° 02.168′ E102°55.503′	1	0.8	0.5	0.04	0.17
B-12	N32° 58.140′ E103° 05.045′	2.4	6	0.2	0.15	0.07
B-13	N32° 57.313′ E103°07.168′	4.5	5	0.3	0.2	0.1

Table 5

Table 5 Rate of riverbed incision measured at bridges and culverts along Highway S301 during the period 2010-2013 (Wang et al., 2016)

Very quick incision has changed the Tongde Paleo-basin into an erosion area and riverbed incision increased the bank slopes and erosion potential. Fig. 13 shows the Yellow River in the Tongde Paleobasin, in which two phases of stream bed incision can be identified. The sediment consists of sand, gravel, silt and clay, representing a lacustrine environment 0.15 million years ago. The remote flat top was the surface of the lacustrine deposition forming the surface of the Tongde Paleobasin, which was a deposition basin 0.15 million years ago. The Yellow River cut the Tongde Paleobasin 500 m deep after the Longyang Gorge was cut through about 0.15 million years ago. Several thousands years ago the river quickly incised down again by about 50 m, which formed the cliff wall by the river channel, as shown in the figure. The picture also shows clearly severe bank erosion due to increased bank slope.

Fig. 13

Uplift of the Qinghai-Tibet plateau has been increasing the bed gradient of the river, which resulted in continuous incision of the river bed and high rates of soil erosion. The Yellow River incised more than 500 m in the reach flowing through the Tongde Basin

Carrying sediment with concentration up to 200 kg/m³ the Yellow River flows from the Qinghai-Tibet plateau down to the loess plateau. The loess plateau has an area of about 640,000 km² with sediment of very high erodibility. Fig. 14 (left) is a map of the loess plateau, which is located between the north China plain and the Qinghai-Tibet plateau at an elevation between 1000 m to 3000m. The highest rate of soil erosion occurs in the north part of the plateau where the rate reached to 30,000 t/yr/km². The lowest rate of erosion occurs in the south part of the loess plateau, where the composition of clay particles in the loess is 30-40%, much higher than the north part of the plateau, and relatively good vegetation has developed. The average rate of soil erosion of the loess plateau was about 10,000 t/yr/km². Fig. 14 (right) shows the typical loess plateau where water erosion and gravitational erosion occurs with a total rate of erosion between 5000-10,000 t/yr/km².

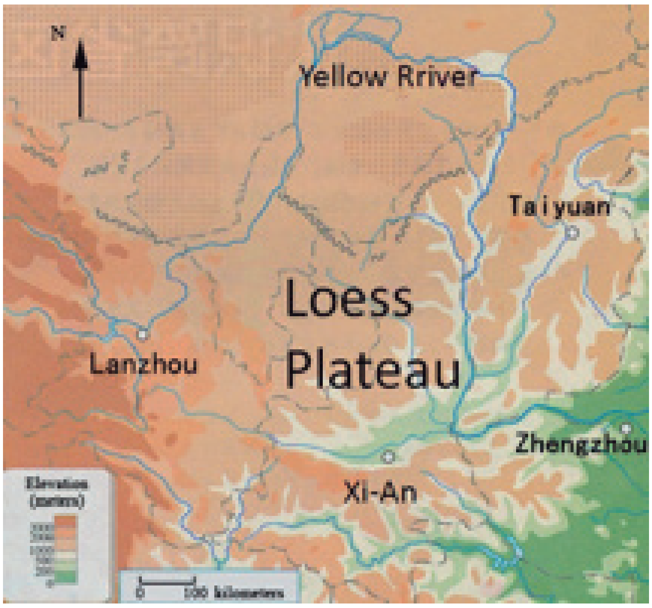


Fig. 14 (A)

Map of the loess plateau, which lies between the Qinghai-Tibet plateau and the North China plain at an elevation between 1000m- 2500 m.

Fig. 14 (B)

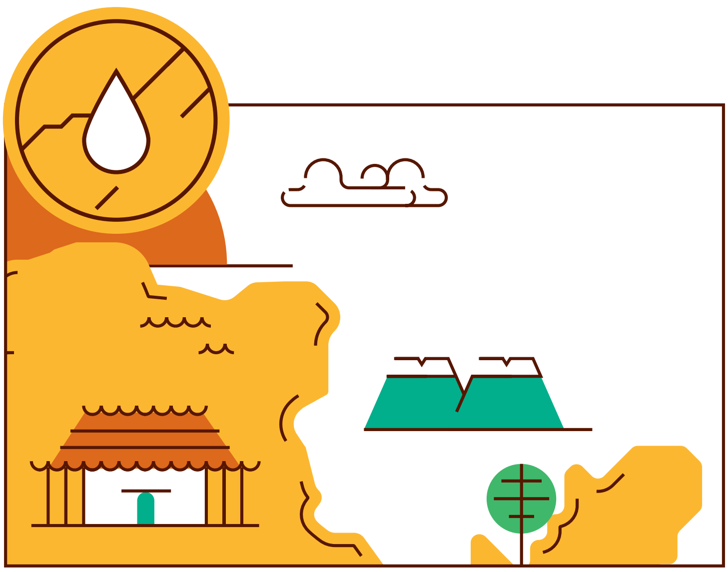
A typical loess landscape in the middle of the loess plateau, where water erosion and gravitational erosion occur with a total rate of erosion between 5,000-10,000 t/yr/km².

Human activity plays an important role in the soil erosion occurring within the Yellow River basin. Agriculture and fodder harvesting impair or even destroy vegetation. People used to cut tree branches as firewood. Many people lived in caves dug in the loess, which resulted in more soil erosion. Fig. 15 shows these human activities, which exacerbate soil erosion. According to the Erosion distribution atlas of the Yellow River basin published by the Ministry of Water Resources of China, the total erosion rate of the Yellow River basin was 2.3 billion tonnes/yr, of which about 1.6 billion tonnes/yr was transported by the lower Yellow River.

Fig. 15

Agriculture and other human activities exacerbate soil erosion

2.
Two thousands years of debate on control strategies



2.1.
Controlling the Yellow River

The flood defence history of China is essentially a history of the people's struggle against Yellow River floods, because the floods were disastrous and training of the river is most challenging due to the heavy sediment load. Training of the Yellow River has a history of more than 3,000 years. Levee construction was the major strategy of flood control. The Qin Emperor united the country and linked the flood defence levees into an entire levee system about 2,200 years ago. The lower Yellow River was confined within the levees but sediment deposition raised the riverbed and made the river frequently breach its levees and shift its course. In the Han Dynasty, Jia Rang proposed three river harnessing strategies: (1) widen the river channel and construct flood diversion basins to enhance the flood conveyance capacity of the river and mitigate flood disasters; (2) build gates and diversion channels, divert flood water through diversion channels into the Zhanghe River and other rivers; and (3) enhance and reinforce the levees every year. The main principle of Jia Rang was to give enough space for flood flow and sediment deposition. Any agricultural development should not occupy the flood plain, which was necessarily a flood way.

People developed many theories and methods for the river training, among them the wide channel and narrow channel theories had the most influence. The wide channel theory is to confine the river within a wide river valley with levees and divert floods with diversion channels. Wang Jing - a minister of the Han Dynasty (206 B.C. to 220 A.D.) - was the advocate and major practitioner of the strategy. The second strategy is to narrow the river and confine the flood within the main channel in order to raise the velocity and maintain the high carrying capacity of the flow, preventing sediment from depositing and even scouring the bed. Pan Jixun - a minister of the Ming Dynasty (1368-1944) - was the most outstanding advocate and performer of this strategy.

In summary the following two conflict river training strategies have been proposed and applied in the past 2000 years: depositing sediment with a wide river channel and scouring sediment with a narrow river channel. Four great masters of Yellow River training have applied the two theories: Wang Jing applied the wide river strategies about 1,950 years ago, Pan Jixun applied the narrow river strategy about 450 years ago, Jin Fu applied the narrow river strategy about 350 years ago, and Wang Huayun applied the wide river strategy about 50 years ago.

The high sediment load of the Yellow River has existed since a million years ago. Zhang Rong (A.D. 0004) described the Yellow River "Bucket of water, sediment six", which means 60% of the Yellow River flood water was sediment (Li and Li, 2003). In other words, the sediment concentration in flood season could be as high as 800 kg/m³ about 2000 years ago.

From 168 B.C. to 69 A.D., the river was active; it flooded and changed its course several times. Wang Jing (A.D.30-85) implemented a large-scale training project in A.D.69, as shown in Fig.16. He constructed the grand levee of about 500 km long from Xingyang to Qiancheng (Ancient county name, near the present Lijin county town). The distance between the levees on the two sides of the river was very wide giving enough space for sediment to deposit. Generally speaking the river was confined by the enhanced levees tens of kilometers apart. Along the levees, he constructed many "water gates" per 5 km. The so called water gates were essentially overspill weirs on the levees (Fig.16). The water gates were made of stones, which can effectively resist the scouring of the flow over the weir. The crest of the weirs was lower than the levees. During low flow seasons, water flowed in the channel. If the discharge was larger than the bank-full discharge, the high stage flood water flowed over the flood plain within the grand levees. The area of the flood plain was very large and may store most of the flood water. The sediment carried by the flood water deposited on the floodplain because the flow velocity was much lower than that in the channel. During very great events a part of water flowed over the water gates on the grand levee (the overspill weir on the levees) for water and sediment diversion and the flood stage had no chance to be higher than the levee. The discharge over the gate was limited and the flood water was still controlled by the Grand Levees. Thus the flood discharge and flow velocity were effectively reduced. The riverbed silted up at a low rate of less than 1-cm per year. In the meantime the major land use in the Loess Plateau changed from agriculture to husbandry, which reduced sediment yield and the sediment load of the river. In the following 800 years the river was calmed and very few levee breaches occurred (Li, 1992).

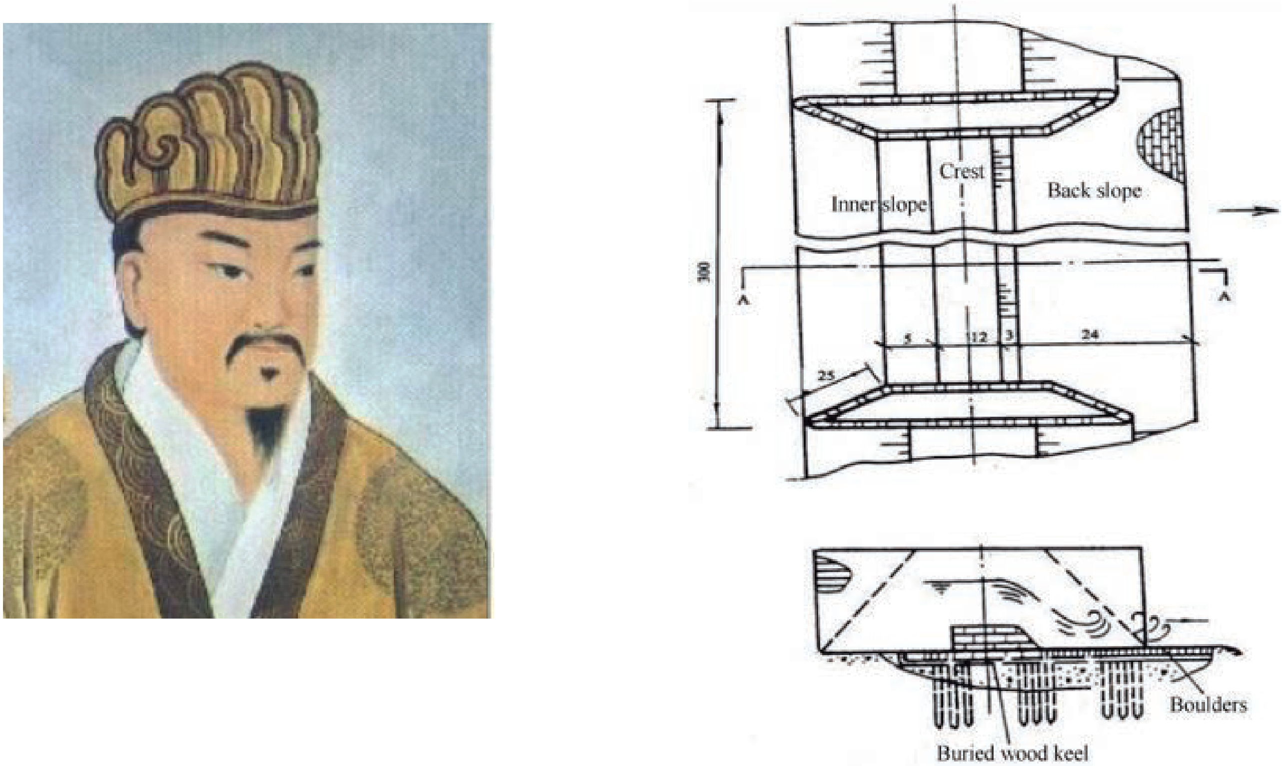


Fig. 16

Wang Jing (0030-0085) and his "water gate" (overspill weir) for training the Yellow River

Wang Jing and his river training strategy were regarded a great achievement in the history of the Yellow River training. "Wang Jing calmed the Yellow River down for 800 years" and has been recognized by Chinese people. The wide river strategy dominated the river training practices. From 850 A.D. to 1500 A.D. the river woke again and became very active. The Grand Levee was breached once every 2 years during the period (IWHR and WUHEE, 1985). Closing the breached levee was a hard job for the river training engineers and the technology of levee defence was developed. Xu Youzhen applied the strategy of wide river and diverting floods and implemented the Shawan Flood Diversion Projects in 1450-1456. He constructed "water gates" and diversion channels for levee breach control, although the Yellow River course was very different from that during Wang's time. Xu Youzhen dug several channels in the downstream reaches and the Yellow River flood water was diverted through these channels to the Yellow Sea.

Because of the population growth in the 15th century, the flood diversion strategy was more difficult to implement. Pan Jixun (Fig. 17) proposed the strategy of narrowing the river and confining the flood within the main channel in order to raise the velocity and maintain the sediment-carrying capacity of the flood,

preventing sediment from depositing and even promoting bed sediment scouring. He observed that the sediment in the Yellow River bed could be scoured by high velocity of flow very quickly. He was acutely aware that the higher the velocity of the flow the more sediment the flow can carry. Thence, he proposed the concept of sediment carrying capacity of flow. Pan strongly criticized the method of diversion channels. He thought that "diversion reduced the flow energy, the low flow velocity caused sedimentation, sedimentation resulted in levee breaches and avulsions".
Pan proposed to increase the flow velocity by constructing inner levees and narrowing the channel. He summarized his strategy in a few word: "concentrating the flow by constructing levees and groynes and scouring the sediment with high flow velocity".

Pan Jixun was appointed as the viceroy of the Yellow River when he was 50 years old. He invented the method of measuring flood stage. Pan regulated the levee system, closed the levee breaches and blocked many branches of the river in the period 1565-1592. Between the inner and outer levees, Pan constructed many lattice levees, as shown in Fig. 17. Thereafter, a flood from the upper Yellow River flowed into the single narrow channel and scoured the river bed very deep. Pan spent his whole life in the Yellow River training and published a book "Overview of the Yellow River training", in which he explained his idea of concentrating flow and scouring the sediment with inner and outer levees (Fig. 17). Pan Jixun enhanced and reinforced the well-known Gaojiayan dam, which was the main structure for protecting the lower reaches of the Yellow (Huaihe) river from floods.

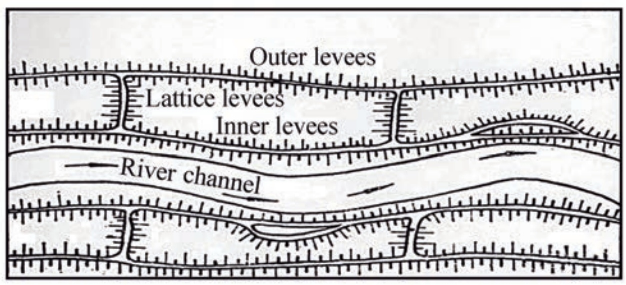


Fig. 17

Pan Jixun (1521-1595) (left) and his book "Overview of Yellow River Flood Defence" (upper right), and a sketch of the inner and outer levees (lower right)

The Yellow River became relatively quiet due to Pan's effort and the number of levee breaches reduced during Pan's time. Nevertheless, the rate of sediment deposition on the river bed increased to 5-10 cm per year. Aggradation and blockage of diversion channels resulted in large difference of the riverbed elevation when compared to the surrounding land. The potential energy for levee breaches was increasing.

Shortly after Pan Jixun the river became very active and numerous levee breaches and flood disasters occurred. The third river training master Jin Fu took to the stage of history. Jin Fu (1633-1692) (Fig. 18) was appointed as the Viceroy of Yellow River Training at the age of 45. The emperor Kangxi (Qing dynasty) entrusted him with flood control of the Yellow River and honored him with the title of Minister of Industry. Chen Huang (Fig. 18) was the main assistant and adviser of Jin Fu. The Yellow River breached the levee frequently and caused great catastrophes as Jin and Chen took over the job of river training. Chen and Jin believed that the narrow channel and scouring sediment theory was suitable for the Yellow River training. They applied Pan's theory and practiced "converging flow with narrow channel and scouring sediment with high velocity of flow". They closed the breaches and blocked the branches to concentrate water and enhance flow velocity. During the process they invented the method of measurement of flow discharge and used the method in the design of channels.

Jin and Chen summarized the training strategy: dredging the river channel by constructing levees and groynes. They introduced clear water from parallel rivers into the Yellow River to increase the sediment carrying capacity. Considering the limited drainage capacity of the narrow channel and the concept of water gates from Wang Jing they constructed 13 water diversion weirs in the downstream reaches, which were used during extremely high flood discharge. Thus it can be seen that the strategy Jin and Chen applied was not purely Pan's "converging flow with narrow channel and scouring sediment with high velocity of flow" but also used Wang Jing's idea of diverting water to reduce the flood discharge.

Jin and Chen's river training project was criticized by their political enemies in 1688. Guo Xiu and Yu Chenglong, both famous honest and upright officials in the Qing Dynasty, criticized them: "construct levees today and dredging channels tomorrow, spent too much money but not control the flood yet in 9 years". Guo Xiu launched a personal attack on Chen Huang accusing him of being a nobody who abused national power and funding. Thence, Jin Fu was dismissed and Chen Huang was arrested. The Yellow River breached the levees soon because the river training project was stopped. The people living by the river complained and said: they enjoyed a short period of flood security during Jin and Chen's training project. Thence the emperor reappointed Jin as the Viceroy of River Training in 1692 but Chen had died in the prison. Jin continued the river training until he died 4 years late.

Fig. 18

Jin Fu (left 1633-1692) and Chen Huang (right) were the third great masters of Yellow River training in its 2000 years history

From the 18th century the Yellow River became extremely disastrous and the number of levee breaches per century increased to more than 300. Wang Huayun (1908-1992) - the fourth great master of Yellow River training- began his river training practice from 1950 (Fig.19). He was appointed as Vice Minister of Water Resources of China and Director of the Yellow River Commission and was in charge of Yellow River training from 1950 to 1990. He applied the wide river and depositing sediment strategy. Wang proposed 16 words for river training in Chinese “宽河固堤，蓄水拦沙，上拦下排，两岸分滞”, which translated into English mean “Widen the river and enhance the levees, store water and trap sediment, deposit sediment upstream and discharge sediment downstream, and divert sediment and water to detention basins” (Wang, 1989). In fact, numerous reservoirs have been constructed in the river basin, including 25 reservoirs on the main river, which trapped a lot of sediment. The grand levees were enhanced and reinforced 9 times and 5 flood diversion basins were constructed. The nation spent $20 million for flood control per year and prevented more than $500 billion in flood losses in the period 1950-1999 (Chen, 1999). The riverbed profile has remained stable for half a century, with only parallel increases in height following the extension of the river mouth into the sea (Zhang and Xie, 1985).

Fig. 19

Wang Huayun-the director of Yellow River commission and the fourth great master of Yellow River training

2.2.
Debates on Control Strategies

Liu E (1857-1909)- A famous writer and river training engineer in the Qing Dynasty commented that "From ancient times to the present there have being two schools on strategies for Yellow River training and flood control. One school has the viewpoint of Jia Rang: giving enough space for sediment deposition and keeping the flood flow in a wide river channel. Another school has the viewpoint of Pan Jixun – narrowing the river channel to scour sediment and keeping a high flow velocity to transport sediment to the ocean. The shortcoming of the wide river strategy is that it results in sedimentation. The shortcoming of the scouring sediment strategy is that it results in levee breaches. The Yellow River flood consists of 60% sediment by volume. Widening the river causes sediment deposition and narrowing the river causes levee breaches. Controlling sediment deposition will induce levee breaches and preventing levee breaches will induce sediment deposition… " Liu supported Pan's narrow river strategy and commented: "The consequences of sediment deposition come much later than levee breaches. Sediment deposition leads to problems for the next generation. But levee breaches cause flood disasters right now. Therefore, many river trainers prefer the wide river strategy. Nevertheless, sediment deposition will result in long-term problems, which is the main reason why the Yellow River has not yet been tamed harnessed. On the other hand, if a river trainer is very skillful and applies the narrow river strategy the problem of sediment deposition can be avoided while levee breaches can be prevented…." (Liu, 2004).

Liu's viewpoint was very popular in the Ming and Qing dynasty. Pan's narrow river and scouring sediment strategy dominated river training until 1950. Although the scouring sediment strategy looks much more sophisticated and received fulsome praise, the long term effect of hazard mitigation was much lower than for the wide river strategy. Data of 543 levee breaches in the past 2000 years (Yao, 2003; EGRYH, 2003), which resulted in great flood disasters and death tolls, were collected and the number of levee breaches per century was calculated. Fig. 20 shows the frequency of levee breaches as a function of time from A.D. 00 to 2016. The timing of river training projects launched by Wang Jing, Pan Jixun, Jin Fu and Wang Huayun are indicated.

Wang Jing applied the wide river and deposing sediment strategy and brought about long-term (800 years) flood security. Pan Jixun applied the narrowing river and scouring sediment strategy and quickly reduced the frequency of levee breaches. Nevertheless, soon after his project the number of levee breaches increased to an even higher level than before him. The same story occurred for Jin Fu. Jin brought down the frequency of levee breaches very quickly. Soon after his death the frequency of levee breaches reached an extremely high level (300 levee breaches per century, which is not shown in the figure because the point is out of the range of the figure). Wang Huayun applied the wide river and depositing sediment strategy from 1950. In the past 65 years the frequency of levee breaches reduced to zero. This is the only period of zero levee breaches in the 4000 year history of the Yellow River. It can be clearly concluded that the wide river and depositing sediment strategy is much better than the narrow river and scouring sediment strategy.

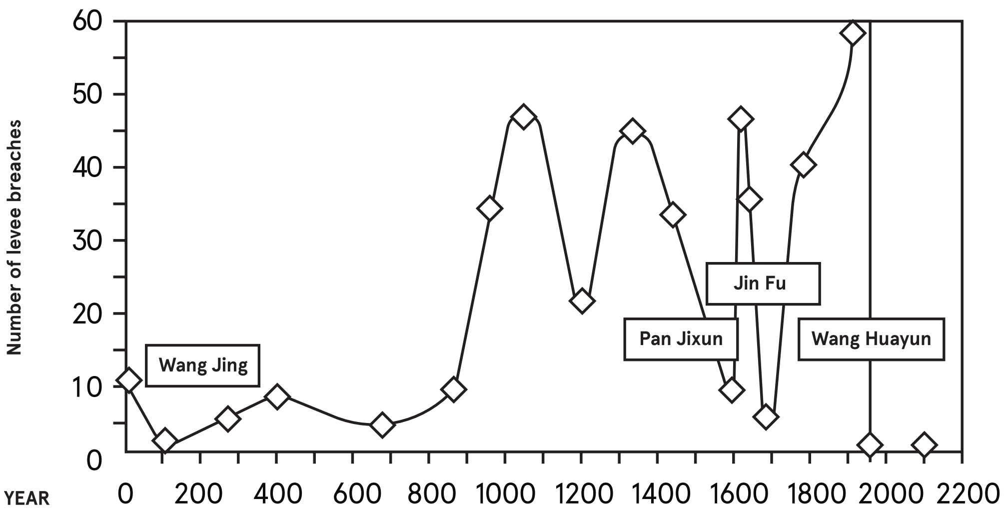


Fig. 20

Number of levee breaches per century as a function of time from A.D. 00 to 2016

The strategy of narrow river and scouring sediment is effective in sedimentation control, which can be used for local sedimentation control but not for the river training and flood control. In fact the narrow river strategy transferred the sediment problem to the downstream reaches and time late. There is evidence proving that the narrow river and scouring sediment strategy can cause long term consequence. In 1680 a flood from the Huaihe River carried a lot of sediment from the Hongze Lake and buried Sizhou Town and killed thousands of people, which is regarded a consequence of the narrow river strategy practiced by Pan Jixun and Jin Fu.

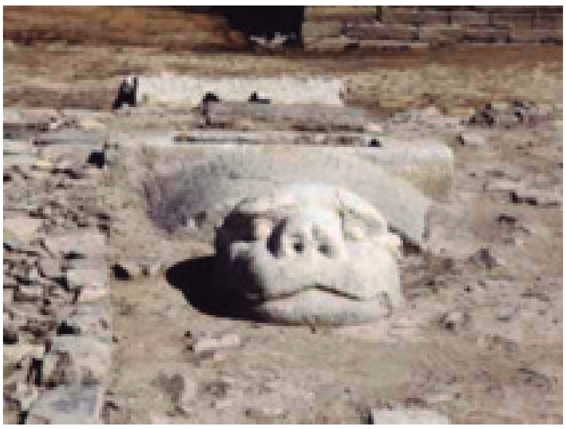
Fig. 21 shows the unearthed Sizhou town, which was buried under 7 m of sediment since 1680. Sizhou town was a center of transportation and commerce with a population of 300,000. Grain and salt were transported from south China through the Grand Canal to Sizhou town. Boats navigated across the Huaihe (Yellow River) through ship locks at Qingkou. The story started in 1128, when the grand levee of the Yellow River was broken by Du Chong (?-1141) in order to resist the invasion of Jin Army. The river changed its course and captured the Huaihe River at Qingkou and poured into the Yellow Sea, as shown in Fig. 22. In the first 500 years after the Yellow River stabilized in its southern course in

1194, the river was wide with a large area of floodplain and had many branches upstream of Qingkou. A lot of sediment deposited on the floodplain and diverted through the branch channels in the reach upstream of Qingkou. Sizhou Town was located close to the Huaihe River and the Grand Canal. The lower reaches of the Huaihe River downstream of Qingkou became the lowest reach of the Yellow River.

Then Pan Jixun applied his narrowing channel and scouring sediment strategy in 1565. He narrowed the river by constructing inner levees and cut off all branches, thus concentrating the flow and carrying a high sediment load to the lower Huaihe River (Yellow River). Because the original bed gradient of the lower Huaihe River was only half of that of the Yellow River it could not maintain a high sediment transport capacity. A huge amount of sediment was deposited at Qingkou and this formed a submerged dam several meters high. Water from upstream of the Huaihe River and water and sediment from the Yellow River was stored upstream of Qingkou and formed the Hongze Lake. In more than 100 years a huge amount of sediment from the Yellow River deposited in the Hongze Lake. Pan Jixun and Jin Fu reconstructed and enhanced the Gaojiayan embankment. Pan and Jin commanded a million labourers for training of the Yellow River and the Grand Canal with their Headquaters in the Sizhou Town. Following enhancement of the Gaojiayan embankment the potential for flood water and sediment to reach Sizhou Town increased.

Fig. 21

In 2014 Sizhou Town was unearthed after 333 years asleep under the Yellow River sediment. It has been called Pompeii of the East.



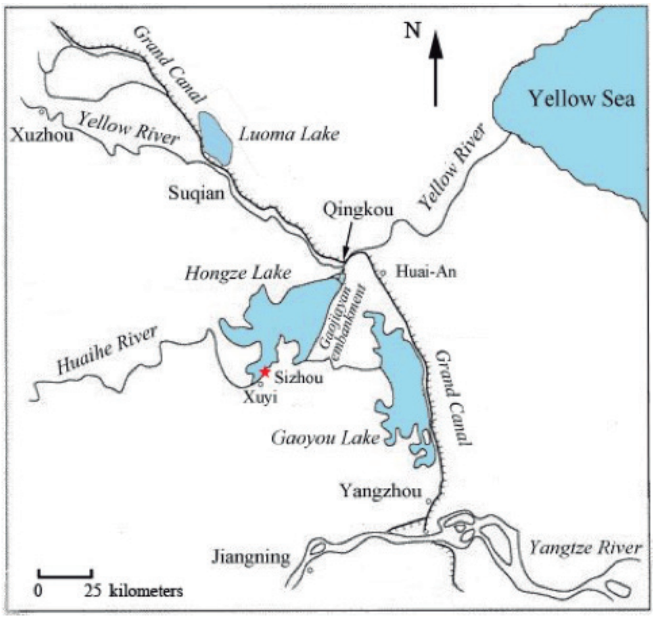
In 1680, a flood from the upper Huaihe River breached the Huaihe levee. Flood water flowed with a 9 m head into Sizhou Town and sediment scoured from the lake bed was transported into the town. Sizhou Town was finally buried under 7 m thick sediment deposit. The Pan's project prevented sediment deposition in the Yellow River channel and floodpain upstream of Qingkou and resulted in a huge amount of sediment deposition at Qigngkou and in the Hongze Lake, which finally led to the failure of the Huaihe levee and burial of the Sizhou Town.

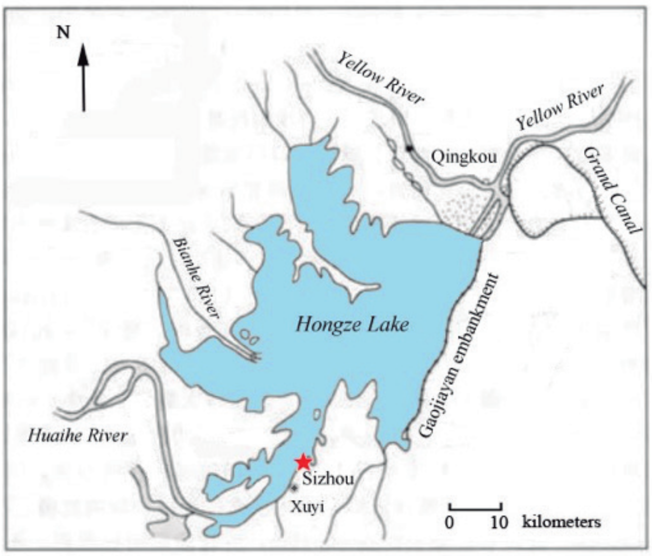
The narrow channel and scouring sediment strategy was spoken highly of, because it needed less land for dealing with the flood and looked more sophisticated. Pan Jixun and Jin Fu enjoyed a high reputation. The Qing dynasty agreed and the local people built temples for Jin. Nevertheless, the result of the strategy was not good. Levee breaches occurred continuously. The narrow channel and scouring sediment strategy is difficult to manage. Pan and Jin were very skillful and very carefully managed the high velocity flow. Thus, they maintained short periods with few breaches. After Pan and Jin, the levee breaches became more than before because high sediment concentrations are very unstable and their successor could not control the flow in the narrow channel. Suffering from levee breaches and floods, people remembered the relatively safer time associated with Pan and Jin and therefore regarded them as gods.

The wide channel and depositing sediment strategy resulted in long term flood safety. Wang Jing applied this strategy and it resulted in 800 years with a low frequency of breaches. Wang Huayun used the strategy and no levee breach occurred in the past 60 years, which is the only period of zero levee breaches in the history of the Yellow River. Wang Jing and Wang Huayun were not so well known as Pan and Jin, although their training projects resulted much better effects for flood control. This can be seen as "A good general has no brilliant achievements in war" (Sun Tzu's The Art of War) because he has defeated the enemy before the war.

Fig. 22

(a) The Yellow River captured the Huaihe River channel at Qingkou and flowed in the lower Huaihe River channel to northeast in the period 1194-1855; (b) Water and sediment stored in the Hongze lake was 9 m higher than Sizhou Town





The debate on wide or narrow river strategies became international in the 20th century. Three foreign names should be mentioned who worked on the training of the Yellow River: Engels, Freeman and Franzius (Yen, 1999). The American engineer Freeman visited China in 1917 and proposed to build cross dikes extending from the existing levees of the lower Yellow River, which were more than 6 km apart, and to build new levees near the tips of the dikes, 800 m apart (Freeman, 1922). Freeman's suggestion rekindled the century's debate on whether the levees should be close or far apart as they were at the time. The German engineer Engels conducted physical model experiments, authorized by the Chinese National Economic Council in 1931-1934. The test results indicated that with the levees set far apart, a somewhat better scour was produced in the main channel than when the levees were close to the main channel edges (Engels, 1932). The result did not support the idea of further narrowing the river channel. The Chinese government authorized Franzius, a student of Engels, to conduct another physical model experiment and obtained different results. Yen (1999) indicated that Franzius' experiments were conducted without tail gate regulation and the results are not as reliable as those of Engels.

2.3. Modern Flood and Sedimentation Control Methods

Based on the wide river and depositing sediment strategy of Wang Huayun people have developed many modern flood control and sedimentation control methods. Ten major floods with peak discharges over 10,000 m^3/s occurred in the past 50 years. These floods were controlled within the Grand Levees and no great disasters occurred. The nation has spent $1 billion for flood control and saved $500 billion in flood loss (Chen, 1999). The main flood control and sediment management methods are described in the following subsections.

2.3.1 Sedimentation Management with a Wide River Valley

The Yellow River flows from mountainous areas into the North China plain near Zhengzhou. A sharp reduction in slope results in sedimentation and continuous silting up of the riverbed. The width of the river valley is 5-20 km controlled by the Grand Levees in the Henan Province reach (about 200 km), thus providing enough space for sediment deposition on the floodplain. Fig. 23 shows the river and the Grand Levee and spur dykes controlling the flow. The channel is about 500 m wide and for most of the time the flow is kept in the channel. If a flood occurs the water is allowed to flow over the floodplain for reduction of flood losses in lower reaches. The wide river provides water detention capacity and space for sediment deposition. The wide river in the Henan reaches detained 2.4 billion m^3 of water during the 1958 flood and greatly reduced the flood discharge to the lower reaches (Wang, 1989). The capacity of the channel in the Henan reaches is 30,000 m^3/s. Nevertheless, the wide floodplain is rarely flooded and about 1.8 million people reclaimed the land and live in villages and towns within the Grand Levees nowadays.

To stabilize the channel and protect the villages and towns within the levees, numerous spur dykes have been constructed. The spur dykes were constructed at the bends of the channel to control the flow direction. Nevertheless, not all the spur dykes work well for channel stabilization. The river channel is very dynamic and often moves far away from the dykes, which makes the dykes abandoned. Statistically, about half of the spur dykes are effective for stabilization of the channel.

The most downstream reach of a length about 500 km of the Yellow River across the Shandong Province has a width of only 0.4-5 km. This reach was the Daqing River channel and was captured by the Yellow River in 1855. There was no place to develop a wide river channel because the two sides of the river were important agriculture areas.

Nowadays, the riparian area of the river has been densely populated and has no way to develop a wide floodplain for sedimentation. Thus, a narrow river channel with strong embankments has been constructed and stabilized. The narrow river favors a stable channel and high flow velocity and maintains high sediment carrying capacity, which is in accordance with the theory of narrowing the channel and enhancing the sediment carrying capacity developed by Pan Jixun. On the other hand, the capacity of the channel is limited, and can only accommodate floods with discharge less than 10, 000 m³/s. The Aishan Hydrological Station is the control point between the wide valley reach in Henan Province and the narrow channel reach in Shandong Province. The Aishan cross section has a width of only 275 m. The location of the Aishan station is shown in Fig.1. The narrow section controls the flow into the Shandong Reach to no more than 10,000 m³/s. Therefore, it is named by the hydraulic engineers as "Aishan Lock". From Aishan to the river mouth the river is narrow. Fig. 24 shows the Lijin cross section, which is the most downstream hydrological station of the river (the location of the Lijin station is also shown in Fig. 1). As a comparison the Mazhai cross section, in the wide river reach near Huayuankou, as shown in Fig. 25.

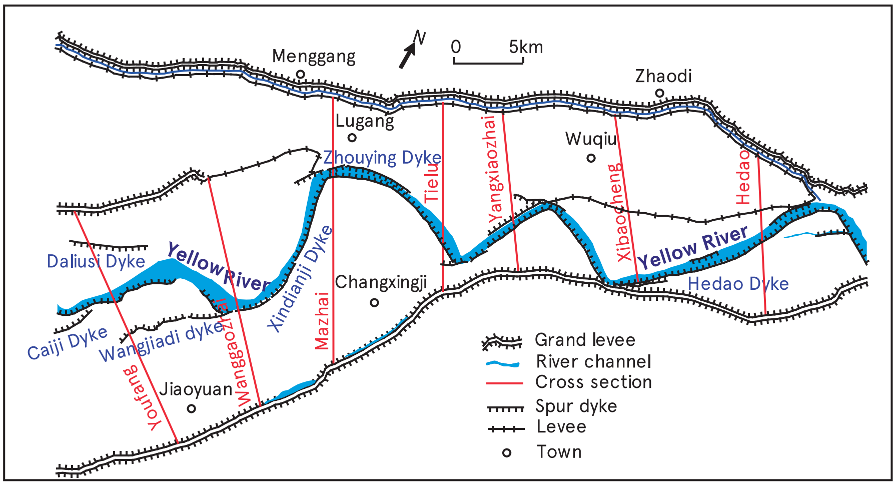


Fig. 23

Wide river valley defined by the Grand Levees in the reach in Henan Province

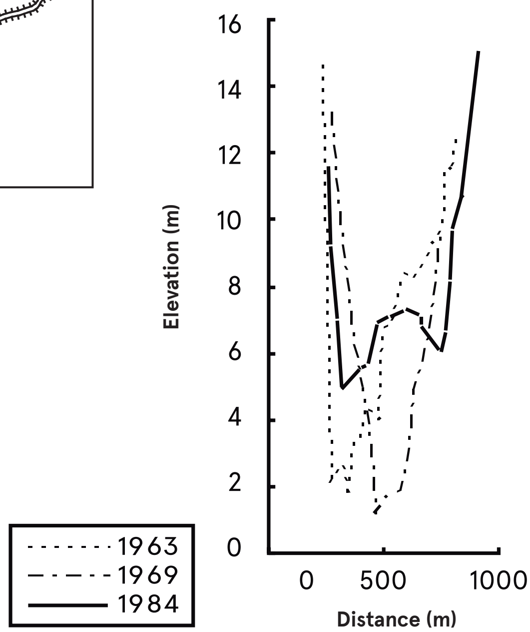


Fig. 24

The narrow Lijin cross section (upper, about 600 m wide), where the most downstream hydrological station of the river Lijin Station is located

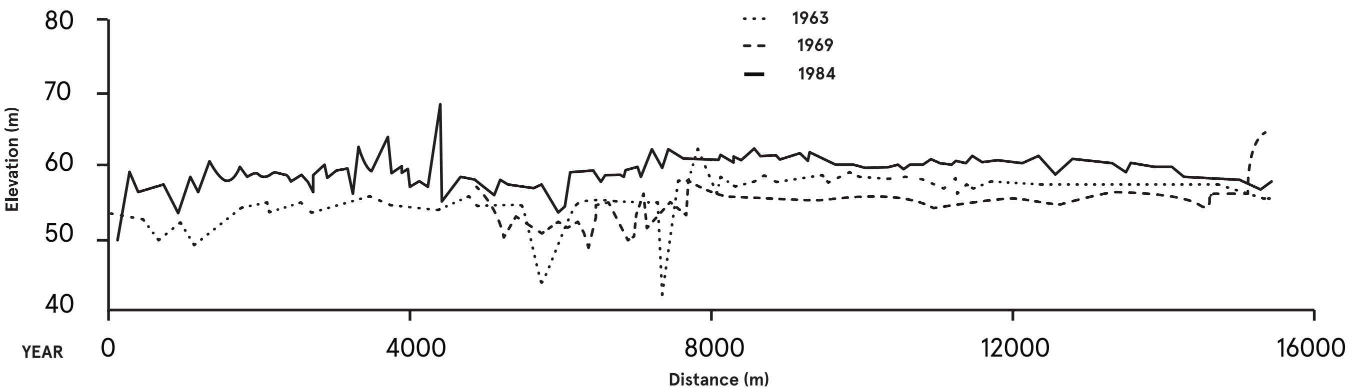


Fig. 25

Mazhai cross section in the wide river reach near Huayuankou

2.3.2 Flood Control with Reservoirs, Levees and Diversion Basins

In the past decades, the Yellow River basin has experienced major development of control measures. More than 30 reservoirs were constructed on the Yellow River from 1957-2012, including Longyangxia, Laxiwa, Lijiaxia, Liujiaxia, Yanguoxia, Bapanxia, Qingtongxia, Sanshenggong, Wanjiazhai, Tianqiao, Sanmenxia, and Xiaolangdi Reservoirs. The total capacity of the reservoirs is about 64 billion m^3, more than the annual runoff of the whole basin. Most of the upstream floods (flood water coming from the watershed of the upper and middle reaches of the Yellow River) can be controlled with these reservoirs (Qian and Li, 2014).

The Sanmenxia Dam is the first dam built on the Yellow River, which was completed in 1960. Impoundment of the Sanmenxia Reservoir caused siltation of the Yellow River and the Weihe River and endangered Xian – capital city of Sha-anxi Province. The operation of the reservoir had to be altered from storing water and trapping sediment to retaining flood water and discharging sediment, and to storing clear water and releasing turbid water. Details of the management of the reservoir is presented in Section 4.

The reservoirs are also used to trap sediment. More than 10 billion tonnes of sediment have been trapped by the reservoirs reducing the total amount of sediment deposited in the lower Yellow River. The Xiaolangdi Reservoir was constructed with one purpose especially to trap sediment and control the siltation of the lower Yellow River. The total capacity of the Xiaolangdi Reservoir is 12 billion m^3 and the sediment-trapping capacity is 7 billion m^3. It is predicted that the sediment from the Loess Plateau can be trapped by the reservoir for at least 20 years, and, therefore, the lower Yellow River will be scoured down and the flood risk will then be eased.

The flood discharge capacity of the lower Yellow River reduces following the siltation of the channel. People have continuously raised the levees in a race with the river sedimentation. A total length of 1, 320-km of levee along the lower Yellow River has been increased in height by by about 9 m in the past 50 years, including three major levee enhancing projects and many local levee reinforcing projects, involving a total of 400 million m^3 of earth works and 4 million m^3 of rock masonry work. Fig. 26 shows the cross section of the levee at Taiqian in Henan Province and 9 stages of enhancement (Zhu, 1991). An important strategy is to use heavy sediment-laden floods to reinforce the levees. Sediment suspensions are pumped (warping) to the lee side of the levee. Deposition of sediment near the levee makes it wider and stronger. Seepage and piping are often the direct causes of levee breaching. A concrete anti-seepage wall has been built in the Grand Levees to control seepage and piping. Fig. 27 (a) shows a machine cutting the land by the levee to a depth of 40 m and casting concrete, and Fig. 27 (b) shows the anti-seepage wall which is 20 cm thick and 40 m deep.

Fig. 26

Cross section of the Grand Levee at Taiqian in Henan Province showing 9 stages of enhancement

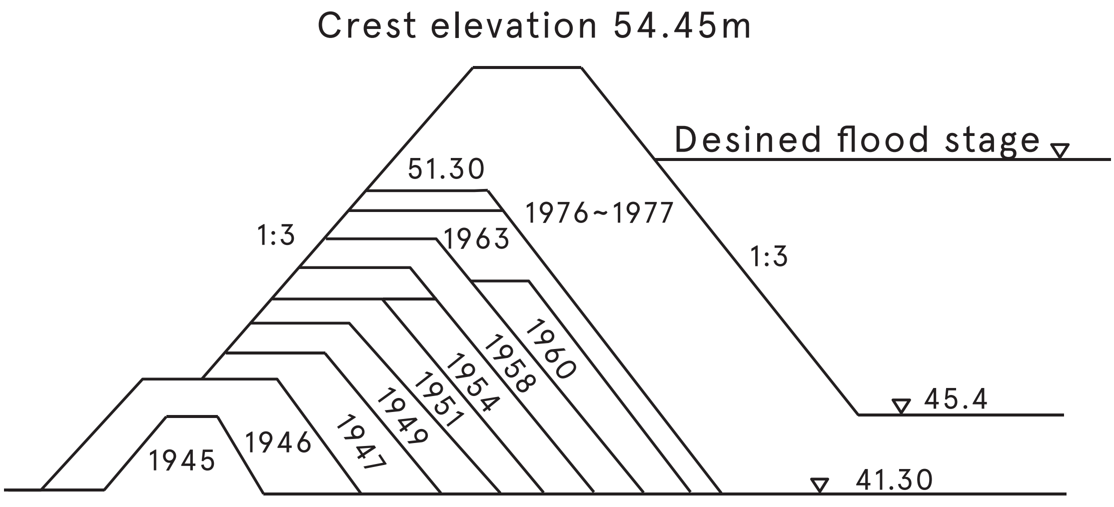


Fig. 27

(a) A machine cutting the land by the levee to a depth of 40 m and casting concrete; (b) The anti-seepage wall 20 cm thick and 40 m deep to control seepage and piping.

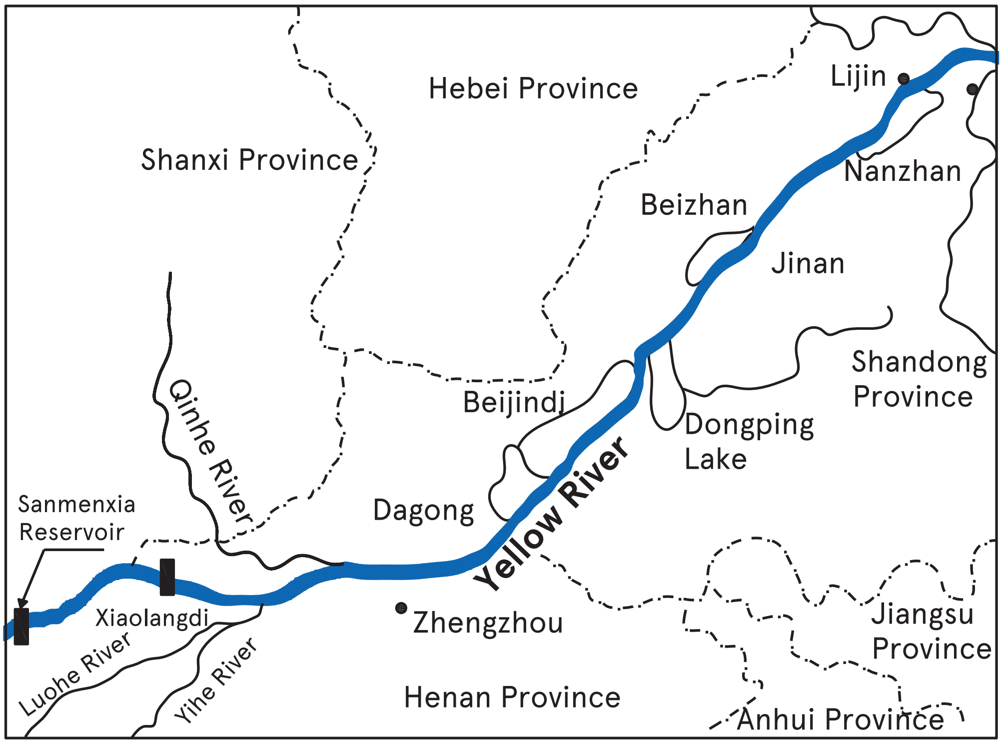


Fig. 28

(a) Locations of the Dagong, Beijindi, Dongping Lake, Beizhan, and Nanzhan flood detention basins adjacent to the lower Yellow River

The capacity of the river channel in the Shandong reaches is only 10, 000 m^3/s, less than that of the upstream Henan reaches (30, 000m^3/s). Floodwater has to be detained in the wide valley in the Henan reaches, which will flood the villages on the floodplain if the discharge is over 10 000 m^3/s. For even higher discharge the flood detention basins must be used. There are 5 flood detention basins adjacent the lower Yellow River, namely Dagong, Beijindi, Dongping Lake, Beizhan, and Nanzhan. Among them the Beijindi and Dongping lake flood-detention basins are the most important. The Dongping Lake basin detained floods in 1954, 1957, 1958 and 1982 and effectively reduced the discharges to the lower reaches. Fig. 28 shows the locations of the flood detention basins.

2.3.3 Erosion Control by Reforestation and Sediment-Check Dams

Reforestation is a long-term strategy to reduce the river sedimentation. The strategy has been successfully applied in many small watersheds (less than 100 km^2). Fig. 29 (a) shows the reforested Xizhao Gully on the Loess Plateau, northwest China. The rate of soil erosion in the area was as high as 10,000 t/km^2yr. Planted trees on the slope suffer from erosion and too low soil water. Only the trees in the gully may grow up and form a forest. The planted trees in the gully have trapped the eroded sediment. Almost no sediment is transported out of the gully. In the southeast part of the Loess Plateau reforestation may be successful on hill slopes as well. Fig. 29 (b) shows the reforestation of the loess hill slopes in Shanxi Province, which effectively reduces soil erosion.

Fig. 29

(a) Planted trees in the Xizhao Gully on the Loess Plateau, northwest China trapped almost all of the eroded sediment from the slopes; (b) Reforestation of the Fengshenshan hill in Shanxi Province in the east side of the Loess Plateau

Sediment-check dams affect the river sediment load more directly. Farmers build the sediment-check dams under the encouragement of the government to create farmland, which is usually much more productive than the slope land. Fig. 30 (a) shows a sediment check dam on the loess plateau, which has trapped sediment and created fertile farmland. Fig. 30 (b) shows a new sediment check dam in the east part of the loess plateau, which has been just completed and begun trapping sediment. Reforestation and thousands of sediment-trapping dams on the Loess Plateau have resulted in a sharp reduction in sediment load to the lower Yellow River. Fig. 31 shows the variation of annual sediment load transported to Lijin on the lower Yellow River. The average annual sediment load transported to Lijin was about 1 billion tonnes before 1985 and the value has been reduced 60% since 1985. It is estimated that about 300-500 million tonnes of the sediment reduction are due to reforestation and sediment-check dams on the Loess Plateau.

Fig. 30

(a) A sediment check dam in the Shaanxi Province has trapped sediment and created fertile farmland; (b) A new sediment check dam in Shanxi Province has been completed and begun to trap sediment

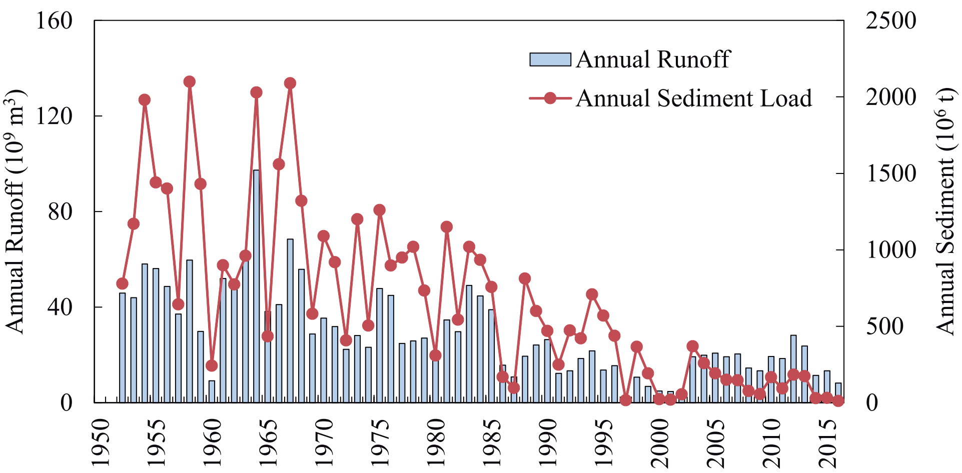


Fig. 31

Variation of water and sediment load at the Lijin Station in the lower Yellow River from 1970 - 2016

2.3.4 Sedimentation Control

Dredging - The main flooding risk is due to the rapid siltation and capacity reduction of the channel. Therefore, sedimentation control and increase of the water-conveying capacity of the channel is a main aim of river training and the key criteria of the new strategies of river management. Besides the traditional strategies and regulation of sediment and water by using the Xiaolangdi Reservoir, Yellow River channel dredging has become an important auxiliary measure. Training of the river by human intervention becomes much more common than before, and, therefore, people have begun to use dredging for controlling sedimentation. They proposed that through dredging the reduction in river channel capacity at selected locations could be alleviated or stopped and a high capacity for carrying sediment, ice, and water preserved.

The functions of dredging are to: (a) widen and deepen the shrinking river channel at selected sections; (b) remove coarse sediment of diameter larger than 0.025-0.05 mm from main channel to the floodplain so to reduce the accumulative siltation of the main channel; (c) raise the elevation of the surrounding ground, reinforce dikes, improve soil quality, and create new wetlands at the river mouth with the dredged sediment.

Historically, the Yellow River channel was dredged many times, but the results were not satisfactory. On the one hand, the annual sediment load was quite high and the dredged channel was soon resilted. On the other hand, dredging was not supported by advanced technology and suffered from lack of experiences. Today, the conditions and requirement for dredging are different. Many river training projects in China and other countries provide rich experience of dredging and the development of technology and dredgers has greatly improved the efficiency of dredging. Furthermore, there are less and less extreme events and the channel bed is rarely scoured. In the meantime economic development has enabled advanced dredgers to be used for river training. The Yellow River can be dredged by mechanical excavation and transportation, agitating with jets and explosions. Various dredgers have been used: dredge boats; agitating dredgers; dipper dredgers; hauling scrapers; excavators and bulldozers; and trailer dredgers (Zhang et al., 1997). Fig. 32 (a) and (b) show two types of agitating jet dredgers scouring sediment during flood season.

Fig. 32

Two types of agitating jet dredgers scouring sediment during the flood season

At the river mouth the width becomes larger, the depth also increases, the slope becomes gentler, and, therefore, the velocity here greatly reduces. The sediment carried by the flow is deposited and a mouth bar is formed. The river mouth bar causes a resistance and results in higher flood stages in the upstream reaches. Sediment was, hence, deposited in the upstream channels before the 1980s, which was one reason for the frequent avulsion and channel shift. In the 1980s, dredging projects were implemented to remove the mouth bar. Different dredgers were used and the river mouth has since then been maintained free from a mouth bar. Because of the dredging of the mouth bar, the Qing-shui-gou channel has been used for much longer than the average life span of previous channels.

The success of dredging the mouth bar encouraged people to dredge the river channel as a solution of the channel sedimentation problem. A dredging test was conducted in a 11 km long section near the river mouth (35-46 km downstream of the Lijin Hydrological

avulsion and channel shift. In the 1980s, dredging projects were implemented to remove the mouth bar. Different dredgers were used and the river mouth has since then been maintained free from a mouth bar. Because of the dredging of the mouth bar, the Qing-shui-gou channel has been used for much longer than the average life span of previous channels.

The success of dredging the mouth bar encouraged people to dredge the river channel as a solution of the channel sedimentation problem. A dredging test was conducted in a 11 km long section near the river mouth (35-46 km downstream of the Lijin Hydrological
Station) in January to May 1998. An 11 km long, 200 m wide, 2.5 m deep ditch was dug in the almost flattened river bed and 5.48 million m^3 of sediment was dredged to the lee side of the levee. Nevertheless, after the first flood in the year the dredged section were basically filled up by sediment deposition. Fig. 33 shows 2 cross sections of the dredged reach. The cross sections were resilted after only one flood. The prospect of dredging the river channel as a general solution for channel sedimentation is far from optimistic.

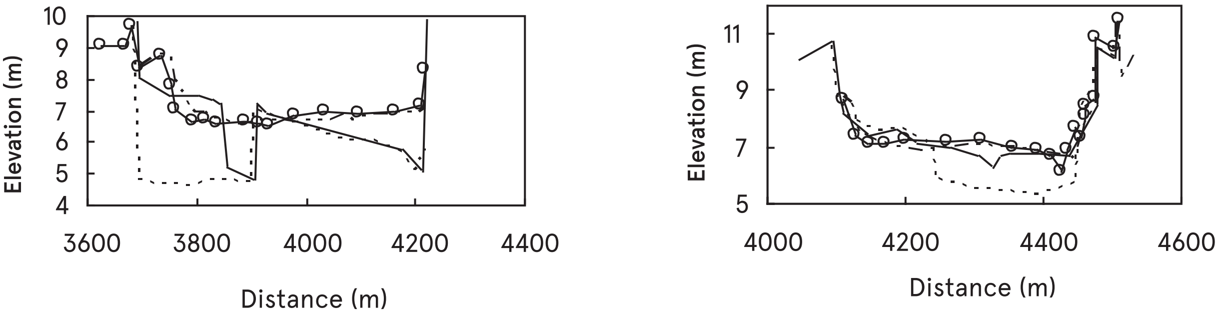
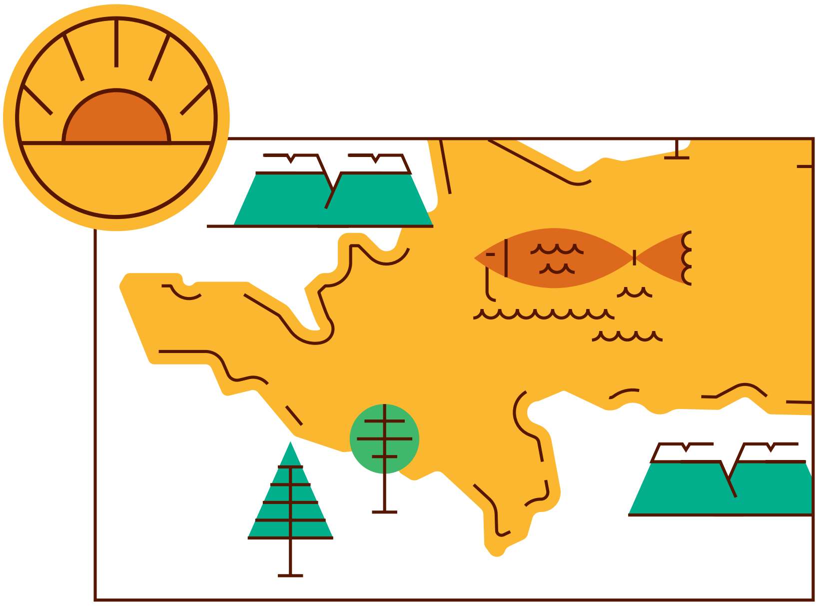


Fig. 33

Resiltation of the dredged sections after the first flood in 1998: (a) Wuqizha cross section; (b) Shibahu Cross section (— Original bed, ····Dredged -o- After the first flood)

3.
New challenges and new strategies



3.1
New Flood Threat due to Human Activities

The width of the river valley controlled by Grand Levees in the Henan Province reach (about 200 km) is 5-20 km. The channel is about 500 m wide and for most of the time the flow is kept in the channel. The floodplain has an area of about 2,700 km² and has been reclaimed by the people dwelling close to the river. Nowadays, about 2 million people are living on the floodplain within the grand levees. Although there is no major infrastructure, the 2 million people and their shelters are threatened by flood risk. In the past the capacity of the main channel was large enough to convey the flood water, except for extremely high flood discharges which were very rare. Nevertheless, the capacity of the main channel had been reducing in the past decades due to flow regulation by reservoirs and the flood threat for the 2 million people on the floodplain has become much higher than before.

The reservoirs on the Yellow River, Longyangxia, Laxiwa, Lijiaxia, Liujiaxia, Yanguoxia, Bapanxia, Qingtongxia, Sanshenggong, Wanjiazhai, Tianqiao, Sanmenxia, and Xiaolangdi, have a total capacity of about 64 billion m^3. The total installed capacity of power generation is about 9,000 MW, of which 1,280 MW is at Longyangxia, 3,500 MW is at Laxiwa, 2,000 MW at Lijiaxia, and 1160 MW at Liujiaxia. These power plants generate 33 billion kw-hr per year, of which the 4 major power stations generate 6-10 billion kw-hr each. The reservoirs are operated mainly according to the requirements of power generation and water supply without consideration of the natural features of the river and maintenance of a high capacity for sediment transport in the channel. The reservoirs store water the during flood season and release water in the non-flood season for power generation. Therefore, the flood peaks are flattened and much less water is transported at high discharges. Flows in the middle and lower Yellow River have changed remarkably.

The Sanmenxia Reservoir was the first reservoir on the Yellow River about 1,000 km upstream from the river mouth. The Longmen Hydrological Station is at the upper end of the reservoir (about 230 km upstream from Sanmenxia Dam) and the measured water and sediment fluxes at the station reflect the influence of human activity in the middle and upper basins. Fig. 34 illustrates the runoff volume at different discharges at the Longmen Hydrological Station during the flood season (July to September). From 1950-1969 more than 7 billion m^3 of water, or 30% of the runoff in flood season, was transported at a discharge of about 3, 000 m^3/s. In the period 1970-1985, the peak runoff-conveying discharge was still 3, 000 m^3/s but only 3.8 billion m^3 of water flowed at that rate. In the period 1986-1995, however, the peak runoff-conveying discharge reduced to 1, 500 m^3/s, which reflects the effects of discharge-regulation by the reservoirs, water diversion, and soil and water conservation works in the basin (Pan and Li, 1998).

The average annual runoff and sediment load released from the Sanmenxia Reservoir to the lower reaches of the river in the period 1986-1994 were 30.7 billion m³ and 0.8 billion tonnes which were 11.3 billion m³ and 0.36 billion tonnes less than the long term (1950-1990) average values, and those to the river mouth were 17.2 billion m³ and 0.42 billion tonnes, 23 billion m³ and 0.58 billion tonnes less than the long term average values. The main causes for the marked reduction are attributed to soil conservation projects and sediment trapping by the reservoirs in the upper and middle reaches, increasing water and sediment diversion, and sedimentation in the lower reaches (Zhang et al., 1997).

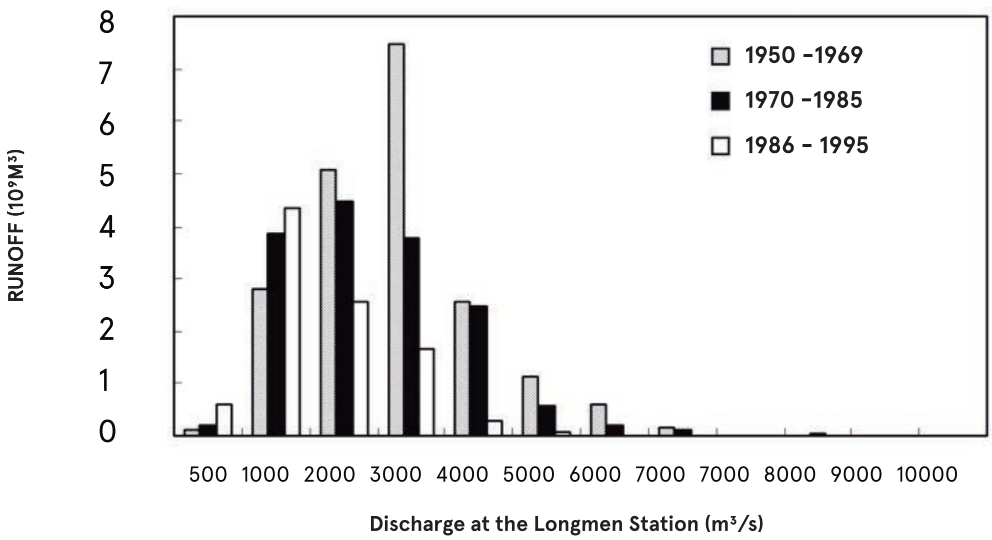


Fig. 34

Comparison of runoff volume in the flood season (July –Sep) at different discharges at the Longmen Hydrological Station in the periods 1950-1969, 1970-1985 and 1986-1995

In the past decade, the lower reaches changed rapidly in their hydrological features. With the development of reservoirs and irrigation projects upstream, less water was released to the lower reaches. Only 700 million tonnes of sediment were transported to the lower reaches annually due to sediment trapping projects in the Loess Plateau and fewer rainstorms. Nevertheless, sedimentation in the lower reaches was not reduced by the reduction of the sediment load. Between 1985 and 1994 the average sediment accumulation in the lower reaches was 307 million tonnes during the non-flood season, of which 67 million tonnes were scoured during the flood season, resulting in a net sediment deposition of 240 million tonnes per year. In the meantime, on average 495 million tonnes of sediment were transported to the delta and into the Bohai Sea per year. The huge amount of sediment deposition caused serious aggradation of the riverbed and seabed. Table 6 lists the rise of the water stage at a discharge of 3,000 m^3/s at the main hydrological stations along the river in the period 1985-1994.

The stage rise is due to sediment deposition in the river channel. The important facts of sediment movement in the lower reaches of the Yellow River are: (i) siltation takes place in the low flow season and net scour occurs in the flood season; and (ii) scour occurs during the rising limb of a flood and siltation occurs during the receding limb of a flood. Analysis of the data from the lower Yellow River yield the following empirical formula relating the sediment load from scouring to the flow discharge:

$$\Delta Q_s = 0 \quad \text{if} \quad Q = 1{,}800 \ m^3/s \qquad (1)$$

in which ΔQ_s (in tonnes/s) is the increased sediment discharge due to scour in the section from Aishan to Lijin, Q is the water discharge in m^3/s. In other words, Q=1800 m^3/s is the critical discharge for channel bed erosion and siltation. The bed is scoured if the flow discharge is greater than and sediment deposition occurs if the flow discharge is less than 1,800m^3/s. A similar law was found by other researchers, with the critical flow discharge at 1,500 m^3/s (Qi, 1993). Fig. 35 shows the average bed elevation at the Lijin Station corresponding to the discharge from July to November of 1977 (Yin and Chen, 1993). High discharge caused deep erosion of the riverbed, whilst flood recession and low flow were accompanied by aggradation.

Hydrologic Station	Zhengzhou	Gaocun	Aishan	Jinan	Lijin
Distance from Lijin (km)	670	456	270	168	0
Stage rise (m)	0.99	0.93	1.13	1.35	1.62
Average rate of stage rise (m/year)	0.11	0.10	0.13	0.15	0.18

Table 6

Flood stage rise (at a discharge of 3,000 m^3/s) at the main gauging stations along the lower reaches of the Yellow River in the period 1985-1994

Reservoirs have trapped a huge volume of sediment that resulted in a rapid reduction in the sediment load transported to the lower reaches. The reservoirs also reduced water flow to the lower reaches, clipping peak flood discharges. The sediment carrying capacity of the flow is proportional to the power of the discharge. Sediment used to deposit in the lower river channel in dry years and was scoured away in wet years when high discharge occurred. Reservoir regulation removed the opportunities for bed scour and the channel progressively silted up.

Development of the economy and growth of the population led to the reclamation of the river floodplain. Nowadays about 2 million people are living on and cultivating 270, 000 ha of farmland in the lower Yellow River floodplain within the Grand Levees. The people built levees adjacent to the main channel and prevented the floodplain from flooding. Therefore, sediment mainly deposited in the main channel. In the 1950s, 80-100% of the deposited sediment was on the floodplain, whereas in the 1990s 74-113% of the sediment was deposited in the main channel. Although the total amount of sediment deposited annually in the lower Yellow River was less, the amount of sediment deposited in the main channel was much more than before. Consequently, the channel shrank and the water conveying capacity of the river channel reduced greatly. Fig. 36 shows the variation of the water discharge capacity of the river channel below elevation 93.5 m at Huayuankou in the period from 1958 to 1999. The capacity was about 18, 000 m^3/s in 1960 and is now less than one tenth of that. In many sections the channel is silted up to an elevation higher than the floodplain and is therefore referred to as the “perched channel” within the “suspended river”.

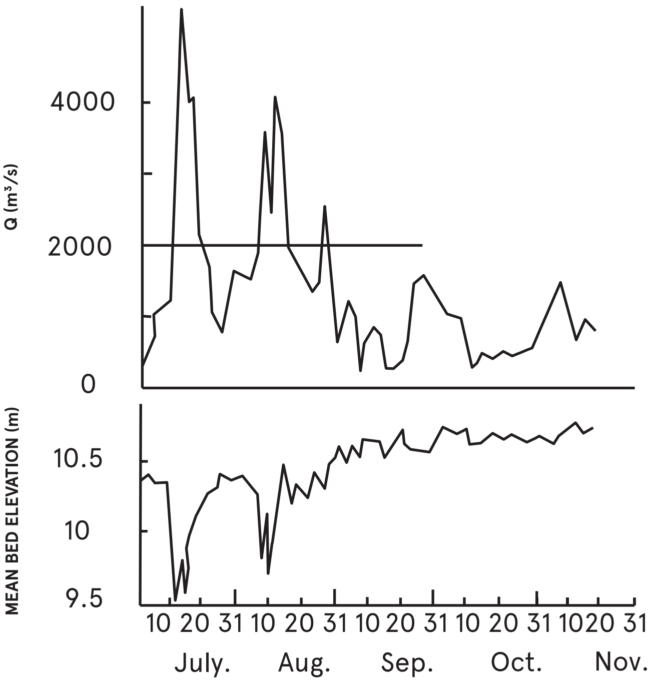


Fig. 35

Variation of bed elevation and the flood discharge at the Lijin Station during the flood season in 1977

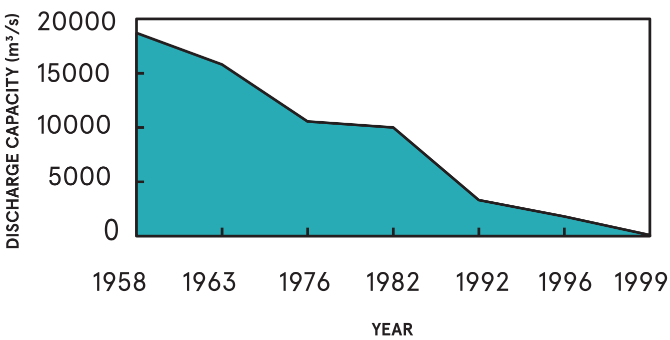


Fig. 36

Reduction of the discharge capacity of the Yellow River Channel below elevation 93.5 m at Huayuankou during the period from 1958 to 1999

Due to the high rate of population growth and the lack of land people reclaim the floodplain in the lower Yellow River valley. They are not protected by the Grand Levees and are exposed to high risk of flooding. When the inhabitants of the town close to Changdong Bridge of the Yellow River were woken by a muffled roaring sound on August 5, 1996, some part of the town were already a meter under water. A flood discharge 7,860 m^3/s moved through the lower reaches of the river, breaching levees and destroying 2,898 villages and 212 towns. About 2.41 million people were affected by the flood and $800 million damage resulted. The flood discharge was much less than those of 1958 (22,300 m^3/s) and 1982 (15,000 m^3/s), but the flood caused the highest stage in historical records. Fig. 37 shows the stage-discharge relationships for the 1996 flood and those of 1958 and 1982 (Zhao and Liu, 1997). The recurrence interval of the flood with peak discharge about 8,000 m^3/s is only 2 years according to the 1950-1996 data. In other words a discharge of 8,000 m^3/s or higher occurred once every 2 years, but such heavy loss never resulted prior to 1990.

The high stage of the 1996 flood was due to the siltation of the main channel. Long term river evolution data demonstrate that sedimentation occurs at low discharge and the river bed is scoured if the discharge is over 1,800 m^3/s. With flow regulation by the reservoirs, trapping of water and sediment by thousands of warping reservoirs in the Loess Plateau, and diversion of huge amounts of water from the river, the flood peaks were truncated and the total flood runoff of floods was greatly reduced. It was estimated that if the 1996 rainstorm had occurred in 1950-1960, the peak discharge at Huayuankou would have been over 12,400 m^3/s (Zhao and Liu, 1997). Because the river channel is now rarely scoured by turbulent floods, the main channel silted up at a high rate, 0.1-0.2 m/yr. Now the river bed is 6-10 m higher than the surrounding ground and is named the "suspended river". In many sections the main channel was flat and was at the same elevation as the floodplain. Therefore, the 1996 flood did not flow down the river in a well-defined channel but flowed randomly within an up to 10 km wide valley confined by the Grand Levees. In many sections the flow was directed to the levees causing the levees to burst. The propagation speed of the flood wave was much lower than normal, thus, the 1996 flood took 17 days to travel the 800 km from Huayuankou to Lijin although the average travel time for floods of the same discharge in 1950-1990 was only 7-8 days.

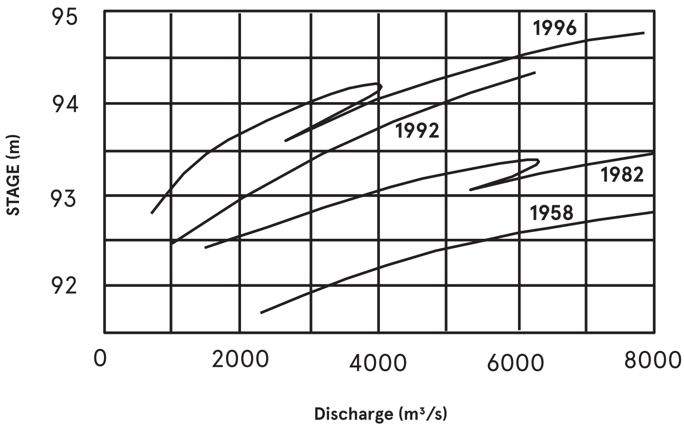


Fig. 37

Stage-Discharge relationships of 1996, 1992, 1982 and 1958 floods (after Zhao and Liu, 1997)

To protect the farmland and settlements on the floodplain and stabilize the channel of the wide river valleys in the lower Yellow River, many spur dykes have been constructed. The spur dykes have, to a certain degree, fixed the channel and concentrated the flow and caused sediment deposition between the spur dykes. The channel was therefore deepened and relatively stabilized. The degree of channelization is defined as the ratio of the total length of the spur dykes to the length of the channel, or the length of spur dykes per channel length. Fig. 38 shows the distribution of the degree of channelization along the river downstream from Sanmenxia Reservoir. From the 1970s to 2002, the degree has increased from 0.2-0.8 to 0.8-1.35. Nevertheless, the natural fluvial processes tend to attack of the spur dykes, and the flow scours the dykes and causes them to collapse.

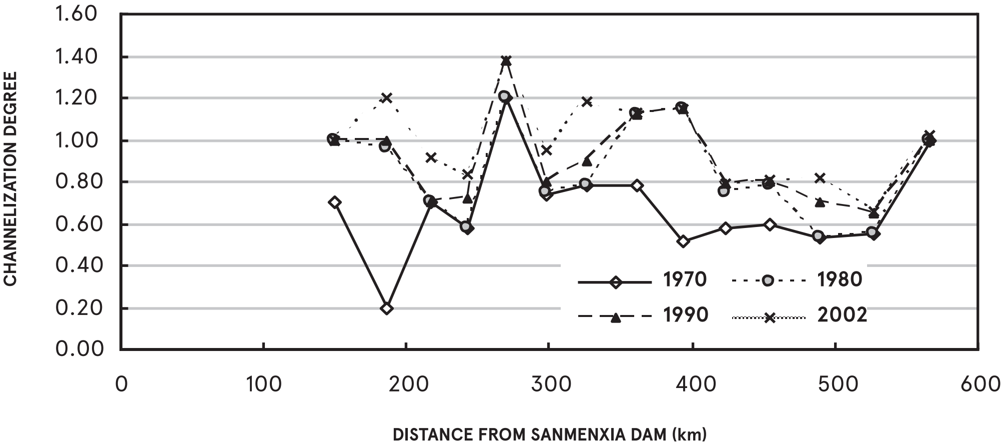


Fig. 38

Distribution of the degree of channelization (ratio of the length of the spur dykes to the length of the channel) along the lower Yellow River (Cheng et al., 2007)

Fig. 39 shows the probability of collapse of each dyke as a function of the degree of channelization. The probability is calculated as the total number of collapse occurrences per year over the number of spur dykes. The probability is low as if the degree of channelization is lower than 0.8. For a degree of channelization higher than 0.8, however, the probability of dyke collapse abruptly increases from 10% to 30%. The high probability of dyke collapse reflects the conflict between the natural fluvial processes and the constraint of channelization. In fact, the strongest conflict occurs for a degree of channelization in the range of 0.8-1.0, and, therefore, there is a corresponding high probability of dyke failure. Nevertheless, if the degree of channelization approaches 2 (the two sides of the channel are completely controlled by spur dykes), the channel motion will change from lateral to vertical. The channel will be deepened, resulting in an increase in the bank-full discharge. Fig. 40 shows the probability of dyke failure as a function of the bank-full discharge. Following an increase in bank-full discharge the probability of dyke failure decreases.

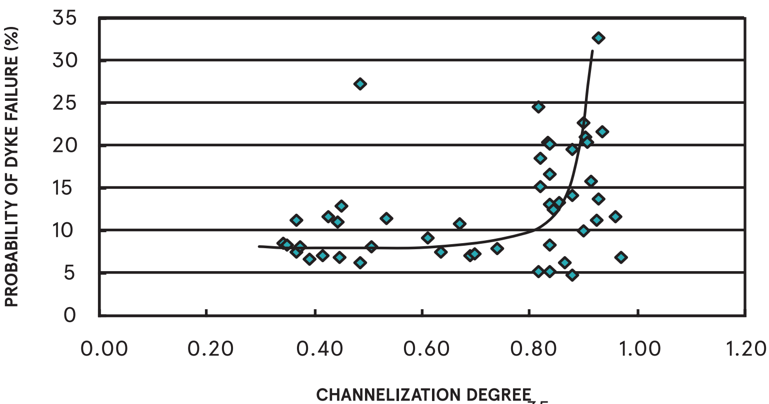


Fig. 39

Probability of dyke collapse as a function of the degree of channelization.

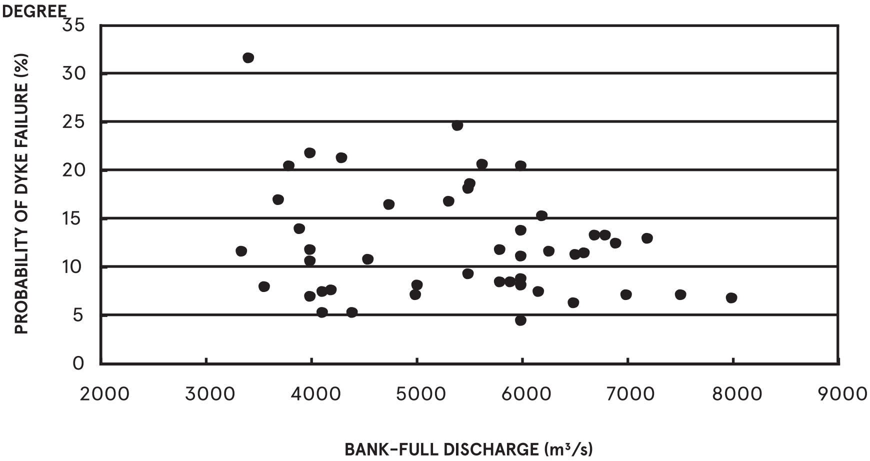


Fig. 40

Probability of dyke failure as a function of bank-full discharge

3.2 Water resource development affecting fluvial processes

The average precipitation on the Yellow River basin is 476 mm, but the potential evaporation is 1,000-3,000 mm per year. The total runoff from the basin is 58 billion m^3, about 2% of the total for the country. There is about 40.2 billion m^3 of ground water in the area, but it must be recharged with surface water and rain water. Water resources per capita is 590 m^3 and the water resource for farmland is 4,850 m^3/ha. Moreover, the neighbouring areas, such as the Haihe River basin and the Huaihe River basin, also divert water from the Yellow River because the two areas also suffer from water shortage and the Lower Yellow River is higher than the surrounding ground and can be directly diverted to these areas. For instance, Tianjin has been supplied by Yellow River water almost every year since the end of the 1990s. To supply 600 million m^3 of water more than 2 billion m^3 must be diverted from the Weishan water Diversion Station because more than 70% of the diverted water is consumed and diverted on the way from Weishan to Tianjin.

There are now 3,147 reservoirs in the whole basin with a total storage capacity of 57.4 billion m^3. More than 4,500 water diversion projects have been completed and 29,000 pumping stations are working for irrigation and water supply. The irrigation area has increased from 0.8 million ha in 1950 to 7 million ha in 1995. The irrigated farmland is about 45% of the total farmland area but produces more than 70% of the grain. In the past 50 years people have invested $5.4 billion to develop water resources for agriculture and benefited by $57 billion in grain production. $8 billion has been has been invested for urban water supply, and industries have benefited by $14.6 billion.

Sediment transport is an important role of the Yellow River water. It is roughly estimated that at least 20 billion m^3 are needed to transport 1 billion tonnes of sediment to the ocean. Fig. 41 shows the average runoff and sediment load along the river course in the 1950s. The runoff remained unchanged from Huayuankou to the river mouth and the sediment load reduced slightly along the course of the lower reaches. Since 1985, however, the runoff has become less and less along the river course from Huayuankou to the river mouth and the sediment carrying capacity reduces even more. The reduced flow discharge is not able to carry the same amount of sediment, and, thus, results in rapid siltation of the lower reaches channel.

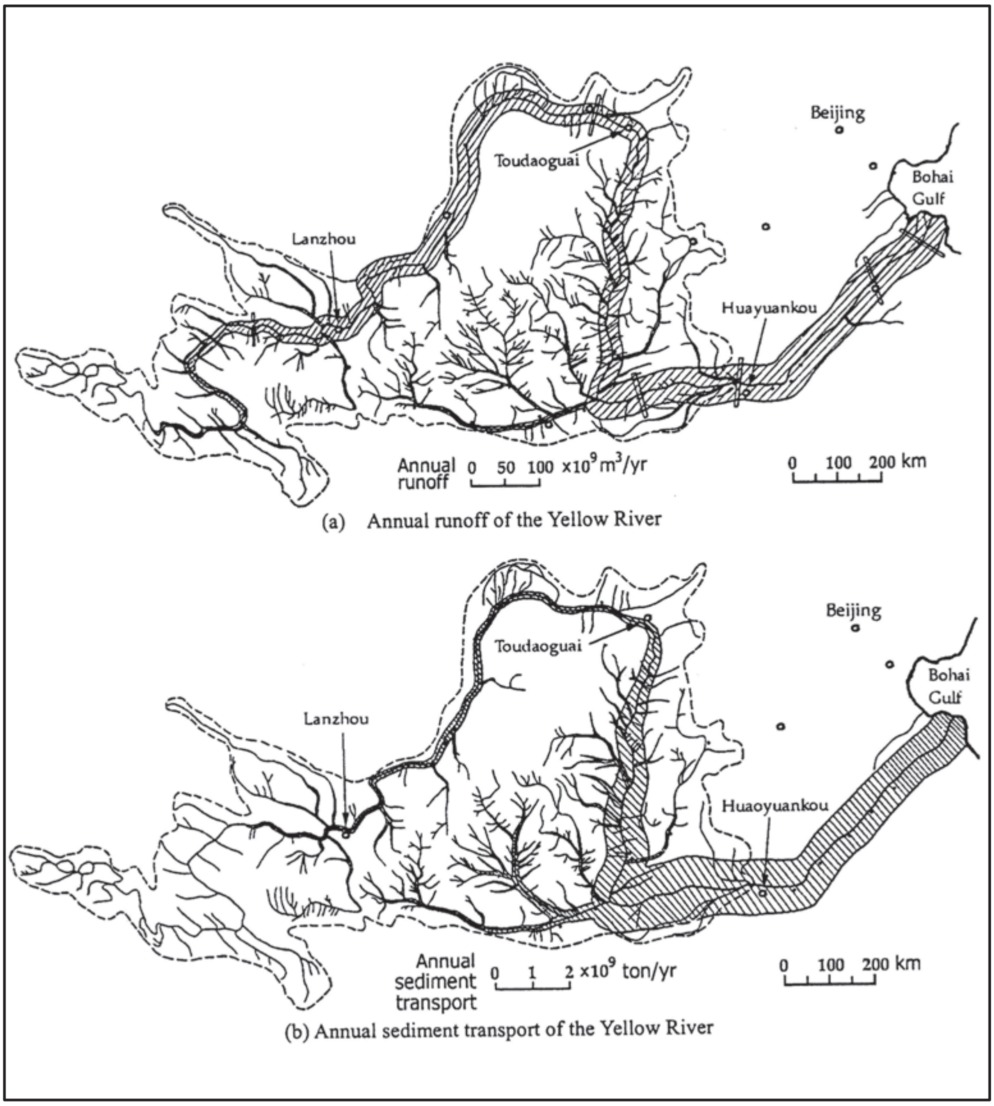


Fig. 41

Average runoff and sediment load of the Yellow River in the 1950s (after Qian and Zhou, 1964)

The Yellow River basin is one of the thirstiest areas in China and economic development is plagued by increasingly serious water shortages. All provinces have tried to use as much water as they can, which resulted in conflict between areas and Provinces. The use of water resources needs central government coordination. Because the whole area of the Yellow River valley suffers from water shortage, the central government produced an allocation scheme for use of the water resources in 1987. The quotas of water resources for the 11 provinces are listed in Table 7.

It is obvious that except for Shandong Province and the Inner Mongolia Autonomous Region, the water consumption of most Provinces and Autonomous regions in the 1990s was less than the allocation quota. It can be foreseen that water consumption of the upstream Provinces and Autonomous regions will increase following the development of the economy and increase in the ability to withdrawing water.

The allocation scheme was made based on the long-term average annual runoff of 58 billion m³ across the whole Yellow River basin. The allocation scheme has not worked well because not so much water was available while the water demands of these Provinces were more in dry years. Increased water was available in wet years but less water was needed. Much less water was released from upstream reservoirs as the lower reaches were thirsty in dry years. The lower reach channel became completely dry from March to July during the 1990s. It is necessary to work out a more sophisticated allocation scheme in which the differences between dry and wet years are taken into consideration.

Table 7

Allocation of the Yellow River Water Resources

Provinces and Autonomous regions	Quota (billion m³)	Water consumption in the 1990s (billion m³)
Qinghai	1.41	
Sichuan	0.04	
Gansu	3.04	1.76
Ningxia	4.00	3.70
Inner Mongolia	5.86	6.00
Shanxi	3.30	2.50
Shaanxi	4.81	2.00
Henan	5.54	3.50
Shandong	7.00	8.00
Hebei and Tianjin	2.00	0.50
Total	37.00	27.96

Note: The central government adjusted the quota in 1995 allowing the Provinces to use 120% of the quota in wet years but only 80% in dry years

The Yellow River basin is a semi-arid area and the river is the main water resource for 150-200 million people in the middle and lower reaches. With the booming economy, demand for water has rapidly increased. Water diversion in the middle and lower reaches of the Yellow River has escalated. Because of the serious water shortages and the absence of a workable plan for distributing the valuable water to various Provinces and regions, all localities on both banks of the river try to store and use water as much as they can. Not only low concentration water during the nonflood season is diverted, but also the high concentration flow in the flood season. As a result, less and less water is released to the lower reaches. The annual runoff and sediment load at Lijin (110 km from the river mouth) is shown in Fig. 31. The annual water flow before 1985 was 40 billion m^3 but reduced to only 15 billion m^3 after 1985. Fig. 42 shows the days and length of dried-up channels of the lower Yellow River from 1970 to 1998. In 1972, the Lijin Station in Shandong Province recorded a 15 day period when the river dried up. For the first time in known history, the mother river stopped flowing. The river suffered two major droughts, one from 1875-1878 and another from 1922 to 1932 without drying out, but it began to dry out in the 1970s. Flow cut-offs have occurred in 19 of 27 years in the period 1972-1998.

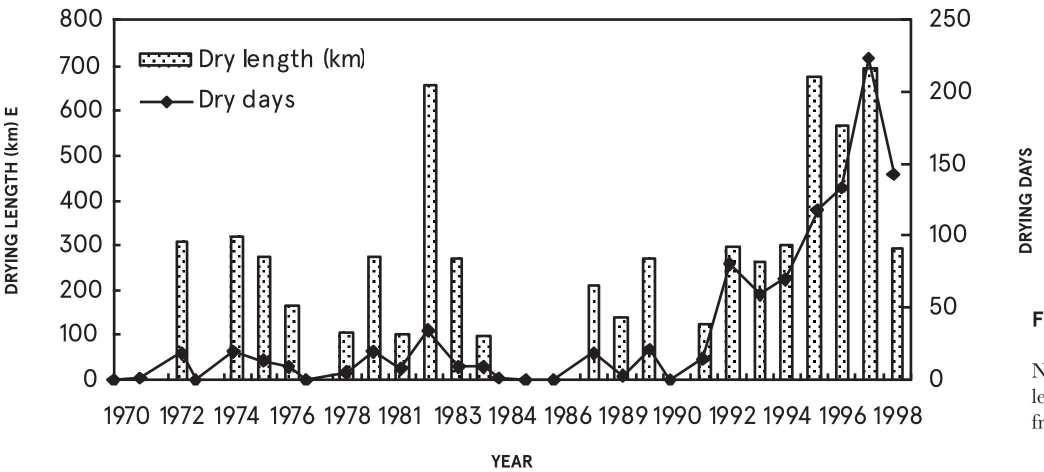


Fig. 42

Number of dry days and dry length of the lower Yellow River from 1972-1998

Fig. 43

The cut off river flow and the dry river bed during the flood season in 1977: (a) A boat is resting on the bed ; (b) A floating bridge is not used because vehicles may drive across the riverbed at any place

Before 1990, the drying up of the river often took place in May and June. But after 1990, the drying up started early in February, and ended as late as October. In 1970s, the river only dried for about 10-20 days and the dry section was only 135 km long. The river remained dry for 80 days in 1994, 122 days in 1995, 133 days in 1996 and 226 days in 1997 and the dry section stretched 700 km from the river mouth. The river flow was cut off in the flood season because the floodwater was diverted for irrigation and drinking. Fig. 43 shows that the river flow cut off and the dry river bed in the flood season in 1977. Boats were resting on the bed and the floating bridge was not used because vehicles could drive across the riverbed at any place. The river is in danger of transforming into an inland river in the foreseeable future. Without prompt measures, China may someday find her mother river exhausted. No sediment and organic material were transported into the sea during the dry perid, which cut off the food chain for some species. This will result in complex ecological problems, for instance, the fish in the estuary have been greatly affected and some rare species have vanished. The river is usually regarded as an "artery" of the country and the cutting off of the river flow will seriously damage its "health". This is sounding a warning that water shortage is becoming a more serious problem than the need for flood control in northern China.

Too much water diversion not only caused the flow cessation of in the lower Yellow River but also changed the river profile. Water diversion may even change a section of a perennial stream to an ephemeral river section (Fogg and Muller, 1999). While water diversion projects have become a popular and important strategy to meet increasing water demand, the streamflow, sediment transport and fluvial processes of rivers are increasingly affected. The amount of water diverted from the lower Yellow River has been increasing in the past 50 years. Water diversion inevitably affect the fluvial processes.

Fig. 44 (a) and (b) show the variation of the annual water and sediment load from 1960 to 1997 at Xiaolangdi and Lijin hydrological stations, in which the horizontal lines represent the average runoff and sediment load. The differences between the figures at the two stations are due to the inflow from tributaries and outflow by water diversions along the course from Xiaolangdi to Lijin. From 1960-1969 there was more water flowing through Lijin than Xiaolangdi because the water diversion was less than the inflow from tributaries. From 1970-1985, the annual runoff at Lijin was equal to or slightly less than at Xiaolangdi because more water had been diverted. From 1986 to the present, however, the total volume of water diverted was much more than the inflow from tributaries, and the flow decreased along the course. The annual runoff was about 11 billion m^3 less at Lijin than at Xiaolangdi. The reduction in runoff over a long stretch of the river resulted in a sharp reduction in the sediment-carrying capacity of the flow. Therefore, the annual load was much less at Lijin than at Xiaolangdi from 1986 to the present.

From 1986, water and sediment load increased along the course and reached their maximum values at Huayuankou, and then reduced further downstream due to diversion. The sediment load at Lijin is less than that at Sanmenxia by more than 300 million tonnes, which must have deposited in the reach between Sanmenxia and Lijin and consequently changed the morphology of the river.

One of the impacts of the runoff reduction on the fluvial processes was the shrinkage of the channel. Fig. 45 shows the bank-full discharge of the lower Yellow River during different periods. Water diversion has reduced the discharge and sediment-carrying capacity, and sediment has been deposited in the channel, which has made the channel shallow and unstable. As a result, the bank-full discharge has decreased steadily. The bank-full discharge was about 9,000 m³/s in 1958 and 1964; it decreased to about 6,000 m³/s in 1985, and to only 3,000 m³/s in 1999.

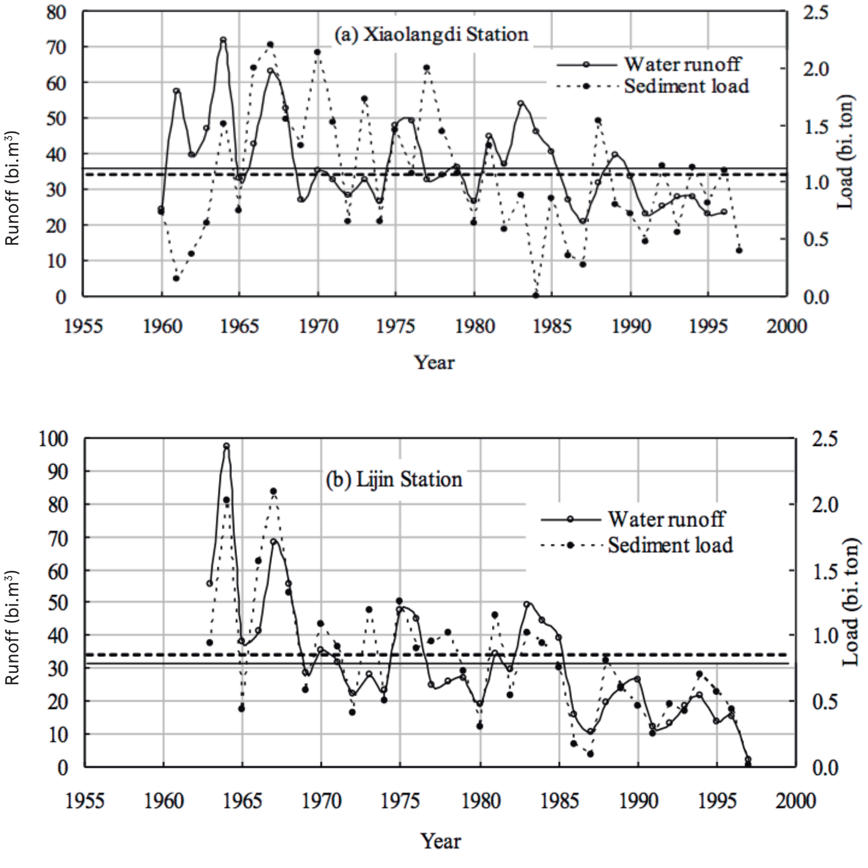


Fig. 44
(A)

Variation of annual runoff and sediment load in the period from 1960 to 1997 at Xiaolangdi (130 km from Sanmenxia Dam)

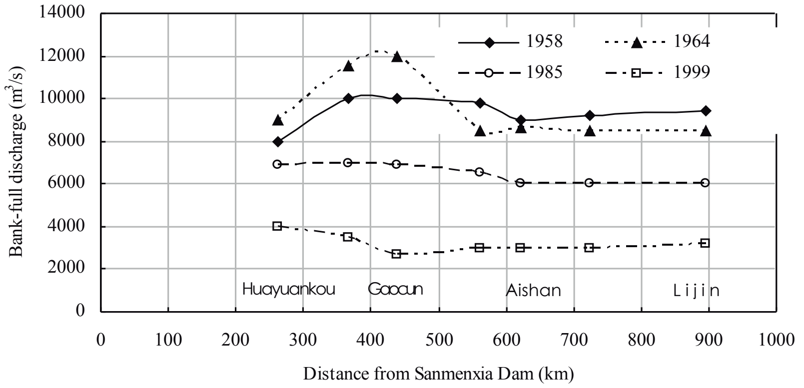


Fig. 45

Bank-full discharge along the lower Yellow River course during different periods

The second important impact of water diversions is the adjustment of the riverbed profile. Field evidence from natural streams shows that variations in successive processes and forms result from a system's tendency to minimize the rate of energy dissipation with time (Simon, 1992). For an alluvial river with bed material consisting of sand and silt, no bed structures except for sand dunes can develop, the river morphology depends mainly on the stream power. According to the minimum stream power theory (Yang, 1996), the bed gradient develops to reach the minimum stream power, thus:

$$\frac{dP}{dx} = \frac{d}{dx}(\gamma sQ) = \gamma\,(Q\frac{ds}{dx} + s\frac{dQ}{dx}) = 0 \qquad (2)$$

in which P is the stream power in tonnes/s, is the specific weight of water in tonnes/m^3, s is the riverbed slope, x is the distance along the river course in km, and Q is the discharge in m^3/s. For most rivers, the discharge increases along the course due to the inflow from tributaries; thus, the term sdQ/dx is positive.

According to equation (2), the term Qds/dx must be negative, or the slope of the riverbed decreases along the course; so that these rivers exhibit concave riverbed profiles. Equation (2) indicates the direction of morphological processes and the equilibrium state of the longitudinal river profile. Sediment load plays an important role in the speed of morphological processes but does not change the direction and the final equilibrium of the profile. The higher the sediment load the faster the morphological processes. For a low sediment load river the riverbed profile often does not meet Eq. (2) because it takes a very long time to reach the minimum stream power profile.

The Yellow River carries a heavy sediment load and the morphological processes are fast. The large quantity of water diverted along the course of the Yellow River makes the term sdQ/dx negative. For instance, since 1986 the average discharge has decreased along the Yellow River course in the reach downstream of Huayuankou, i.e. dQ/dx<0. According to Eq. (2) the term Qds/dx must be positive. In this case, the riverbed profiles will develop toward a convex shape, which is different from the normal concave curve. Fig. 46 shows the bed profiles of the lower Yellow River for 1977 and 1997. The mean bed elevation is the average bed elevation of the channel with a cross-section of wet area about 500 m^2. The figure shows that the lower section of the river is developing toward a convex profile. Because the profile of the upper section is concave, the river shows an "S-shape" longitudinal bed profile. The trend will continue and the turning point in the profile will move upstream because the water diversion is continuing and more water will be diverted in the foreseeable future (Wang and Hu, 2004).

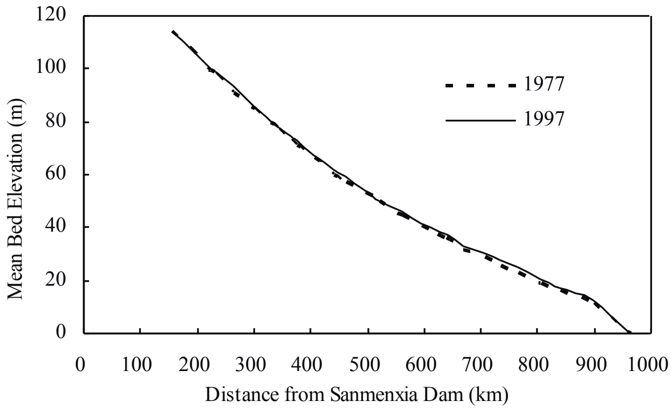


Fig. 46

Longitudinal bed profiles of the lower Yellow River in 1977 and 1997 (Wang and Hu, 2004)

3.3 Land Creation and Land Loss in the Yellow River Delta

The modern Yellow River flows into the Bohai Sea via Lijin since the river levee at Tongwaxiang (about 600 km from the present river mouth as shown in Fig. 1) was broken and flood water captured the Daqing River channel, in 1855. Thence the reaches upstream of Lijin have been densely populated and the levees in the reaches were enhanced and reinforced many times, and no avulsion and channel shift occurred in these reaches since 1855. The population density downstream from Lijin was low and the levees downstream of Ninghai were too weak to resist the assault of floods.

The river reach in the delta shifted to the present Qing-shui-gou channel in 1976. In the early Qing-shui-gou period, the river channel was not well shaped. The sediment-laden flow built up its channel by depositing sediment in low velocity areas and scouring sediment in high velocity areas. During this process, seasonal variation of discharge and sediment deposition in the delta area has resulted in a high frequency of mouth migration, as shown in Fig. 47 (Ji et al., 1994). In the first 3 years (1976-1979), the channel was unstable and the new river mouth wandered across an area within a range of 30 km. The main stream flowed eastward into the sea in October 1977, but changed northward in October 1978. In the flood season of 1979 the river mouth moved from northeast to southeast again. The frequent shift of the mouth and channel is due to the floods with high sediment concentrations in these years, with a maximum sediment concentration up to 240 kg/m³. Since 1980, the main channel has moved east again and a relatively stable meandering channel formed. In 1986 the local people extended the guiding levees and the channel upstream from Q8 was not allowed to wander anymore (Fig. 47).

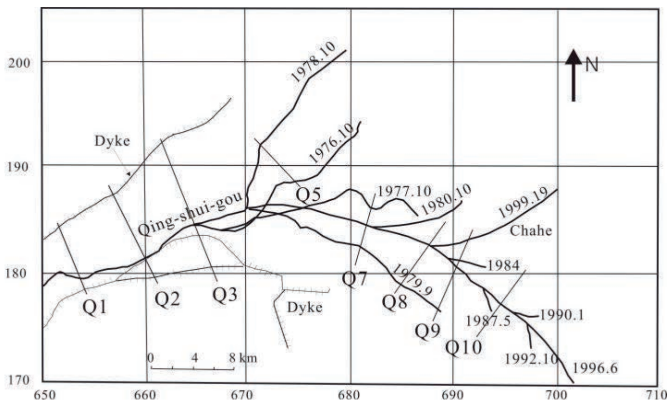


Fig. 47

Wandering of the Qing-shui-gou channel (Q1-Q10 are the cross sections for measurement)

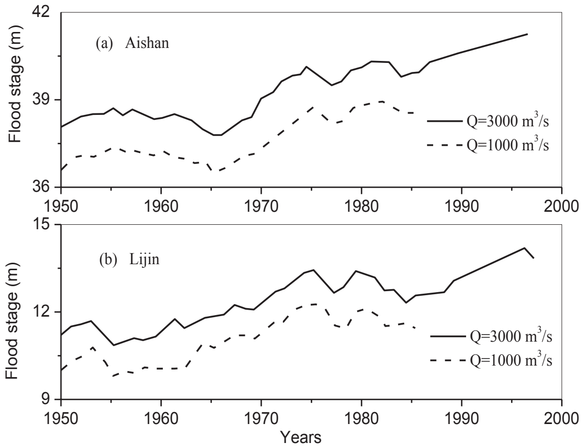


Fig. 48

Fluctuation of flood stage at (a) Aishan and (b) Lijin Stations at discharges of 1000 and 3000 m³/s due to avulsions (Stage reductions occurred in 1953, 1964, and 1976, which are coincidental with the avulsions)

A shift in the river course caused stage reduction in the upstream reaches. The new channels were shorter than their predecessors and had greater slope. Thus, the flow velocity was higher and stages at the same discharges were lower. Fig. 48 shows the stages at Lijin and Aishan (locations of the two station in Fig. 1) for discharges of 1,000 and 3,000 m^3/s in the period from 1950 to 1990. The stages decreased abruptly in 1953, 1964, and 1976, corresponding to the three shifts of the river course. The effect reached Aishan, which is more than 350 km from the river mouth. Following these short periods of stage reduction there was a sharp stage increase because of a quick extension of the new channel following the avulsion. Another stage reduction occurred in the 1980s, which is not due to a shift of the channel but to dredging of the river mouth.

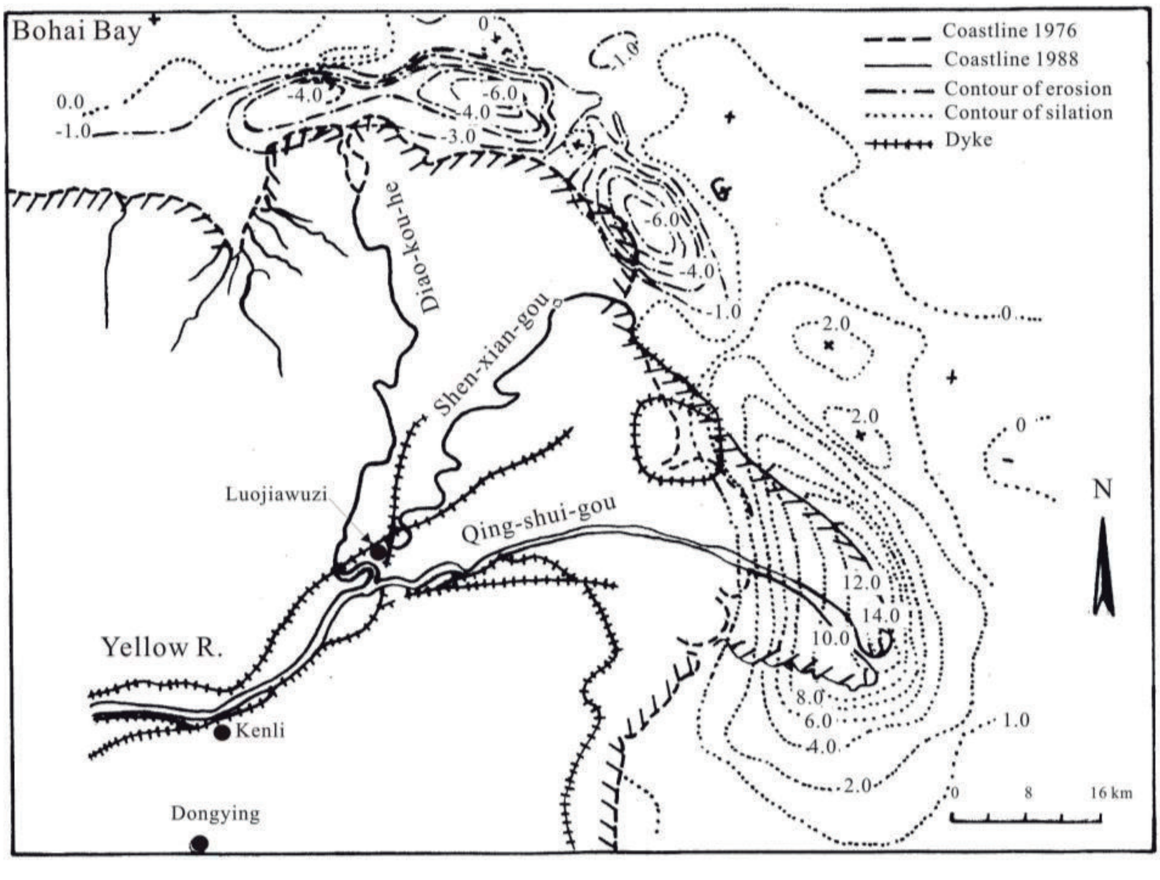
The delta is very dynamic and fluctuates in response to the alluvial regime, tide, and storm surges. The deposits in the delta consist mainly of silt (d_{50}=0.02 mm), which is very erodible. The riverbed can be eroded and filled with several meters in one day during a flood (Wang, 1999).

The Qing-shui-gou channel extends into the sea for over 40 km, and the shape of the Yellow River delta has changed markedly since the river shifted to this channel in 1976. In the meantime, the silt deposited in the previous channel (Diao-kou-he) mouth was eroded. By comparing satellite images of the Yellow River Delta in 1976 and 1988, a map of topographic change in the two areas has been derived. The present river mouth was in the sea with a water depth of 10-20 m before the shift and the previous river mouths-Shen-xian-gou mouth and Diao-kou-he mouth were land of a few meters elevation. As shown in Fig. 49, the new river mouth area (about 30 × 40 km) was silted up and emerged from the sea, with the maximum siltation of 14 m. In the meantime the old river mouths were eroded by waves and tidal currents. The maximum erosion depth is about 6 m (Zhang et al., 1997). The Qing-shui-gou channel extended by 11 km in 1976 and 5 km in 1977.

The speed of extension decreased sharply in the succeeding years. The average speed of the river mouth moving into the sea was about 2.3 km/yr in the period from 1976-1994 and was zero in the period from 1994-1996. The rate of land creation is reduced because of the stabilization of the river mouth.

Fig. 49

Contours of siltation of the Qing-shui-gou mouth (1 to 14 m) and erosion of the Diao-kou-he and Shen-xian-gou mouths (-1 to -6m) from 1976-1988



The Yellow River delta is rich in oil and gas resources. The Shengli Oil Field, the second largest in China, is developed on the delta. No long or medium term construction of oil fields can be planned if the channel cannot be stabilized. The Kendong Oil Field is located in the offshore area near the river mouth (the Chahe mouth in Fig. 47), with oil reserves of 257 million tonnes and could be developed into an oil field with an annual production of 5 million tonnes/year. The water depth in the area is in the range of 1-5 m. By utilizing sediment transported by the Yellow River to silt up the field, the cost of oil extraction can be reduced by 0.35 billion USD.

The river was artificially switched to the Fork Channel in July 1996 for land creation (Zhang et al., 1997). When the first flood flowed through the Fork Channel in 1996, erosion took place and the channel became 3.5-4 m deep and 300-400 m wide. The new fork channel can be clearly seen on the satellite image shown in Fig. 50. The stage of the 2,100 m^3/s flood on August 5, 1996, was recorded at 5.8 m at Ding-zi-kou and at only 5.81 m for a flood of 3, 860 m^3/s on August 26, 1996, due to scouring of the channel. Because the new channel was 16 km shorter than the previous one, the energy slope was higher and retrogressive erosion occurred in a section of 30 km from the river mouth. The shift to the new channel reduced the flood stage upstream of Lijin by more than 0.3 m. The peak discharge of the flood at Lijin was 4, 100 m^3/s. The flow was kept in the main channel and no overbank flow occurred. Therefore, the 25, 000 ha of farmland and 4 oil fields on the floodplain were free from flooding. More than 60 km^2 land were created at the new river mouth by the 1996 flood. According to the predicted sediment load and runoff, more than 200 km^2 of land could be created by the Yellow River sediment around the new river mouth in several years. The offshore oil field there would emerge. This was a successful operation integrating river mouth training and oil production. Fig. 50 is a satellite image from 2000, 5 years after the shift to the Qing-shui-gou – Chahe channel. The rate of land creation is less than predicted, because the flux of sediment and water to the river mouth in the past years were much less than the long term average. However, the new channel is stabilized quite soon. The original Qing-shui-gou channel bed is now covered with vegetation of shrubs and herbaceous.

Fig. 50

Satellite image of the modern Yellow River delta and the Qing-shui-gou-Chahe channel in 2000

3.4 New Strategies

Interbasin Water Transfer projects - The water shortage in the Yellow River basin was estimated to be around 7 billion m^3 in 2010 and is predicted to be 15 billion m^3 in 2030 (Chen, 1991). The main strategies to solve or ease the water shortage and save the river from dying out are reallocation of water resources and interbasin water transfer projects. Three routes of South - to North Water Transfer Projects have been proposed and will be implemented. The West Route will transfer water from the Qinghai-Tibet plateau to the upper reaches of the Yellow River. The west route of water transfer project will transfer water from the Jinsha River (the Yangtze River), Yalong River, and the Dadu River to the upper Yellow River. About 1.95 billion m^3 water can flow to the Yellow River by building dams and tunnels. The water shortage problem of the Yellow River basin can be solved and the clear water may carry sediment into the sea, thence the siltation of the river channel can be stopped. Nevertheless, the ambitious project needs a lot of investment. The Jinsha, Yalong and Dadu Rivers are only 100-200 km from the upper Yellow River. The total annual runoff of three rivers is 120 billion m^3. The project will divert 19.5 billion m^3 water from the three rivers to the Yellow River. However, the water diversion dams will constructed on tributaries of the three rivers, for instance, the Ake River, Duke River, Make River and Sequ River are tributaries of the Dadu River. The runoff of these tributaries are much less than that of the Dadu River. Water diversion will reduce the runoff by about 50%, which will impact the local ecology. It is necessary to study the impacts of water diversion on the local ecology and to introduce measures to mitigate the impacts as the water diversion is implemented.

Artificial flood - To mitigate the delta retreating and coastal erosion and to restore a high bank-full discharge of the lower Yellow River, artificial floods were created by using the Xiaolangdi Reservoir. The Xiaolangdi Reservoir impounded in 1999, which is located about 800 km upstream of the Yellow River mouth and is the most downstream gorgetype reservoir on the Yellow River. The multipurpose reservoir is mainly for flood control and sediment retention to reduce siltation in the lower Yellow River. The total capacity of the reservoir is about 12 billion m^3, of which more than 7 billion m^3 will be used for trapping sediment. The sedimentation in the lower reaches of the river will be reduced after impounding of the reservoir. In the first 20 years of the reservoir impoundment, coarse sediment will be trapped and clear water will be released to the lower reaches. The reservoir is operated so as to trap coarse sediment and discharge fine sediment. Most of the fine sediment will be released with water discharges over 2,000 m^3/s or more. The sediment load can be roughly calculated as the incoming sediment load into the reservoir minus the fraction trapped in the reservoir, plus the scoured sediment from the lower reaches channel and the incoming sediment from the catchment below the reservoir. Most of the sediment load is transported during the flood season and the sediment load transported has higher concentrations during floods.

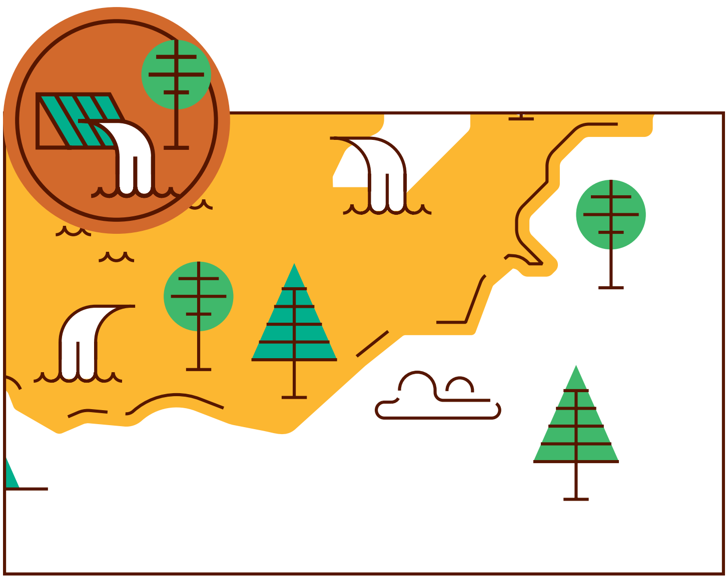
Because the coarse fraction of sediment is trapped by the reservoir, the rate of sedimentation of the lower Yellow River channel is greatly reduced. According to numerical models, the Xiaolangdi Reservoir may control sedimentation of the lower Yellow River for more than 20 years. Nevertheless, the fine sediment will be released into the lower Yellow River to reduce the rate of sedimentation of the reservoir. Sediment finer than 0.02 mm in the river is mostly wash load and can be transported into the sea.

On July 4, 2002 the first experiment of an artificial flood created with the Xiaolangdi Reservoir was conducted to explore the possibility of scouring the lower Yellow River bed. A flood with a peak discharge of about 2600 m^3/s was released from the reservoir and maintained for about ten days. Fig. 51 shows the artificial flood created with the reservoir. The concentration of the released flow is planned to be 10-20 kg/m^3. In order to control the concentration of released sediment, the water is released from the bottom, middle, and top outlets. The concentration of water released from the bottom outlet is high causing yellow and red water. Water released from the top outlet is clean and white. The flood scoured the river channel bed and the average concentration of suspended load increased from less than 20 kg/m^3 to 30 kg/m^3. From 2002 to 2004 three experiments were conducted to scour the lower Yellow River using an artificial flood before the flood season. Each year 40-60 million tonnes of bed sediment were scoured by the artificial flood. Now the artificial flood has become a routine operation of the Xiaolangdi Reservoir before the flood season and a total of about 600 million tonnes of sediment has been scoured from the channel and transported to the delta.

Fig. 51

Artificial flood created by releasing water from the Xiaolangdi Reservoir on July 04, 2002. Water was released from different elevations to control the sediment concentration. The released concentration from the bottom outlet is high colouring the water yellow and red, whereas the water from the top outlet is clean and white.

4.
The Sanmenxia project and its merits



Sanmenxia Reservoir demonstrates the perils of giving inadequate consideration to sediment management in the planning and design of a reservoir. Because the problems of siltation and induced flooding risk to the lower Weihe river have not been solved, decommissioning of the Sanmenxia dam has been under discussion for a long time as an alternative strategy to eventually solve the problem. The flood disaster that occurred on the Weihe River in the fall of 2003 has rekindled the argument for decommissioning of the dam. The main cause for the disastrous high stage is the continuously increasing river bed and flood plain level due to sedimentation. If there were no Sanmenxia Dam, the river bed would be much lower and the flood would cause no such disasters. Nevertheless, only 3 years ago when the Yellow River Conservancy Commission celebrated the 40 year anniversary of the Sanmenxia Reservoir, many people spoke highly of the reservoir. Sanmenxia Reservoir was seen as a great achievement in hydro-construction in China and a great example in the training of heavy sediment load rivers. The half century of safety in the lower Yellow River and the development of the river basin is attributed to the operation of the reservoir, which played an important role in flood control, ice-jam flood control, power generation, irrigation, and water supply. Moreover, scientists and engineers have accumulated experiences from the management of the reservoir for design and operation of dams on high sediment concentration rivers. Sanmenxia reservoir is a mistake or a great achievement? What we should learn from Sanmenxia Reservoir? The following section is attributed to the Sanmenxia Reservoir.

4.1 Sanmenxia Reservoir

The Sanmenxia Dam, 105-m high and 739-m long, was the first large dam on the Yellow River. The crest elevation of the dam is 353 m and the designed reservoir capacity is 35.4 billion m^3 with a normal pool level of 350 m. The main purposes of the dam are flood control, ice jam flood control, trapping sediment to reduce the downstream channel sedimentation, power generation, and irrigation. The reservoir controls a drainage area of 688,000 km^2 and 89% of the total runoff of the Yellow River basin. The reservoir area is shown in Fig. 52, in which the lower Weihe River is a part of the reservoir. The design of the dam and the reservoir was undertaken by the Yellow River Conservation Commission (YRCC) under the guidance of Russian experts from the Soviet Union (ECASP, 1993).The heavy sediment load was considered and the design planned to use a big part of the reservoir capacity for sediment deposition, which is mainly in the Yellow River.

The construction of the dam was initiated in 1957 and water impoundment commenced in September 1960. The reservoir area extends upstream a distance of 246 km to Longmen. The Yellow River flows south from Longmen to Tongguan, then makes a 90∞ turn and goes east. The Weihe River flows into the Yellow River at Tongguan.
To mitigate the sedimentation, the operation scheme of the dam was changed to detain only

flood water in the flood season. The primary function of Sanmenxia Dam was originally for flood control. For this purpose a capacity of 10 billion m³ was reserved (even after the change in operational mode) to cope with floods that occur only once in a thousand years, such as the 1933 flood. However, the flood-releasing capacity of the outlet structures was limited. Though the reservoir was operated at a low level during the flood season with all the outlet structures fully opened, the reservoir stage was still high and serious sedimentation in the reservoir due to the detention of large amounts of flood water was still inevitable. The net accretion of sediment deposits amounted to $2.04 \times 10^9 m^3$ from April 1962 to May 1966. During this period, 16 floods lasting 89 days in the summer of 1964 caused 0.93×10^9 m³ of sediment to be deposited in the reservoir area (Yang et al., 1994).

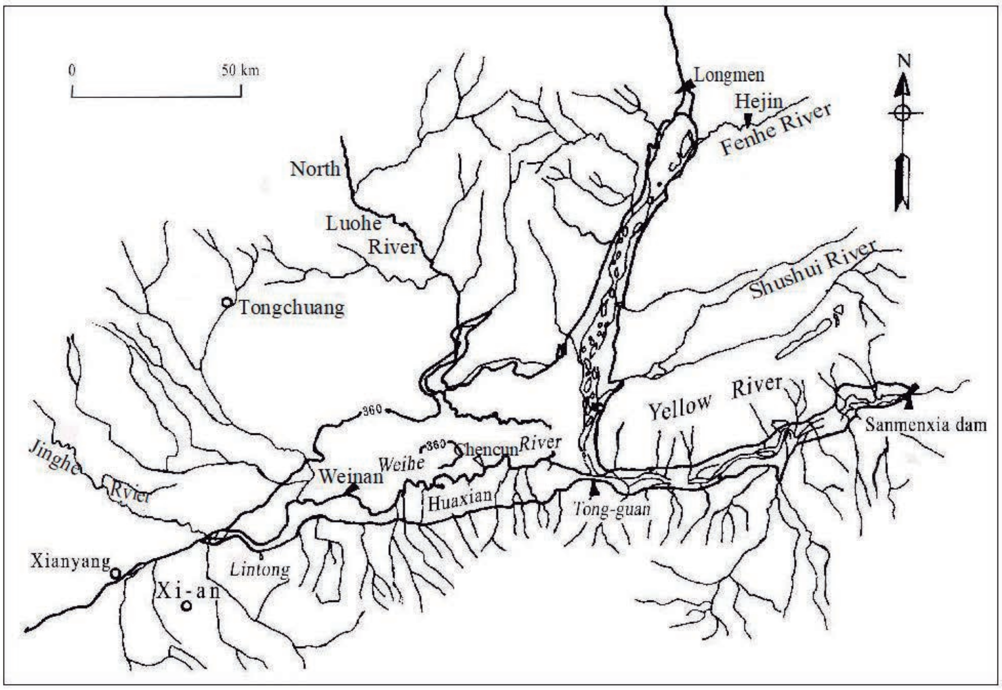


Fig. 52

Sanmenxia Reservoir area (enclosed by 360 m contour line) and the Weihe River, in which the Tongguan Hydrological Station on the Yellow River, and the Huaxian, Weinan, Lintong, and Xianyang stations on the Weihe River are indicated

During the impounding period from September 1960 to March 1962, the "Tongguan's Elevation", which monitors riverbed level variations and is defined as the stage corresponding to a discharge of 1,000 m³/s at Tongguan station, rose 4.5 m (Long and Chien, 1986; Long, 1996), finally reaching 327.2 m in March 1962. Backwater sediment deposition extended over Chishui in the lower Weihe River, about 187 km upstream of the dam, and extended 152 km in the Yellow River. After the mode of reservoir operation was changed, the backwater sediment deposition continued to rapidly extend upstream, raising the bed elevation and flood levels in the Yellow River as far as 260 km upstream of the dam. This threatened the industrial and agricultural bases, and more importantly the capital city of Shanxi Province, Xi'an, in the lower reaches of the Weihe River. In addition, it potentially required the relocation of an additional one million people. There was much pressure to improve the situation because of the dense population and the scarcity of farmland in China. In order to alleviate the serious reservoir sedimentation problem and to achieve a balance between sediment inflow and outflow, a special meeting was held in Xi'an City in December 1964 to find a solution to the sedimentation problem in the reservoir. The late Premier Zhou Enlai presided over the meeting, showing the high pressure for a resolution to this problem. A policy was established to "ensure the safety of Xi'an City in the upstream area as well as that of the lower Yellow River" and a decision was made on the reconstruction of outlet structures to increase the discharge capacity.

The reconstruction work was carried out in two stages. In the first stage, two tunnels at an elevation of 290 m were added on the left bank and four penstocks were reconstructed into outlets for the purpose of sluicing sediment from the reservoir, as shown in Fig. 53. After work on the first stage was in completed in August 1968, the discharge capacity had been increased from 3,080 m³/s to 6,100 m³/s at a water level of 315 m. The reconstructed outlets were put into operation one after another and played a clear role in reducing sediment deposition in the reservoir area below Tongguan. However, the sills of the outlet structures were too high and the capability of the reservoir to release floodwater was inadequate. The ratio of outflow-inflow sediment was 80%. The amount of backwater deposition was still high and the bed elevation at Tongguan continued to rise.

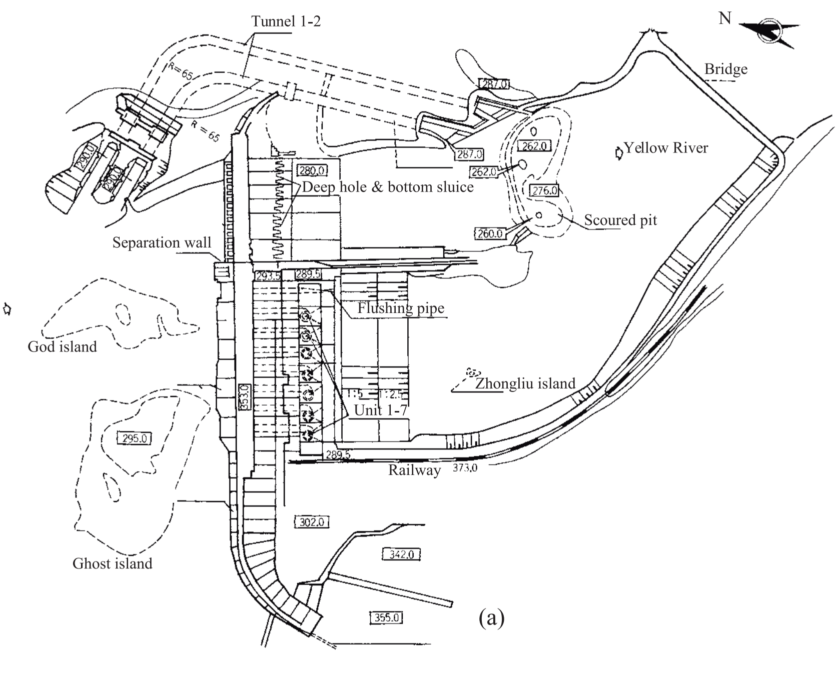


Fig. 53
A

General layout and outlet structures of Sanmenxia Dam: Plan view.

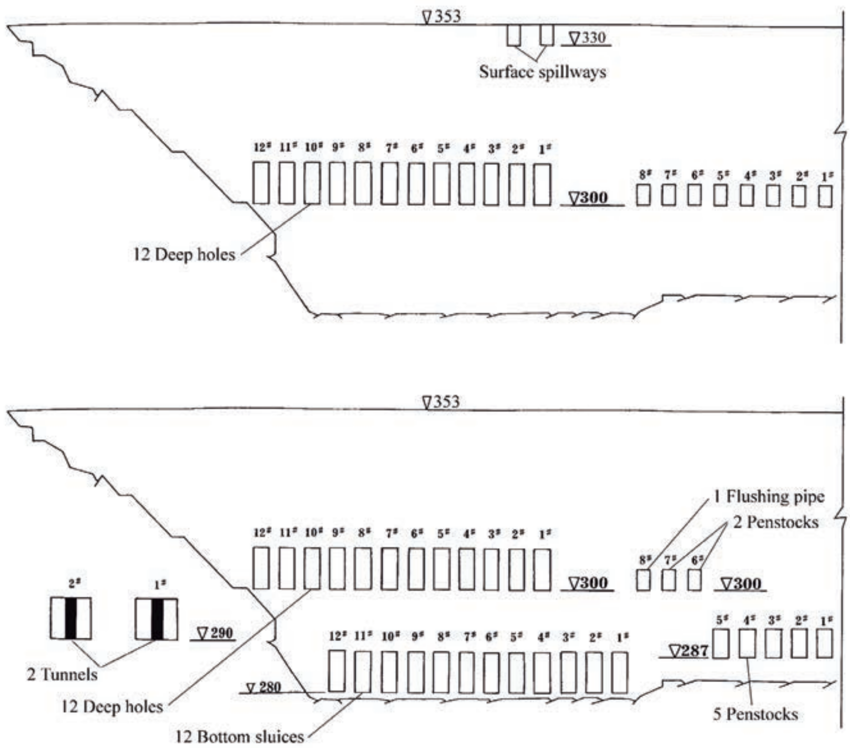


Fig. 53

General layout and outlet structures of Sanmenxia Dam:
(b) Front view of original design; (c) Front view after reconstruction (Wu et al., 2006)

The work on the second stage commenced in December 1970. In this stage, 8 bottom outlets at an elevation of 280 m previously used as diversions were reopened to sluice sediment at the lower elevation and to generate stronger headward erosion. In order to permit power generation at a lowhead during the flood season when reservoir levels were reduced, the intakes of penstocks No. 1 - 5 were lowered from an elevation of 300 m to 287 m, and 5 generation units with a total installed capacity of 250 MW were installed. The first generating unit started to operate at the end of 1973, and the rest were put into operation by the end of 1978. After the second stage of reconstruction, the release capacity of all the outlets increased to 10,000 m^3/s at an elevation of 315 m (Fig. 54). With this capacity, no significant backwater could accumulate immediately behind the dam during medium or minor floods, and the outflow to inflow ratio of sediment reached 105%. In the period from the beginning of the summer in 1970 to the end of the flood season in 1973, about 4.1 million m^3 of sediment in the reach extending from the dam to Tongguan was scoured away, and part of the reservoir capacity was restored. Correspondingly the bed elevation at Tongguan dropped by 2 m.

After these two stages of reconstruction, the dam can discharge sediment-laden water and causes no significant detention of large amounts of flood water. However, due to surface abrasion and cavitation, the bottom sluices were severely damaged, and, therefore, they underwent repairs from 1984 - 1988. As a result the total discharge capacity of bottom sluice openings No. 1 to 8 was reduced by about 471 m^3/s due to compression. To compensate for the reduction resulting from bottom sluice repairs, two more bottom sluices, nos. 9 and 10, were opened in 1990. In an attempt to make the most of the dam by fully utilizing the potential for hydropower generation in the non-flood season, penstocks nos. 6 and 7 were converted back to power generation in 1994 and 1997, respectively. Considering the effectiveness of sediment flushing by discharge at low levels, the last two bottom sluices, nos. 11 and 12, were also opened in 1999 and 2000, respectively. To date, there are 27 outlets in Sanmenxia Dam for discharging flood flows.

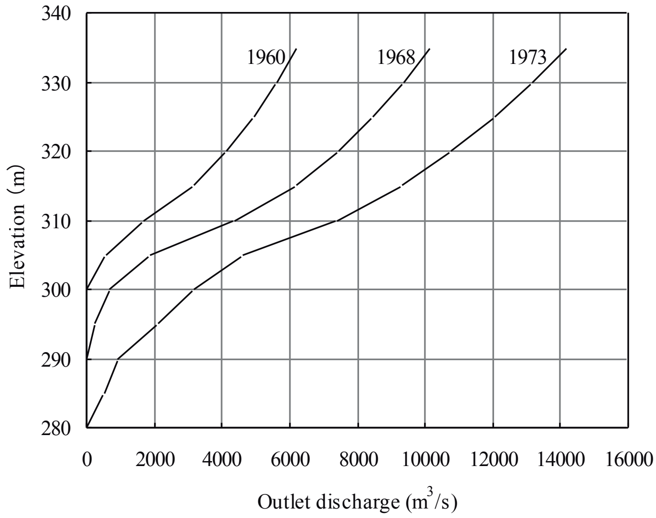


Fig. 54

Discharge capacity of the outlets of Sanmenxia Dam (Wu and Deng, 2005)

4.2 Management of Reservoir Sedimentation

Sedimentation in the reservoir depends on the incoming water and sediment, the discharge capacity, and the operational mode. Reconstruction of the outlet structures has significantly increased the discharge capacity, providing the dam with the necessary facilities for avoiding significant detention of flood water which is important for maintaining the sediment balance across the impounded reach in the reservoir. On top of this, the dam must be properly operated to maintain the reservoir level in order to increase the benefits of the project and to maintain the sediment balance. For this purpose, the Sanmenxia Reservoir has adopted three different modes of operation. The average pool levels corresponding to each operation mode are shown in Fig. 55.

(1) **Storage.** The mode was used during the initial period of reservoir impoundment, from September 1960 to March 1962, when the reservoir was operated at a high storage level throughout the whole year, according to the original project design.

(2) **Flood detention.** The mode was applied from March 1962 to October 1973, during which the reservoir was used for flood detention and sediment sluicing with the water being released without restrictions. The reservoir was operated at a low storage level throughout the year, detaining floods only during flood seasons and sluicing sediment with the largest possible discharges.

(3) **Controlled release.** The mode has been used since November 1974, to store relatively clear water in the non-flood seasons (November-June) and pass muddy water in the flood seasons (July - October). In this period, the reservoir has been operated at a high water level in non-flood seasons, and at a low storage level during flood seasons, and all the outlets were to be opened in times of flood peaks to sluice the sediment as much as possible.

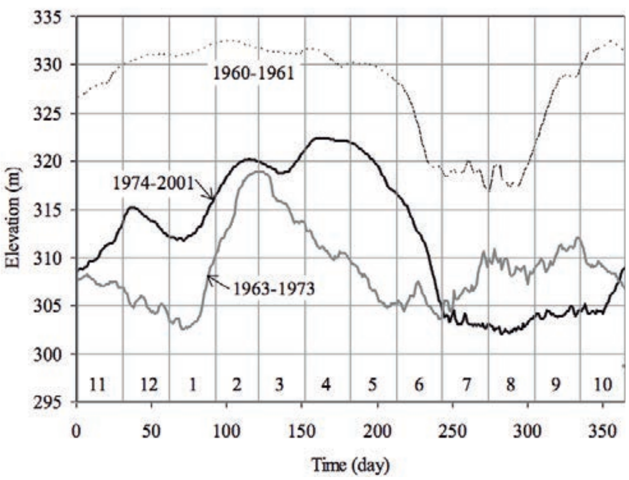


Fig. 55

Variation of average pool level of the Sanmenxia Reservoir in the three periods with different operational mode: storage 1960-1961; flood detention 1963-1973; controlled release 1974-2001

Sedimentation in the reservoir was different corresponding to different operational modes and the outlet discharge capacities. Table 8 presents a summary of the amount of sediment deposited in the reservoir from Tongguan to the dam during the period covered by different operational mode. The mean annual deposition volumes in the reservoir area are 620.38x10^6, -102.51x10^6, and 12.57x10^6 m^3 during the periods of storage, flood detention, and controlled release, respectively.

Because the reservoir was operated at a low storage level and the discharge capacity was enlarged in the period of flood detention, the reservoir sediment changed from accumulating to scouring. In the period of controlled release, deposition occurred during non-flood seasons while scouring occurred in the flood seasons.

Time period	Mode of Operation	Maximum Discharge at 315m (m^3/s)	Average Annual Runoff (10^9 m^3)	Average Annual Sediment (10^9 tonnes)	Mean Annual Deposition (10^6 m^3)		
					Non-flood season (Nov.-June)	Flood season (July-Oct.)	Year
9/1960 - 10/1964	Storage	3,080	46.2	1.34	70.11	550.27	620.38
11/1964 - 10/1973	Flood Detention	6,100	38.2	1.44	-63.61	-38.90	-102.51
11/1973 - 10/2001	Controlled Release	10,000	31.6	0.86	129.02	-116.45	12.57

Table 8

Summary of sedimentation during different operation periods at Sanmenxia Reservoir

Fig. 56a shows the accumulated volume of sediment deposition in different reaches in the reservoir area and Fig. 56b shows the variation of reservoir storage capacity. Within the range of operation levels below 323 m, the capacity of 1.05 billion m^3 is available for controlling medium floods in the flood season whenever necessary. About 3 billion m^3 of the reservoir capacity below 330 m has been kept for use in the event of an extremely large flood. In the normal operation of the reservoir, the floodplain in the reservoir would be inundated only during extremely large floods; the major operational goal is the detention of such floods.

The detained sediment would be eroded in the next several years. However, once the direct backwater effect reaches the confluence area above Tongguan during a flood event and lasts for a certain period of time, sediment deposition on the floodplain would be inevitable and a part of the reservoir capacity would become unavailable for use in the later periods. It is obvious that for preserving a usable capacity in the reservoir, one of the guiding principles of the reservoir's operation is to prevent the direct backwater effect from extending beyond Tongguan as much as possible.

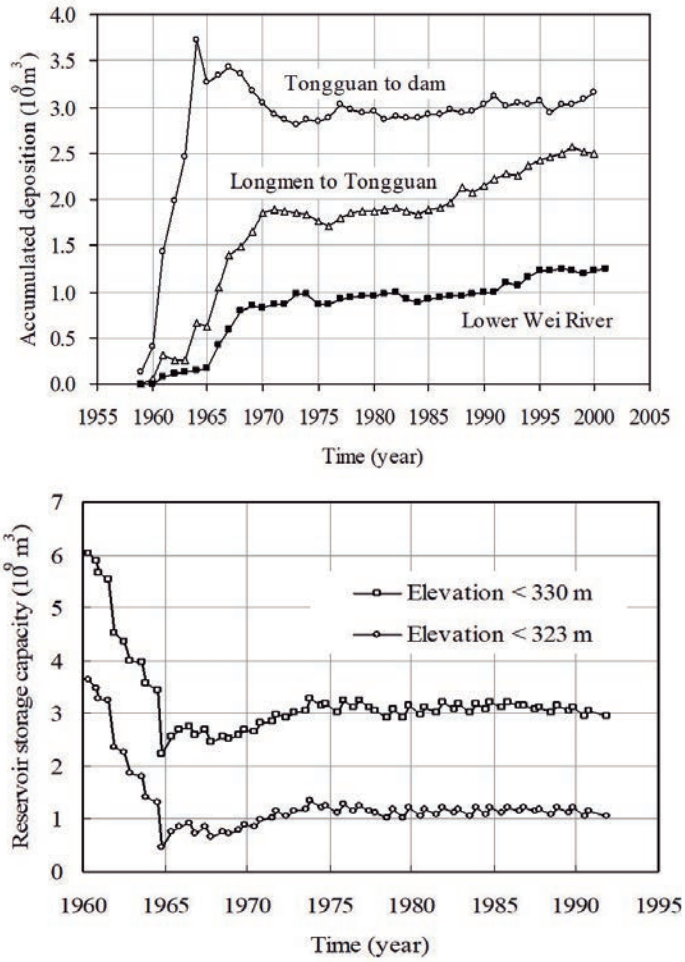


Figure 56

Variations of accumulated deposition and reservoir capacity in Sanmenxia Reservoir: (a) accumulated deposition; (b) reservoir storage capacity

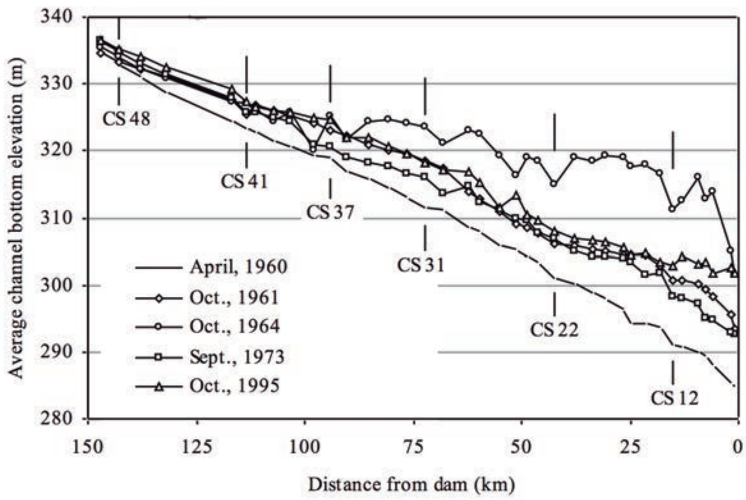
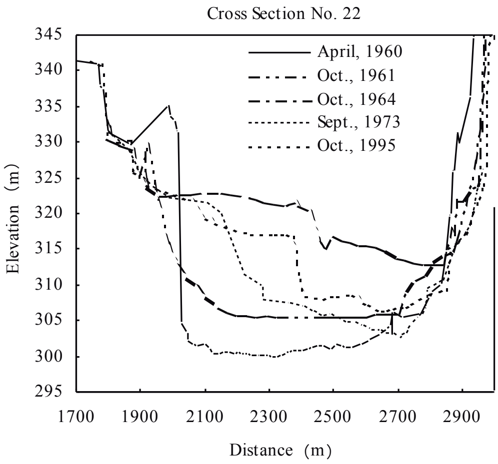


Figure 57
A

Longitudinal profiles in the reservoir varying with the changes of operational conditions for the Sanmenxia Reservoir



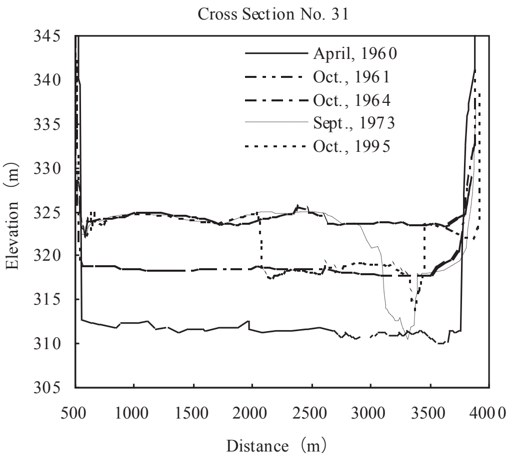


Figure 57
B

Transverse (right) profiles in the reservoir varying with the changes of operational conditions for the Sanmenxia Reservoir

As shown in Fig. 57, the longitudinal and transverse profiles in the reservoir have varied with the changes of operational conditions. The figures show that during the impoundment up to October 1961, i.e., the first year of operation, deposition was in the form of a delta with a topset slope of 0.00015 - 0.00017, nearly half the original river bed slope, and a foreset slope of 0.0006 - 0.0009. The apex of the delta was near section 31, and the cross section was raised evenly in the transverse direction, making no distinction between the main channel and floodplain. During the wet year of 1964, the annual water and sediment inflows were 69.7 billion m^3 and 3.06 billion tonnes, respectively. The reservoir was severely silted because the outlet capacity was too small and the sluice holes were located too high. About 1.95 billion tonnes of oncoming sediment was deposited in the reservoir during the flood season, which was 70% of the total incoming sediment. This was the most serious year of siltation.

Longitudinal deposition was in the form of a cone, and a channel-floodplain configuration was formed. This can be seen from the transverse section, in which the floodplain rose simultaneously with the main channel. In 1973, deposition occurred, with the main channel being eroded because the reservoir was used for flood detention only during the flood season and the outlet discharge was enlarged after reconstruction. The figure reveals that the main channel had been lowered by erosion with basically no changes in the floodplain. The longitudinal bed slope of the main channel was 0.0002 - 0.00023 and that of the floodplain was 0.00012. A high floodplain and deep main channel had been formed; about one billion m^3 of channel storage below Tongguan was recovered.

4.3 Sedimentation of the Weihe River

The Weihe River is 818 km long and has a drainage area of 134,800 km^2 with more than 23 million people dwelling in the river basin. The river basin was known as the “800 li (1 li = 0.5 km) fertile Qin Valley”. The most serious adverse effect of Sanmenxia Dam is the unanticipated sedimentation in the lower Weihe River and consequently the high flood risk to the lower Weihe Basin and Xi’an, an ancient capital of China. Sedimentation in the Weihe River has changed the valley into a wetland with a high ground water table. Local people complained and some officials and scientists suggest decommissioning the dam. The Weihe River has been experiencing a striking change in fluvial processes since the impoundment of Sanmenxia Reservoir. The river channel has been changing from meandering with a sinuosity of 1.65 to straight with a sinuosity of only 1.06 and slightly meandering with a sinuosity about 1.3.

The long-term average annual runoff of the Weihe River is 8.06 billion m^3 and annual sediment load is 386.6 million tonnes, which account for about 1/5 of the annual runoff and 1/3 of the annual sediment load of the Yellow River at Sanmenxia. In the past decades the water and sediment load in the Weihe River and the Yellow River have been reducing due mainly to human activities. Table 9 lists water and sediment load in the rivers in the periods 1960-2001 and 1986-2001. Water and sediment loads in the two periods are less than the average values before 1980, but the ratios of water and sediment load from the Weihe River to the Yellow River water and sediment load remain unchanged. The majority of the sediment load consists of silt with a median diameter of about 0.03 mm. Before the impounding of Sanmenxia Dam, the Weihe River carried 386.6 million tonnes of sediment into the Yellow River annually and the Weihe River itself maintained a relatively stable longitudinal bed profile.

The elevation of Tongguan or Tongguan’s Elevation is defined as a flood stage corresponding to a discharge of 1,000 m^3/s at the Tongguan Hydrological Station on the Yellow River, which acts as the base level of the bed profile of the Weihe River. Before the Sanmenxia Dam Tongguan’s Elevation was about 323.5 m. Since impoundment of the Sanmenxia Reservoir, sediment has been depositing in the reservoir, which causes Tongguan’s Elevation to increase. The energy slope and sediment carrying capacity of the flow in the Weihe River have been reduced. The sediment load could not be transported into the Yellow River and sedimentation occurred in the lower Weihe River. In other words, the increase in Tongguan’s Elevation has changed the lower boundary of the Weihe River, inducing a new cycle of fluvial processes.

River/ Hydrologic station	Distance to the Yellow River mouth L (km)	Annual runoff (1960-2001) (bil. m^3)	Annual sediment load (1960-2001) (mil. tonnes)	Average sediment concentration (1960-2001) (kg/m^3)	Annual runoff (1986-2001) (bil. m^3)	Annual sediment load (1986-2001) (mil. tonnes)
Weihe/ Huaxian	1177	6.79	312	46.04	4.66	248
Yellow/ Tongguan	1092	34.61	1043	30.13	25.16	722
Yellow/ Sanmenxia	996	34.69	1009	29.09	24.62	712
Yellow/ Huayuankou	734	37.44	910	24.20	25.88	610
Yellow/ Aishan	374	33.07	770	25.00	19.16	440
Yellow/ Lijin	100	28.56	700	36.80	13.56	350

Table 9

Water and sediment load of the Yellow and Weihe Rivers

Fig. 58 shows the variations in Tongguan's Elevation over time from 1960 to 2001. There were three ascending periods, denoted by I, II, and III, and two descending periods, denoted by 1 and 2. The abrupt rise and fall in 1960 and 1962 were caused by the impoundment in 1960 and change of the operational mode from storage to flood detention. The time of high elevation (329 m in Fig. 6.45) was short and its influence on the Weihe River sedimentation was temporary, although it caused an obvious flood stage rise in 1961. Therefore, the period of 1960-1962 is not separated from the ascending period I.

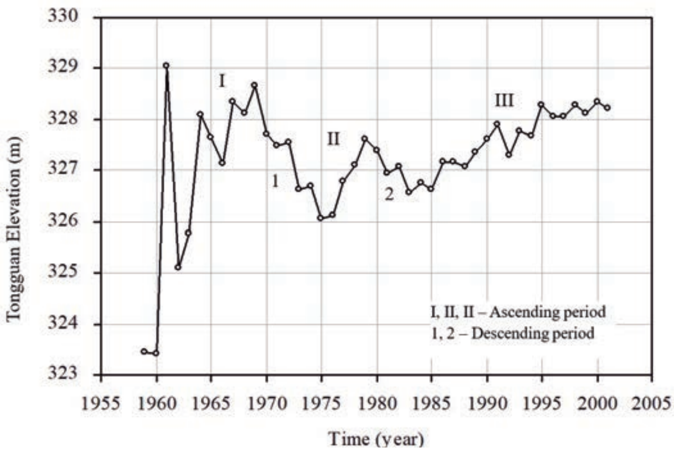


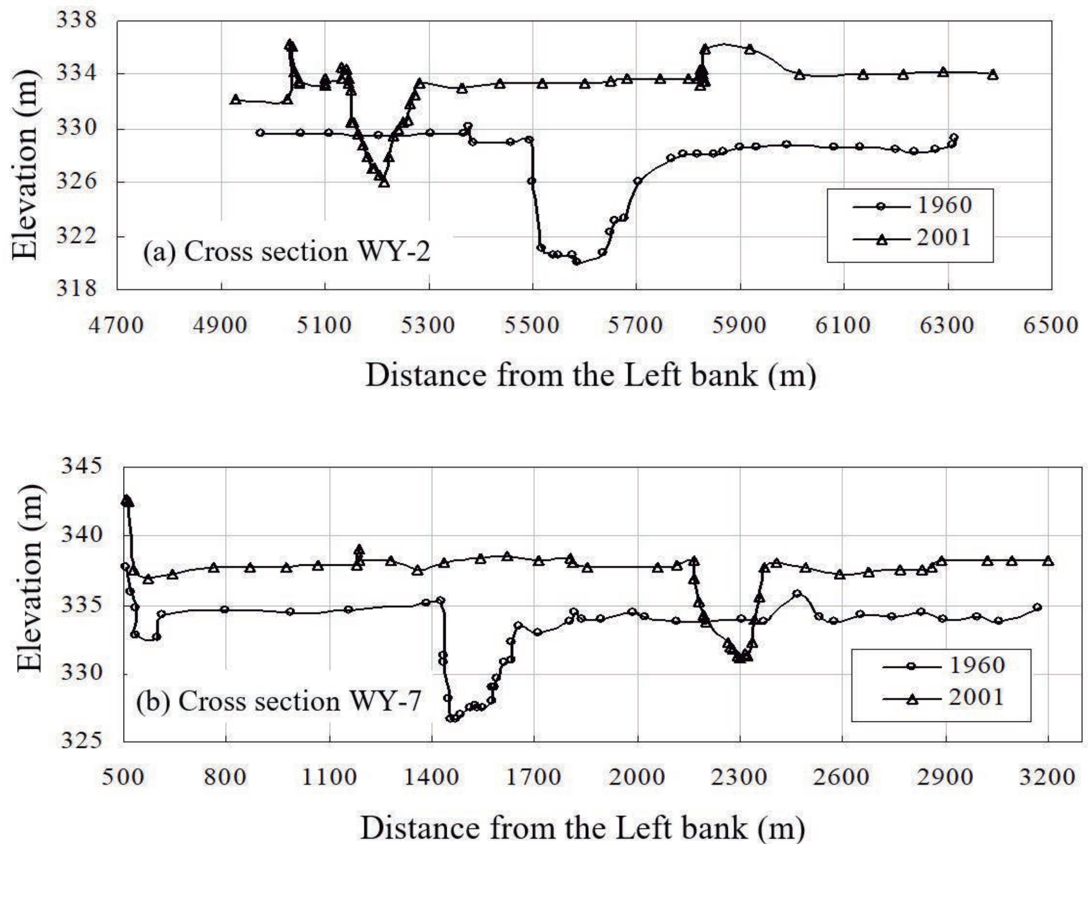
Fig. 58

Variation of Tongguan's Elevation (water-surface elevation at Tongguan for a flow of 1,000 m³/s)

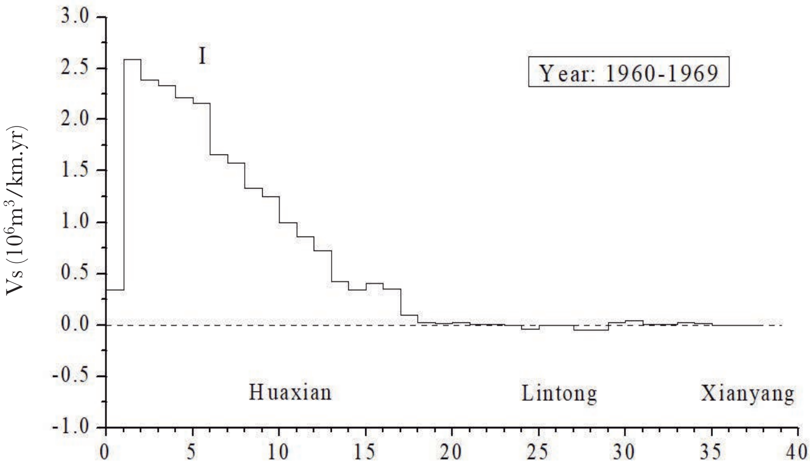
The increase and decrease of Tongguan's Elevation were the result of reservoir sedimentation and erosion, which in turn were caused by variations in the pool level of the reservoir. Generally speaking, sedimentation in the lower Weihe River occurred during the periods when Tongguan's Elevation rose, and erosion occurred during the periods when it fell. The total volume of sediment deposited in the lower Weihe River up to the year 2001 was about 1.3 billion m^3. The sedimentation was distributed mainly in a 100 km long reach from the confluence. The accumulated deposition volume per unit length was high near the confluence, reduced upstream, and to nearly zero near Xi'an. Fig. 59 shows the transect of the profiles of the channel bed and floodplain in the lower Weihe River measured in 1960 and 2001 at the cross-sections WY-2 and WY-7, which are 21 and 59 km from Tongguan, respectively. The floodplain elevation had risen by 3 to 5 m due to sedimentation, and the main channel had shrunk and become more unstable. The flood discharge capacity of the channel was thereby reduced and the flood stage at the same discharge was substantially enhanced (Wang and Li, 2003).

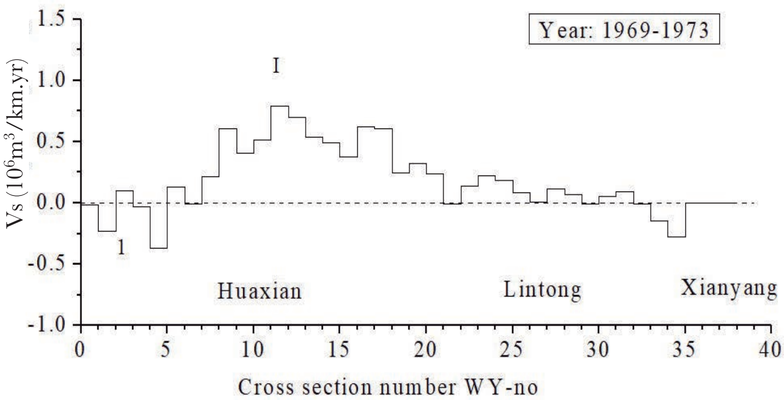
Fig. 59

Aggradation of the lower Weihe River measured at cross-sections WY-2 (21km from Tongguan) and WY-7 (59km from Tongguan) from 1960 to 2001



Simon (1989, 1996) studied channel response in disturbed alluvial channels and found that the changes imposed on a fluvial system tend to be absorbed by the system through several stages of channel adjustment and following exponential decay functions. The response of the Weihe River to the Sanmenxia Dam closure is more complex because the raised Tongguan's Elevation is not stable and the effect has transmitted from the confluence to Xianyang Station (180 km upstream from Tongguan. Erosion and sedimentation caused by the increases and decreases of Tongguan's Elevation propagated upstream in retrogressive waves. Fig. 60 a-c shows the distribution of the deposition rate per unit river length in the periods 1960-1969, 1969-1973, and 1973-1980, respectively, in which the horizontal axis is the number of the measurement cross-sections on the Weihe River; the average distance between the neighboring cross-sections is about 6 km. In the period from 1960 to 1969, Tongguan's Elevation rose abruptly from 323.5 to 328.5 m (see Fig. 58). As a result, sedimentation occurred in the reach around Huaxian at a rate of up to 2.5 million tonnes per km per year (Fig. 60a). The mark "I" indicates that the sedimentation corresponding to the first ascending period of Tongguan's Elevation. In the period from 1969 to 1973, the sedimentation wave moved upstream to the reach between Huaxian and Lintong, but the rate of sedimentation decreased to about 0.75 million tonnes per km per year (Fig. 60b). In the meantime the first erosion wave occurred near the river mouth, which corresponded to the first descending period of Tongguan's Elevation, indicated by the mark "1". In 1973-1980 the first sedimentation wave had moved upstream to Lintong, the first erosion wave had moved to Huaxian, and the peaks had obviously decreased too. During this period, the second sedimentation wave occurred in the reach between the river mouth and Huaxian, indicated by the mark "II". This wave of sedimentation was associated with the second ascending period of Tongguan's Elevation. The ascending and descending of Tongguan's Elevation generated erosion and sedimentation waves, which propagated retrogressively along the Weihe River, at a speed of about 10 km per year.





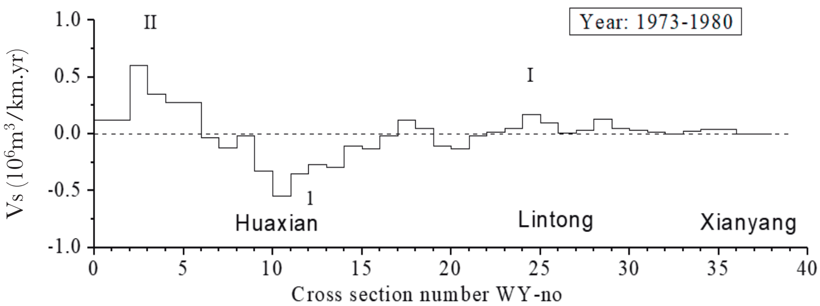


Fig. 60

Erosion (-) and sedimentation (+) per unit length per year showing retrogressive waves in the lower Weihe River, as a result of increases and decreases of Tongguan's Elevation. (The cross-sections are numbered from the river mouth. Huaxian, Lintong, and Xianyang are hydrological stations by the river and are about 50 km, 128 km and 180 km upstream from Tongguan. The distance between neighboring cross-sections is about 6 km.)

Sedimentation has caused flood stage to rise, escalating flood hazards in the lower Weihe River. Fig. 61 shows the stage rise at the Huaxian Hydrological Station for flood discharges of 250 and 3,000-5,000 m^3/s. The stage rise is defined as the difference between the present flood stage and the stage for the same discharge before the impoundment. For a discharge of 250 m^3/s the flow is confined in the main channel and the stage rise reflects only the sedimentation and shrinking of the main channel. For a flood discharge in the range 3,000-5,000 m^3/s the stage rise is due mainly to sedimentation on the floodplain. During the ascending periods of Tongguan's Elevation in the 1960s both the flood stage and low flow stage sharply increased by 4 m and 3 m respectively, because sediment deposition and channel reshaping increased the resistance. During Tongguan's Elevation reduction periods 1970-1975 and 1980-1985, however, erosion occurred in the channel and the flood stage rise was reduced by 1-2 m. In the mid-1990s the enhanced floodplain had been not flooded for several years and invasive and ruderal vegetation had developed, which greatly increased the flow resistance. As a result the flood stage rise increased sharply from 3-4 m to 6 m for floods flowing over the floodplain. At present the low flow stage is 4 m higher than that before the impoundment of Sanmenxia Reservoir and the flood stage is now 6 m higher, which poses a severe flood risk to the lower reaches of the Weihe River.

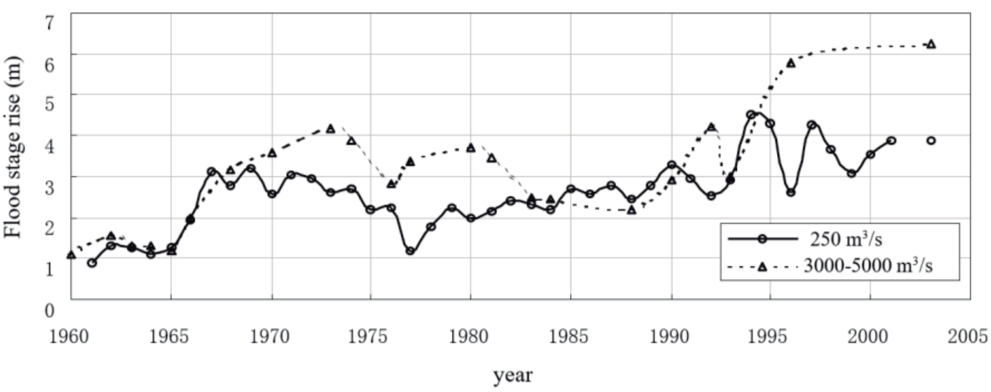


Fig. 61

Flood stage rise due to sedimentation at Huaxian station for discharges of 250 m^3/s and 3,000-5,000 m^3/s

4.4 Equilibrium Sedimentation Model

Two questions to be answered about the fluvial processes in the Weihe River induced by Sanmenxia Dam are: Is there any equilibrium of sedimentation in the Weihe River? And whether the sedimentation has reached the equilibrium? The authors proposed a simple model to answer the questions (Wang et al., 2004). Assume there is an equilibrium sedimentation volume, Ve,, for a given increment of Tongguan's Elevation. If the real sedimentation volume, V, is much less than Ve, the rate of sedimentation in the river is high. The rate of sedimentation is proportional to the difference between the equilibrium and real sedimentation volume:

$$\frac{dV}{dt} = K(V_e - V) \qquad (3)$$

In which K is a constant with dimension of [1/T]. The solution of the equation is:

$$V = e^{-Kt}[\int KV_e e^{Kt} dt + const] \qquad (4)$$

The equilibrium sedimentation volume Ve is proportional to the enhancement of Tongguan's Elevation ΔZ_t,, which is given by $\Delta Zt = Zt - 323.5$, in which Zt is Tongguan's Elevation at time t and 323.5 m is the Tongguan's Elevation before the dam. In simple term, the equilibrium sedimentation volume can be imagined to have a shape like a cone, then it may be assumed

$$Ve = A\Delta Zt/2 \qquad (5)$$

In which A is a representative area of riverbed and floodplain on which sedimentation occurs. Substituting equation (5) into (4) yields,

$$V = \tfrac{1}{2} AKe^{-Kt}[\int_0^t \Delta Z_t e^{Kt} dt - \Delta Z_t] \qquad (6)$$

In which t is the time from 1960, when Sanmenxia Dam begin to fill and the Tongguan's Elevation began to rise. The parameters in the equation are determined from data as $A=5.30 * 10^8 (m^2)$ *and* $K=0.15/yr$. Fig. 70 shows the calculation result of the sedimentation volume (solid curve) in comparison with the real sedimentation volume (pyramids). The dashed curve in the figure is the calculation result with the value of ΔZt remaining unchanged at 5 m ($\Delta Z_t = 328.5 - 323.5 = 5$), which shows that the equilibrium sedimentation volume is around 1.3 billion m^3.

As shown in Fig. 62 the model agrees well with the data of sedimentation, which indicates that for a given Zt, there is indeed an equilibrium sedimentation volume. If the increment in Tongguan's Elevation remains unchanged, the sedimentation of the lower Weihe River may reach equilibrium in about 25 years. At present the sedimentation of the lower Weihe River is approaching to the equilibrium volume and there will be no great volume of accumulated sedimentation if Tongguan's Elevation stops rising. Nevertheless, the equilibrium sedimentation volume is dynamic and increases with rising lower boundary. If Tongguan's Elevation continues to rise the equilibrium sedimentation volume will be greater than 1.3 billion m^3 and longer time is needed to reach the equilibrium (Wang and Li, 2003).

4.5 Changing River Patterns

Sanmenxia Dam not only caused retrogressive sedimentation and erosion in the lower Weihe River, but also changed the river patterns. Before the reservoir began to be used, the lower Weihe River was a meandering river, with a value of sinuosity of about 1.65, where sinuosity is defined as the ratio of the length of the channel to the length of the river valley. The closure of the dam reduced the sinuosity to 1.06 in 1968, as shown in Fig. 63a. Very rapid sedimentation in this period buried the meandering channel. In the meantime, a straight channel developed which was affected mainly by the reservoir operation. In the period from 1970 to 1975 the Weihe River experienced erosion and the channel developed gradually from straight to meandering. The sinuosity had gradually increased to 1.2. In the following period more and more meanders have developed and the lower Weihe River has been developing toward meandering with a sinuosity about 1.3.

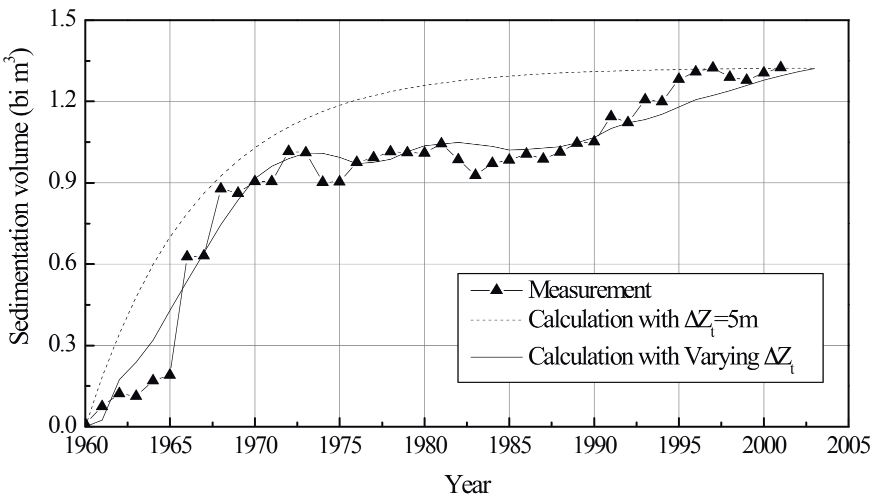


Fig. 62

Calculated cumulative sedimentation volume with Eq. (6) (solid curve) in comparison with the real sedimentation volume (pyramids). The dashed curve in the figure is the calculation result with the value ofΔZt remaining unchanged at 5 m.

Moreover, the river channel has become quite unstable since the closure of the dam. Fig. 63b shows the migration distances of the stream channel measured at cross-sections WY5-35 during the first ascending and descending periods of Tongguan's Elevation. The migration distance was up to 1.8 km at the cross-sections near Huaxian (WY11). The dam had less effect in the reaches further upstream and the migration distance was less than 1 km at cross-sections WY18-35.

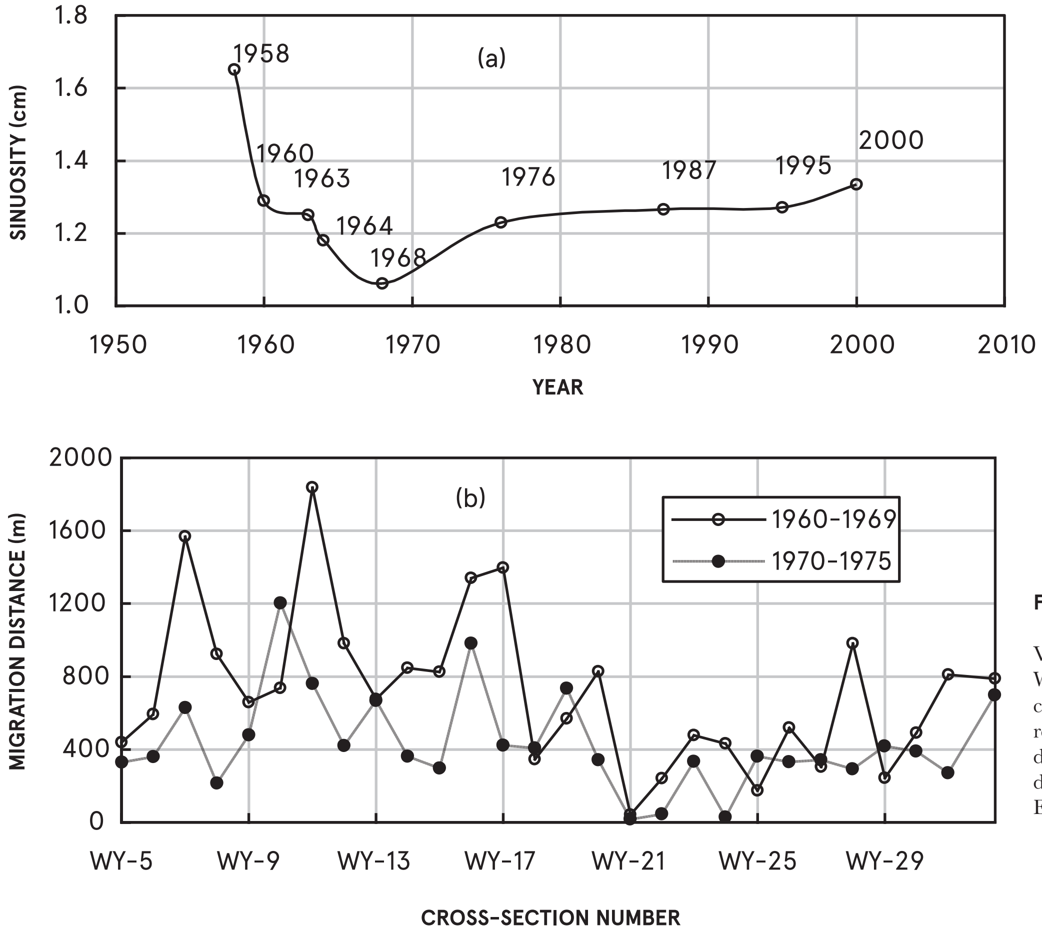


Fig. 63

Variation of sinuosity of the lower Weihe River; (b) Migration distances of the stream channel measured at cross-sections WY5-WY35 during the first ascending and first descending periods of Tongguan's Elevation

4.6 Erosion and Resiltation below Sanmenxia Dam

Sanmenxia Reservoir has trapped about 7.1 billion m³ of sediment in 45 years, including the sedimentation volume in the Weihe River. The sediment load and runoff in the downstream reaches was then greatly reduced, especially in the first 4 years, which induced a complex morphological process downstream of the dam. The water and sediment released from Sanmenxia Dam varied with the operational mode of the reservoir. Consequently, erosion and resiltation occurred in the reaches downstream from the dam. The process of bed erosion and resiltation was very rapid because the sediment load was high and the bed material was erodible. The erosion and resiltation occurred mainly in the reach about 180-600 km downstream from the dam. About 2.31 billion tonnes of sediment had been eroded from the riverbed in the first 4 years since the closure of the dam. In the following 9 years, however, the reservoir changed its operation mode from storage to detaining flood water and sluicing sediment, and the downstream channel was resilted at a high rate, with a total volume of sediment deposition of about 3.95 billion tonnes (Yang et al., 1994). The erosion and resiltation occurred both in the river channel and on the floodplain, with roughly 60% in the channel and 40% on the floodplain.

The lower Yellow River was a wandering river although it has been confined within the strong grand levees, which are on the two sides of the river 5-25 km apart. The migration rate of the channel was quite high. The closure of Sanmenxia Dam did not change this situation. The river migrated at high speed with a maximum value of more than 5 km/yr. Even during the period immediately following the closure of the dam, when clear water was released into the reach, the channel migrated more than 3 km per year.

Generally, dams tend to cause a reduction in migration rates in the downstream reaches. For instance the closure of the Danjiangkou Dam on the braided Hanjiang River caused an initial reduction in bank erosion intensity from about 25 m/yr during 1955–1960 to about 7.0 m/yr during a period of 17 years immediately after the dam closure (Xu, 1997). The lower Yellow River did not respond the dam closure with reduced channel migration because of the specific features of reservoir operation.

Sanmenxia Reservoir has caused the lower Yellow River to change from a wandering-braided channel into a wandering-single thread channel. Fig. 64 shows the channel morphology of the Tiexie-Peiyu reach, which is about 157-189 km downstream of Sanmenxia Dam, before and after the construction of the dam (Yang et al., 1994). There were many sand bars before closure of the dam; the number of bars had decreased 3 years after the dam was used for impoundment. The river had become a single thread channel by 1964.

Meanders have generally developed after Sanmenxia Dam. The reach from the dam to Tiexie (0 to 157 km directly below the dam) is constrained by mountains and no meanders develop within it. A statistics is made for a 400 km long reach, from 150 km to 550 km below the dam, which was an active fluvial reach. Before the impoundment of the dam there were only 16 meanders in the 400-km long reach and more meanders have generally developed after the impoundment. Fig. 65 shows the numbers of meanders with different wavelength in the reach in the 1970s, 1980s, and 1990s.

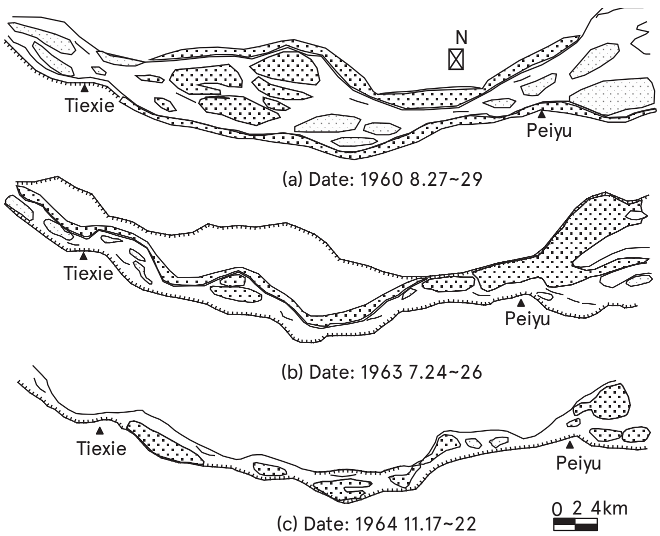


Fig. 64

Channel morphology of the Tiexie-Peiyu reach (157-189 km from Sanmenxia) pre- and post-Sanmenxia Dam

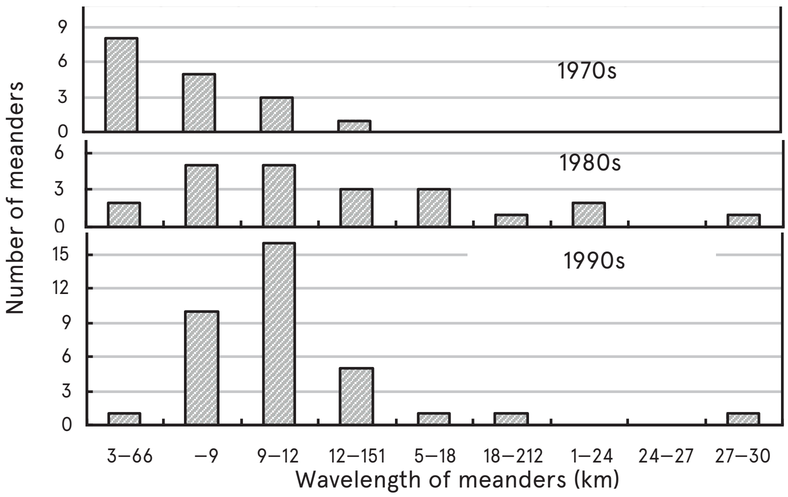


Fig. 65

Numbers of meanders with different wavelengths in a 400 km long reach downstream of Sanmenxia Reservoir in the 1970s, 1980s, and 1990s

The meander wavelength is defined as the distance from one turning point of the channel on one side of the valley to the next turning point on the same side. As shown in Fig. 73, there were 17 small meanders in the reach in the 1970s: Some meanders were separated by straight sections and some other meanders connected with each other forming small meandering sections. Between two small meandering sections was a section with straight channel. After the reservoir operation became stable, more meanders developed and the meandering sections became longer. In the 1980s, however, 22 meanders with a wavelength from 3 to 30 km had developed in the reach. In the 1990s, the number of meanders continued increasing and the meanders became regular; 31 of them have meander wavelength within the range of 6-15 km. The river became more and more meandering. In the process, human constructed spur dykes affected, more or less, the development of meanders.

CONCLUSIONS

Training of the Yellow River has a history of more than 2,000 years. Extremely severe soil erosion and a very high sediment load resulted in levee breaches and great flood disasters, and frequent avulsions in the lower reaches of the river. Two extremely different strategies were proposed and practiced in the past 2000 years: wide river and depositing sediment strategy and narrow river and scouring sediment strategy. Wang Jing (0030-0085), Pan Jixun (1521-1595), Jin Fu (1633-1692) and Wang Huayun (1908-1992) are the most famous and great masters of Yellow River training. Wang Jing and Wang Huayun practiced the wide river and depositing sediment strategy and Pan Jixun and Jin Fu practiced the narrow river and scouring sediment strategy. Both strategies provide evidence of successful flood control and reduction of the frequency of levee breaches. Nevertheless, the narrow river and scouring sediment strategy has only a short term effect on levee breach control and flood mitigation. The wide river and depositing sediment strategy can essentially mitigate flood disasters and reduce levee breaches for a long period of time. The paper also discussed the new challenges and new strategies for the Yellow River training and management. Although the sediment load has been greatly reduced and there have being no levee breaches since 1950, the Yellow River delta has stopped creating land and the coastline is retreating. Moreover, the river experienced cessation of flow in the lower reaches due to water diversions. New strategies have been proposed and put into practice to solve these new problems. The Sanmenxia Project was the first large dam on the Yellow River, which was regarded as a failure in the modern river training because the extremely high rate of sedimentation caused floods in the Weihe River and the capacity for power generation had to be reduced to the minimum. The merit of the project and its role in the river training strategy have been discussed and the future fate of the dam has been reviewed.

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List of credits of the Figures and Pictures

CONTROLLING THE YELLOW RIVER: 2000 Years of Debate on Control Strategies

All Figures with the exemption of the following are the property of the authors.

Fig. 3 (a) Water flowed out of the breach one day after the levee explosion at Huayuankou; (b) About 4 million people left their homeland and fled for safety (YRCC, 2001).

Fig. 5 Closure of the Huayuankou breach finally moved the river back to its north channel

Fig. 6 Sedimentation rate in the lower Yellow River during the 4 historical periods: 1) geological sedimentation; 2) sedimentation due to climate change; 3) sedimentation due to human activities; 4) accelerated sedimentation due to human activities (after Xu 1998)

Fig. 12 Rate of uplift of the Qinghai Tibet plateau (modified from Li et al., 2010)

Fig. 16 Wang Jing (0030-0085) and his “water gate” (overspill weir) for training the Yellow River

Fig.17 Pan Jixun (1521-1595) (left) and his book book “Overview of Yellow River Flood Defence” (upper right), and a sketch of the inner levees, out levees and latice levees (lower right)

Fig. 18 Jin Fu (left 1633-1692) and Chen Huang (right) were the third great master of Yellow River training in the 2000 years history

Fig. 19 Wang Huayun-the director of Yellow River commission and the fourth great master of Yellow River training

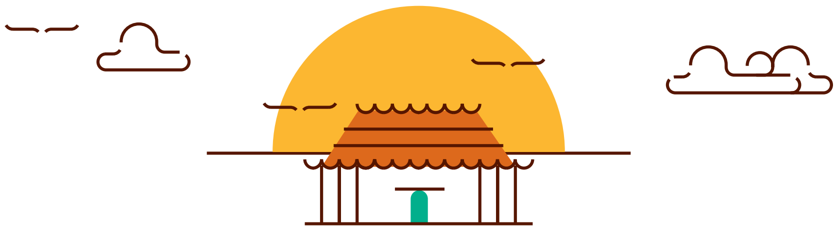
Fig. 21 In 2014 the Sizhou town was unearthed after 333 years sleep under the Yellow River sediment, which is called the East Pompaii

Fig. 37 Stage-Discharge relationships of 1996, 1992, 1982 and 1958 floods (after Zhao and Liu, 1997)

Fig. 38 Distribution of channelization degree (ratio of the length of the spur dykes to the length of the channel) along the lower Yellow River (Cheng et al., 2007)

Fig. 41 Average runoff and sediment load of the Yellow River in the 1950s (after Qian and Zhou, 1964)

Fig. 50 Satellite image of the modern Yellow River delta and the Qing-shui-gou-Chahe channel in 2000 (Satellite image of NASA)



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