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INTERACTIONS BETWEEN FLUVIAL SYSTEMS AND LARGE SCALE HYDRO-PROJECTS

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Abstract: A large-scale hydro-project is defined as one or a chain of engineering structures, whose operation may obviously change the hydrological or hydraulic conditions of the river on which it is constructed. This paper studies the fluvial processes in the upstream reaches and tributaries and downstream reaches affected by dams, and the fluvial impacts of channelization and water diversions. Damming of rivers not only causes sedimentation in the reservoir but also creates additional backwater and deposition even further upstream. The Three Gorges Dam on the Yangtze River may change the upstream reaches from a braided channel into a single thread channel, and Sanmenxia Dam has changed the Weihe River from meandering to wandering-meandering. Downstream reaches of dams experience the following fluvial processes: (1) channel incision; (2) variation in channel width; (3) reduction in bank erosion and channel migration; and (4) changes in river patterns. The study reveals that dams on rivers with low sediment concentration reduce the channel migration remarkably, but dams on rivers with hyperconcentrated sediment have little effect on channel migration. Dams change downstream river patterns from braided to wandering, or from wandering-braided to wandering-meandering. Defining the channelization degree as the ratio of the length of the hardened banks to the length of the channel, we found that if the degree is within the range of 0.8-1.3, the highest probability of bank failure occurs, because the natural fluvial process tends to break the constraint of the channelization. Water diversion has becomes an important stress causing fluvial processes. The lower Yellow River is a perched river with its riverbed 10 m higher than the surrounding land, which poses a flooding risk but also provides flowing potential for water diversion to farmland and cities and towns. At present, more than 10 billion m^3 of water is diverted from the Yellow River, which has caused shrinkage of the channel and readjustment of the bed profiles. If the quantity of water diversions along the course is more than the inflow from tributaries, the riverbed profiles will develop toward a concave profile in the upper reach and a convex profile in the lower reach.

Keywords: Fluvial process, Reservoir, River pattern, Channelization, Water diversion

1 IMPACT OF LARGE DAMS ON UPSTREAM REACHES

According to the International Commission on Large Dams, the world's rivers are now obstructed by more than 40,000 large dams. From 1949 to 1990 the number of large dams in China increased from only eight to more than 19,000. These large dams have provided extensive benefits during the past century, and have fueled the economy by providing cheap power, irrigation and municipal water supplies. Nevertheless, the dams have caused unforeseen impacts on the fluvial processes as well, which were not fully comprehended during the project planning process. This is not surprising since the fluvial processes at the basin scale are immensely complex.

For the upstream reaches the primary consequence of impoundment of rivers is sedimentation. However, sedimentation issues are not confined solely to the reservoir. The backwater reach of the reservoir can extend hundreds of kilometers upstream, as in the case of the Three Gorges Reservoir on the Yangtze River. The current velocity and sediment carrying capacity of the flow are reduced by reduction in energy slope; thence sedimentation occurs in the backwater region. The aggradation reach in turn raises the local water surface elevations, creating additional backwater and deposition even further upstream. This feedback mechanism allows the depositional environment to propagate much further upstream than the initial hydraulic backwater curve might suggest (Goodwin *et al.*, 2001).

In many cases, sedimentation in the reaches upstream of the reservoir have caused an unforeseen rise in the flood stage. Analyses of the Sardar Sarovar Dam in UK have indicated that the upstream river reach will experience aggradation of the riverbed to a depth of 3.5m. This corresponds to an additional 20 villages being inundated by a 100year flood, compared with the situation immediately following the filling of the reservoir (Bettess, 1993). A more notorious example is the flood disasters in the lower Weihe River caused by the Sanmenxia dam on the Yellow River. Aggradation has occurred in the lower Weihe River due to the impoundment of Sanmenxia Reservoir, which has developed in a form of retrogressive sedimentation (Wang *et al.*, 2004).

The Yellow River, with a drainage area of 795,000 km^2 and a length of 5,464 km, is the second longest river in China, as shown in Fig.1. The long-term annual sediment load at Sanmenxia station is 1.6 billion tons, ranking first of all the world's rivers. The annual load/water ratio is 35 kg·m^3. The majority of the sediment load consists of silt with a median diameter of about 0.03 mm. Sanmenxia Dam is located in the lower part of the middle reach of the river (Fig.1). The construction of the dam was initiated in 1957 and water impoundment commenced in September 1960. The crest elevation of the dam is 353 m and the original capacity of the reservoir was 9.705 billion m^3 with a pool level of 335 m. 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. The lower Weihe River is affected by the reservoir as well.

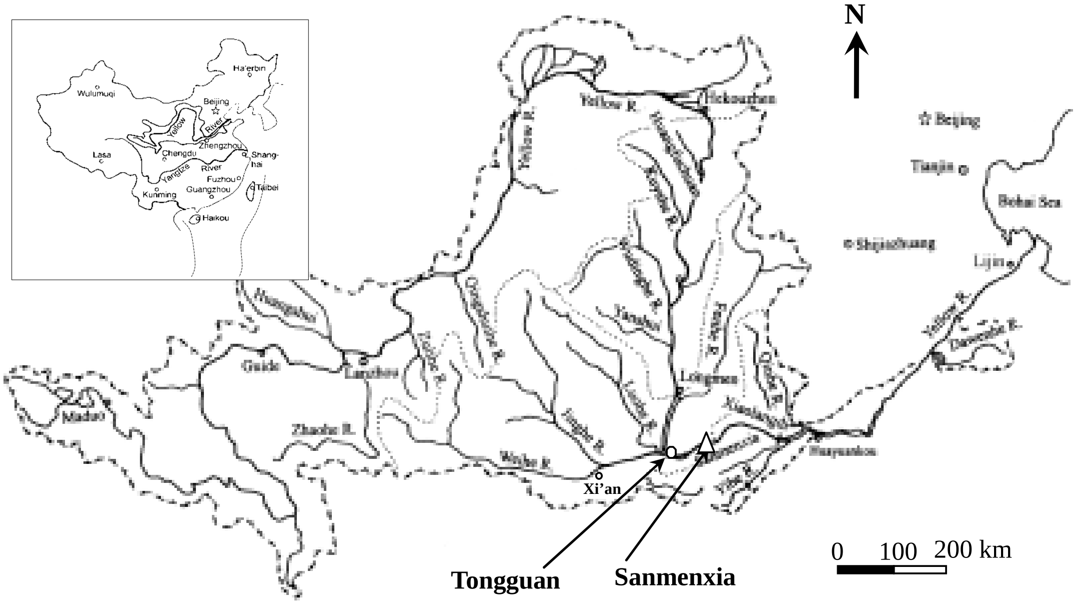


Fig. 1 Map of the Yellow and Weihe River Basins Showing the Locations of Sanmenxia Dam, Tongguan and the City of Xi'an

Due to an alarming rate of sedimentation and the unacceptable negative impact of rapid upstream extension of backwater sediment deposition, the reservoir operation has been substantially changed to achieve a balance between sediment inflow and outflow in the following three reservoir operation modes (Wu and Wang, 2004): (1) Storage. From Sept. 1960 to March 1962, the reservoir was operated at a high storage level the whole year around; (2) Detaining flood water and sluicing sediment. From March 1962 to Oct. 1973, 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) Storing clear water and releasing turbid water. From Nov. 1973 to present, the reservoir has been operated to store relatively clear water in non-flood seasons (Nov.-June) and release high sediment concentrations in flood seasons (July-Oct.). The longitudinal profile in the reservoir has varied with the changes of operation modes as shown in Fig. 2. During the first four years the reservoir was severely silted. In 1964, about 1.95 billion tons of oncoming sediment was deposited in the reservoir, which was 70% of the oncoming sediment. Changing the operation modes has reduced the sedimentation volume, and the bed profiles have been relatively stable since the 1970s.

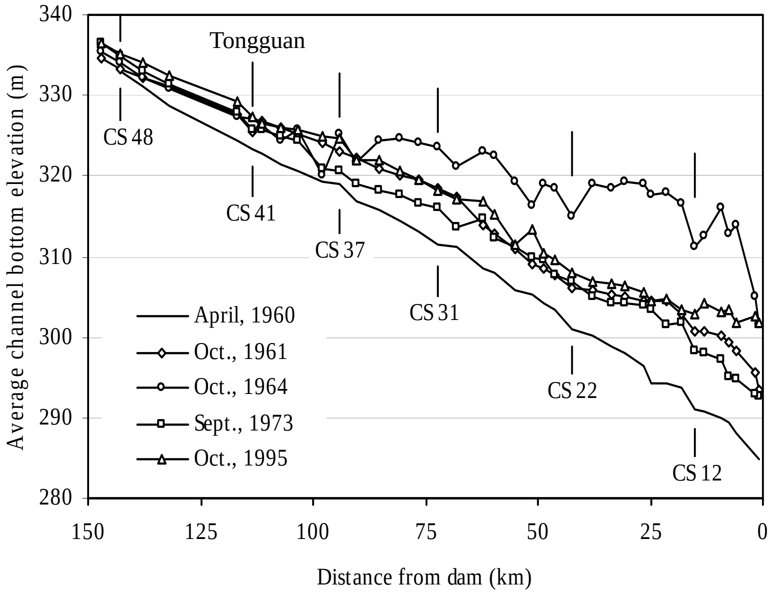
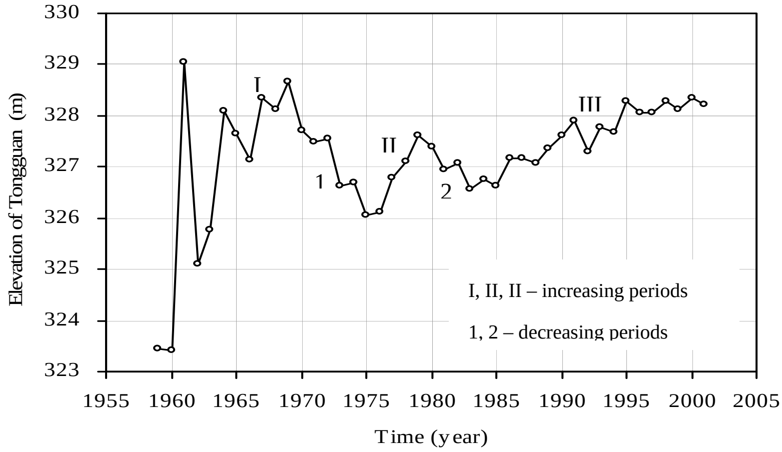


Fig. 2 Longitudinal Profiles at the Sanmenxia Reservoir During Different Periods of Operation (in which CS12-CS48 are the Measurement Cross Sections on the Reservoir Reach of the Yellow River)

The most serious adverse effect of the reservoir is the sedimentation in the lower Weihe River and consequently the high flooding risk to the lower Weihe basin and Xi'an, an ancient capital of China. Tongguan's Elevation is defined as a flood stage with a discharge of 1000 $m^3 \cdot s^{-1}$ at Tongguan, which acts as the base level of the bed profile of the Weihe River. Fig. 3 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 ascent and descent of Tongguan's elevation were results of reservoir sedimentation and erosion, which in turn were caused by variations in the pool level and in the flow's sediment-carrying capacity.

Generally speaking, sedimentation in the lower Weihe River occured during the periods when Tongguan's elevation rose, and erosion occurred during the periods when it fell. The total volume of sediment deposited up to the year 2001 was about 1.3 billion m^3 in the lower Weihe River. The sedimentation was distributed mainly in a 100km -long reach from the confluence (Tongguan). The accumulated deposition volume per unit length was high near the confluence, and became lower upstream, and decreased to nearly zero near Xi'an. Fig. 4 shows the transverse bed profiles in the lower Weihe River measured at the cross-sections WY2 and WY7, which are 21 km and 59 km from Tongguan, respectively. The floodplain elevation had risen by 3 m to 5 m due to sedimentation, and the main channel had shrunken and become more unstable. The flood discharge capacity of the channel was thence reduced and the flood stage at the same discharge was substantially increased.



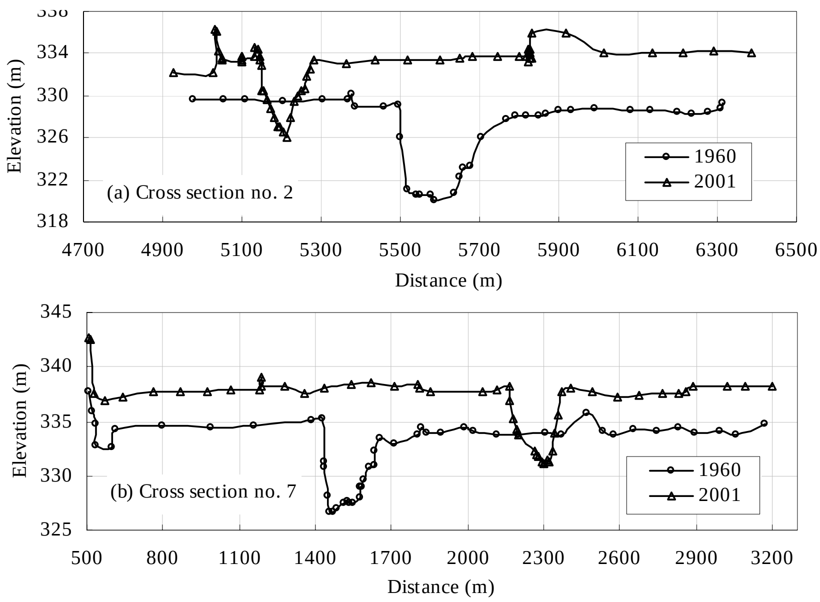
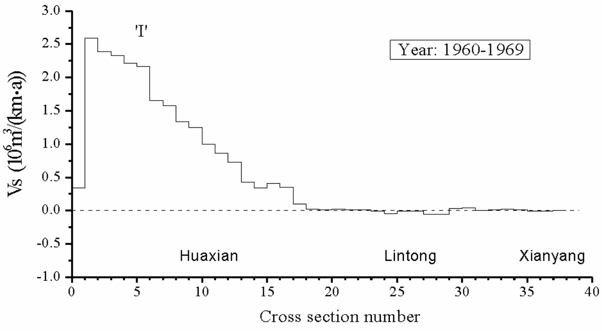


Fig. 3 Variation of Tongguan's elevation

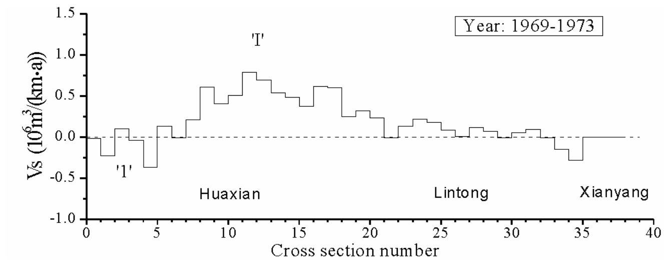
Fig. 4 Aggradation of the lower Weihe River measured at cross-sections WY2 (21km from Tongguan) and WY7 (59km from Tongguan) from 1960 to 2001

Erosion and sedimentation caused by the ascent and descent of Tongguan's elevation propagated upstream in retrogressive waves. Figs. 5(a), 5(b) and 5(c) show the distribution of the deposition rate per unit river length in the periods 1960-1969, 1969-1973 and 1973-1980, 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 m to 328.5 m (see Fig. 3). As a result, sedimentation occurred in the reach around Huaxian station at a rate of up to 2.5 million tons per km per year (Fig. 5(a)). The mark 'I' indicates that the sedimentation in this period corresponded to the first period in which Tongguan's elevation rose. In the period from 1969 to 1973, the sedimentation wave moved upward to the reach between Huaxian and Lintong, but the rate of sedimentation decreased to about 0.75 million tons per km per year (Fig. 5(b)). In the meantime the first erosion wave occurred near the river mouth, which corresponded to the first period in which Tongguan's elevation fell, indicated by the mark '1'.

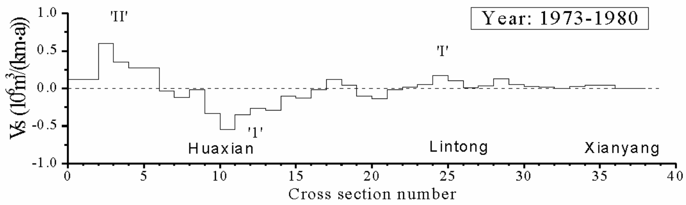
In 1973-1980 the first sedimentation wave had moved upstream to Lintong, the first erosion wave had moved to Huaxian station, and the peaks had obviously decreased too. During this period, the second sedimentation wave occurred in the reach between the river mouth and Huaxian station, indicated by the mark ‘II’. This wave of sedimentation was associated with the second period of rising elevation at Tongguan. The increase and decrease in Tongguan elevation generated erosion and sedimentation waves, which could propagate retrogressively toward the upstream in the lower Weihe River, at a speed of about 10 km per year.



(a)



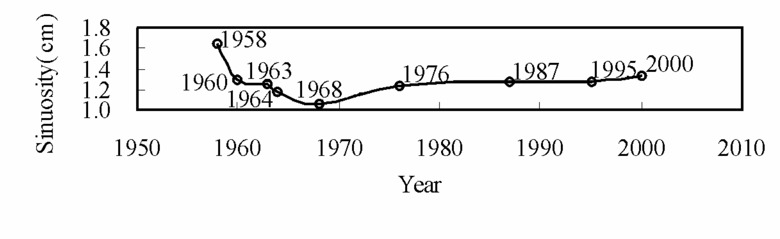
(b)



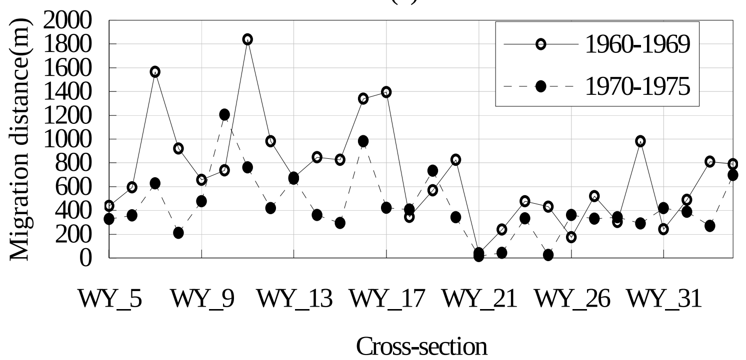
(c)

Fig. 5 Erosion (-) and sedimentation (+) per unit length per year showing retrogressive waves in the lower Weihe River, as a result of ascent and descent of the Tongguan elevation. (The cross sections are numbered from the river mouth. Huaxian, Lintong and Xianyang are cities by the river. The distance between neighboring cross sections is about 6 km.)

The 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 typical meandering river, with a value of sinuosity of about 1.65, in which 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. 6(a). All meanders were buried under the deposit and the channel became straight. Following the development of the fluvial process, the effect of the abrupt change in the lower boundary of the river has been diminished, more and more meanders have developed and the sinuosity has gradually increased to 1.3. The lower Weihe River is not a typical meandering river any more. Moreover, the river channel has been quite unstable since the closure of the dam. Fig. 6(b) shows the migration distances of the stream channel measured at cross sections WY5-WY35 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. The dam had less effect in the reaches further upstream and the migration distance was less than 1 km at the cross sections WY18-WY35.



(a)



(b)

Fig. 6 (a) Variation of sinuosity of the lower Weihe River (The closure of Sanmenxia dam in 1960 caused an abrupt reduction in the sinuosity). (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.

Another example of river pattern changes due to reservoir sedimentation is the Three Gorges Project (TGP) on the Yangtze River, which is the third longest and third largest river in the world. To study the sedimentation problem of the Three Gorges Project, a scale model of a 33 km-long section of the Yangtze River around Chongqing has been made and experiments have been performed. The city of Chongqing is in the fluctuating backwater region of the Three Gorges Reservoir. The Jialing River flows into the Yangtze River at Chongqing. Jiulongpo Harbor, which is about 610km from the dam, is the most important freight ship terminal in southwest China (Fig.7).

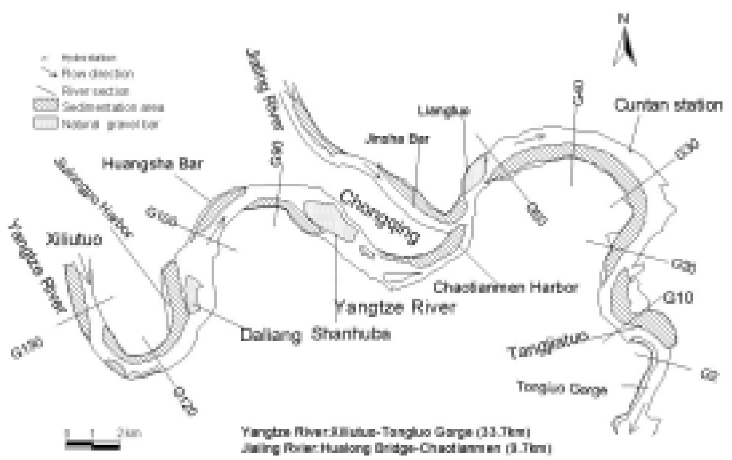


Fig. 7 Sedimentation in the Chongqing reach after 80 Years of Operation of the Three Gorges Reservoir (Physical Model Experimental results). The Shadowed areas Indicate the Places where Cumulative Sedimentation Would occur. G2-G130 Represents the Measurement Cross sections (Wang *et al*., 1990)

The channel near Jiulongpo harbor is stable and braided. There are two channels separated by the Daliang Bar. Water flows in the west channel during the low flow season and the main stream flow shifts to the east channel during the flood season, but the west channel maintains a year-round depth of over 3 m, which is necessary for the harbor. The experiments showed that impoundment of the reservoir will cause sediment deposition in the west channel and at the apron of the harbors, as shown in Fig.7. The shadowed areas in the figure indicate the places where cumulative sedimentation would occur. After 80 years of impoundment of the TGP, however, cumulative sedimentation would occur in the west channel, which could result in blockage of the channel eventually. The river pattern would changes from a braided channel to a single thread channel. Similar to the case of the Weihe River, the sinuosity of the channel would slightly decrease as well. The harbor facilities on the west bank would become nonfunctional. The problem could be solved by building spur dykes and groins to regulate the flow. The dykes and groins would narrow the channel and concentrate the flow, so that flow velocity in the west channel could be increased, which would prevent sediment from being deposited (Wang *et al.*, 1990).

2 FLUVIAL PROCESSES BELOW DAMS

Large dams may reduce the magnitude and frequency of high flows and elevate low flows for the purposes of flood control, power generation and water supply. But the most important effect on the lower reaches of dams is reduction of the sediment load, which results in sediment-starvation of the flow and consequently in changes in fluvial processes (Chien, 1985). The main types of channel adjustment in the downstream reaches are: (a) channel incision, which is commonly on the order of several meters; (b) variation in channel width; (c) rate reduction in bank erosion and channel migration; (d) changes in river patterns.

2.1 Channel Incision and Variation in Channel Width

Channel incision induced by damming has taken place in many of the world's rivers (Leopold, 1973; Knighton and Nanson, 1993; Williams and Wolman, 1984; Collier *et al.*, 1996; Petts, 1979; Gregory and Park, 1974; Kondolf, 1997). In Italy, bed incision of 3m - 4 m is very common, and in some cases incision of 10 m, or even more, has been observed. For example, the Arno River (Tuscany) has been subject to widespread channel incision, with the maximum total bed-level being lowered by an average of more than 6 m in the Lower Valdarno reach (Motiee and Darakhani, 2003).

Numerical models show that impoundment at the Three Gorges Reservoir on the Yangtze River causes bed erosion up to 10 m in the downstream reaches. The riverbed scours in the first 10-20 years and resilts after this period when the amount of sediment trapped by the reservoir lessened (Sedimentation Panel of TGP, 2002).

The process of bed erosion and resiltation in the downstream reaches of Sanmenxia Dam on the Yellow River is very fast because the sediment load is very high and the bed material is erodible. Fig. 8 shows the volume of sediment erosion and deposition per length in the lower reaches of the dam (Yang *et al.*, 1994). The erosion and resiltation occurred mainly in the reach about 180km-600 km downstream of the dam. About 2.31 billion tons of sediment had been eroded from the riverbed in the first 4 years (1960-1964) since the closure of the dam. In the following 9 years (1964-1973), however, the reservoir changed its operation mode from storage to detaining flood water and sluicing sediment, and the downstream channel had been resilted at a high rate, with a total volume of sediment deposition of about 3.95 billion tons. The erosion and resiltation occurred both in the stream channel and on the floodplain, with roughly 60% in the channel and 40% on the flood plain.

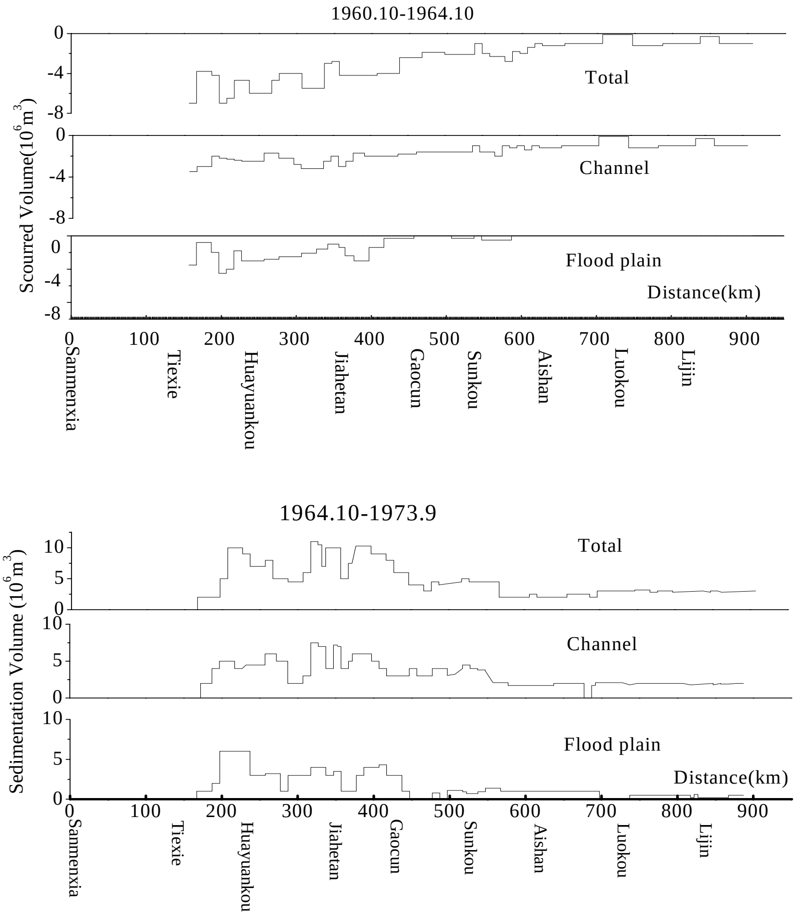


Fig. 8 Volume of Sediment Erosion (from 1960 to 1964) and Resiltation (from 1964 to 1973) per Length in the Lower Reaches Downstream of the Sanmenxia dam. The Erosion and Resiltation Occurred Mainly in the Reach About 180km-600 km Downstream of the Dam (Yang *et al.*, 1994)

The variation in channel width in response to dam closure is complex, with trends of widening, narrowing and no change reported for various rivers (Williams & Wolman 1984). For instance, the Three Gorges Project on the Yangtze River caused channel widening by more than 10 % in some places and cause channel narrowing in other places (You *et al.*, 1987). The Fresno Dam on the Milk River in northern Montana had little effect on mean discharge, but caused a 60% decrease in the magnitude of the two-year return flood and similar decreases in larger, less frequent events. The downstream channel width decreased about 25% in response to the closure of the dam, and the bed was degraded about 1.5 m (Shields, *et al.*, 2000).

2.2 Migration of Channels

The effects of dams on large rivers vary with the pre-existing river patterns: dams tend to cause braided rivers to narrow, and meandering rivers experience little change in width, but a reduction in migration rates. The closure of Ft. Peck Dam has resulted in a four-fold reduction of the mean rate of channel activity of the Missouri River 200 km downstream of the dam. This reduction is linked to the impact of reservoir operations on the frequency and duration of high flows. The mean rate of pre-dam bank erosion and channel migration was $6.6 m\cdot yr^{-1}$, while the mean post-dam rate for the same reach was $1.8\ m\cdot yr^{-1}$ (Shields *et al.*, 2000). The Milk River downstream from the Fresno Dam in northern Montana experienced a reduction in migration rate from $1.7\ m\cdot yr^{-1}$ to $0.46\ m\cdot yr^{-1}$ following dam closure. The Garrison Dam reduced the migration rates of the Missouri River in central North Dakota. Before dam closure, the mean erosion rate for a 166 km reach was 93 ha·yr^{-1}, but only 21 ha·yr^{-1} afterwards. Moreover, much of the reach below Garrison Dam has experienced net channel widening since dam closure, and the deposition rate of alluvial material to form islands and bars was reduced from 165 ha·yr^{-1} before the dam was close to 1.3 ha·yr^{-1} (Williams & Wolman 1984).

In China the closure of the Danjiangkou Dam has affected the braided Hanjiang River by causing an initial reduction in bank erosion intensity from about 25 m·yr^{-1} during 1955-1960 to about 7.0 m·yr^{-1}during the 17 year period immediately after dam closure. However, as the riverbed became coarser, bank erosion rates rebounded to levels typical of pre-dam conditions (22 m·yr^{-1}-25 m·yr^{-1}). Evidently, the coarser bed forced the banks to absorb more of the energy of the flow; during the period of reduced bank erosion, the river bed was degraded, but after bed coarsening, degradation ceased and widening ensued (Xu, 1997).

Table 1 Distances of Channel Migration in the Lower Yellow River in Different Periods (Yang *et al*., 1994)

Period	Tiexie-Gaocun(157 km -440 km downstream from Sanmenxia Dam)		Gaocun-Taochengpu (440km-595 km from Sanmenxia Dam)	
	Average migration distance (m)	Maximum distance (m)	Average distance (m)	Maximum distance (m)
Pre-Sanmenxia Dam (1950-1959)	2,972	6,200	1,178	2,050
Storage operation (1960-1964)	2,914	5,950	747	1,450
Detaining flood water and sluicing sediment (1965-1972)	3,360	5,395	1,006	2,240
Storing clear water and releasing turbid water (1973-1983)	2,870	4,750	734	2,500

The lower Yellow River was a wandering river although it has been confined within the strong grand levees, which are located 5km-25 km apart from each other. The migration rate of the channel in the Henan reaches was quite high. The closure of the Sanmenxia Dam did not change this situation. Table 1 shows the distances of channel migration in different periods (Yang *et al*., 1994). The distances of channel migration during the post-Sanmenxia Dam periods were about the same as for the pre-Sanmenxia Dam period. Fig. 9 shows the wandering of the lower Yellow River channel within the grand levees during the storage operation (1960-1964) and late operation periods (1980-1984) of the Sanmenxia Dam. The river migrated at high speed with a maximum value of more than 5 km·yr^{-1}. 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. It seems that the impact of dams on fluvial processes is less for river with hyperconcentration of sediment than for rivers with normal sediment concentrations. The mechanism behind this is still to be studied.

2.3 Changes in River Pattern

Many studies have investigated changes in river patterns, showing rivers with braided-anastomosed or braided-meandering transitional characteristics (Neill, 1973; Church, 1983; Ferguson and Werritty, 1983; Knighton and Nanson, 1993). The Danjiangkou Reservoir has changed the Hanjiang River from a braided river to a wandering-braided river (Xu, 1996). The wandering braided pattern of the middle Hanjiang River is caused by strong erosion of the riverbank initiated by water impoundment at the Danjiangkou Reservoir. Large quantities of sediment are supplied to the channel by bank erosion and deposited at many mid-channel bars has during floods. Thence a wandering braided channel pattern with many unstable mid-channel bars developed. It is striking that while the river was developing from a braided river into a wandering-braided river the sediment quantity measured at the upstream station was approximately equal to that measured at the downstream station (Xu, 1996). This implies that a huge amount of sediment on the bed and banks was removed, while a small amount of sediment was transported through the channel.

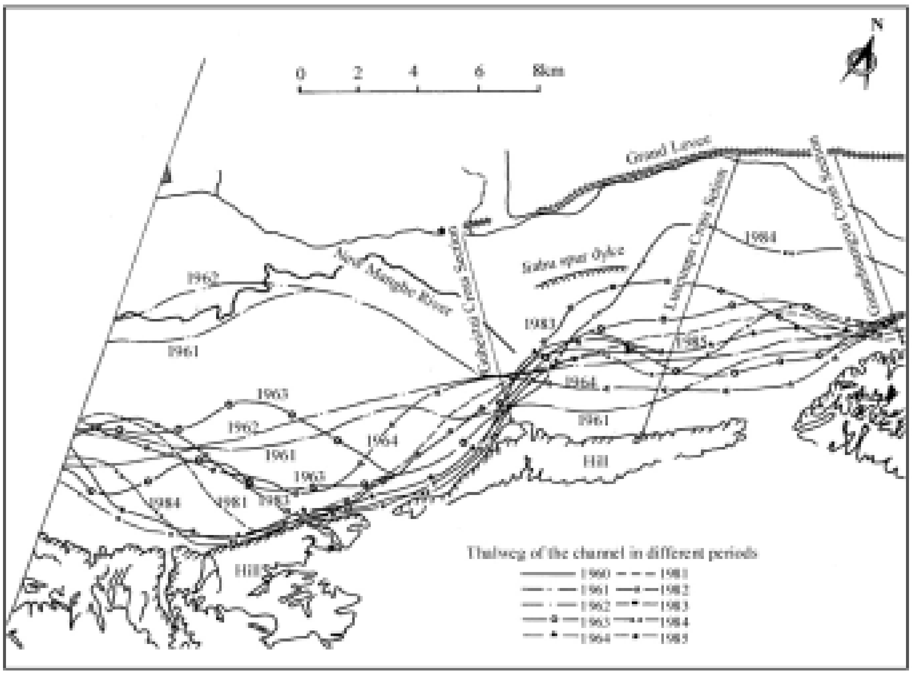


Fig. 9 The Lower Yellow River Channel Wandered within the Grand Levees During the Storage Operation (1960-1964) and Late Operation Periods (1980-1984) of Sanmenxia Dam. (The Curves are the Thalweg of the Channel in Different Periods.)

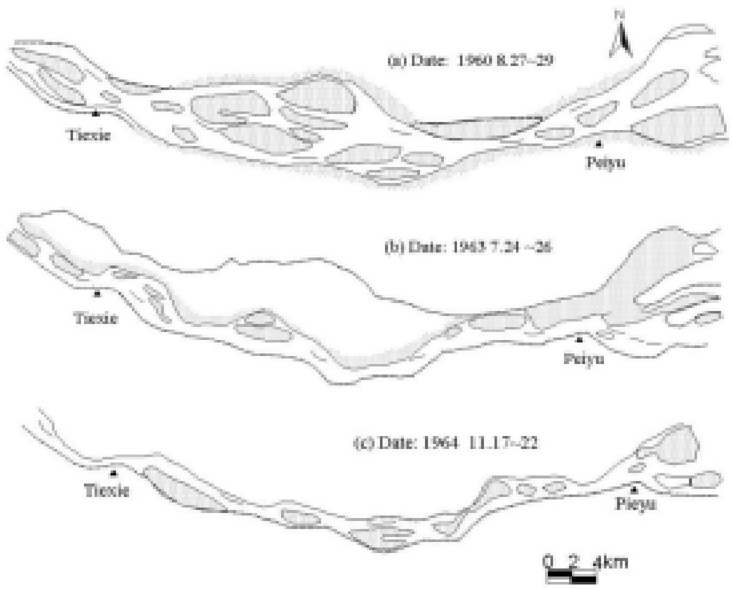


Fig. 10 Channel Morphology of the Tiexie-Peiyu Reach (157km-189 km From Sanmenxia) pre- and Post-Sanmenxia dam Construction

A decrease in the intensity of braiding, an increase in channel sinuosity and a change of channel pattern from braided to wandering have taken place in the Brenta River in Italy during the last century (Surian, 1999). Church (1983) also reported changes of river patterns from braided or multi-thread to single thread. The construction of the Black Butte Dam on Stony Creek in USA in 1963 caused the braided pattern of the reaches downstream of the dam to change to a single-thread, incised meandering pattern by 1967. Following the same principles, the Sanmenxia reservoir has caused the lower Yellow River to change from a wandering-braided into wandering, single-thread channel. Fig.10 shows the channel morphology of the Tiexie-Peiyu reach, which is about 157 km-189 km from the 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. In the meantime, the sinuosity of the river increased. The number of meanders in a 300km-long river reach (150 km-450 km from the dam) has increased from 16 to 22. This reach developed from a wandering-braided channel to a wandering –meandering channel.

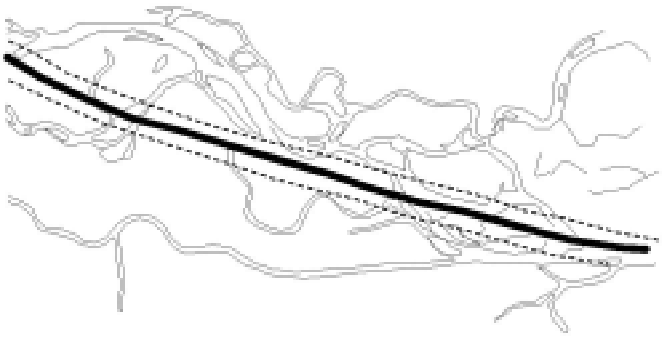
3 Fluvial Impacts of Channelization

Humans channelize rivers for various purposes: urban development, land reclamation, flood control and navigation. In Europe, most large rivers, such as the Rhine, Rhone, Elbe and Danube, have been channelized, mostly for to gain land for development, to eliminate diseases such as malaria, to prevent floods, and to open waterways for shipping (Kern 1994). Fig.11 shows the channelization of the Danube, Rhone and Yellow Rivers. The channelization of the Danube River near Vienna changed the river from a braided to a single-thread channel in 1859 (Humpesch, 1994), providing a large area of land for urban development (Fig.11(a)). The river Rhone was channelized to promote shipping (Bloesch, 2002) (Fig.11(b)). The lower Yellow River is a perched river. Numerous avulsions have occurred in the past millennia with the apex around Zhengzhou, causing devastating calamities. These avulsions have left numerous old channels (Li, 1992). Since 1855 the lower part of the river has been gradually channelized by raising and reinforcing 1300km-long grand levees (Fig.11(c)). The purpose of the primary channelization of the lower Yellow River is for avulsion-control (Wang and Lin, 2004).

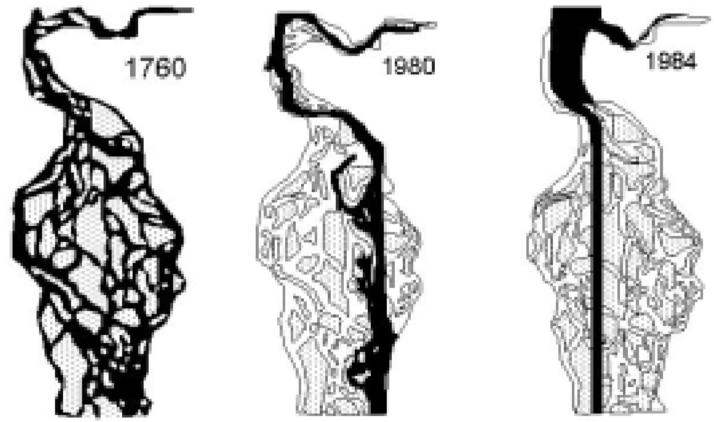
Channelization is an artificial change of river morphology, which may be followed by secondary fluvial processes. The Rio Puerco in central New Mexico is one of the most sediment-laden streams on earth. High sediment concentrations of up to 60% have been observed, which has posed a threat to agriculture and reservoir storage downstream (Gorbach *et al.*, 1996). The stream is ephemeral over much of its length, flowing only in response to precipitation. Channelization in a segment of the river near La Ventana in 1965-1967 led to geomorphic changes in the river. Channel slope before the channelization was 0.004 and exceeded 0.008 after the channelization. The increase in slope led to dramatic vertical and lateral changes in the river (Coleman, 2004).

Fluvial rivers tend to develop into meandering rivers. If the banks of the channel are not hardened, the straightened channel may gradually develop into a meandering channel. Although the lower Yellow River has been primarily channelized and no avulsion is allowed to occur, most of it is still not stabilized and the 500m-wide channel may migrate within a 10 km to 20 km-wide valley defined by the grand levees. Economic development and population growth require more land and further channelization of the river is now being researched. Numerous concrete spur dykes have been built within the grand levees, usually at the turning point of meanders, to control the channel migration and stabilize the banks. The total length of the spur dykes has been increasing rapidly since 1950.

Define a channelization degree 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. In the lower Yellow River, the channelization degree is different at differentreaches. Fig.12 shows the distribution of the degree of channelization along the river. From the 1970s to 2002, the degree has increased from 0.2-0.8 to 0.8-1.35. If the channel were completely controlled by connected dykes, the channelization degree would be equal to 2.



(a)



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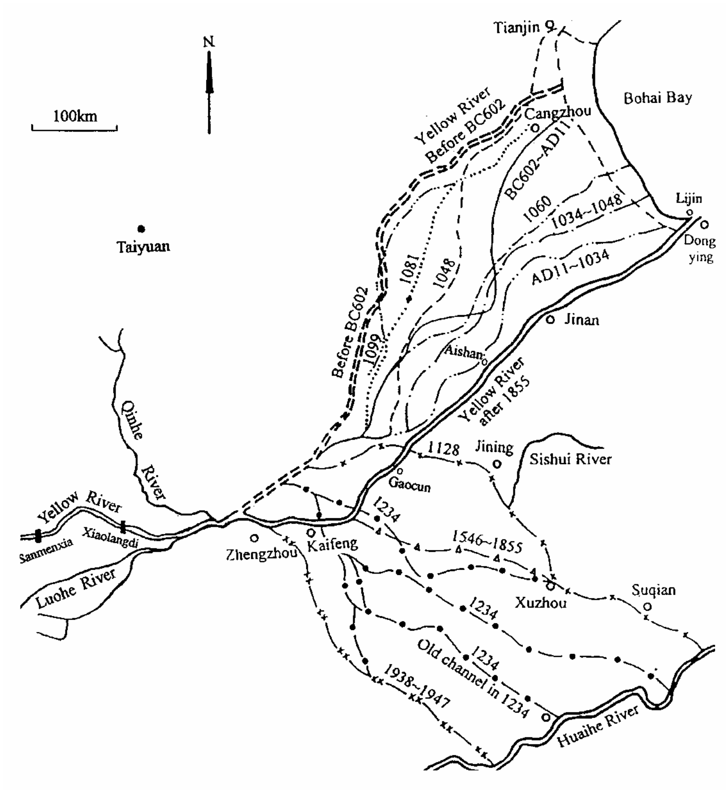


(c)

Fig.11 (a) Channelization of the River Danube near Vienna in 1859 for Land Reclamation (Humpesch 1994); (b) Channelization of the Rhone River for Navigation (Bloesch, 2002); (c) Numerous Old Channels of the Yellow River Resulting from Historic Avulsions and the Modern Channelized Lower Section for Avulsion Control

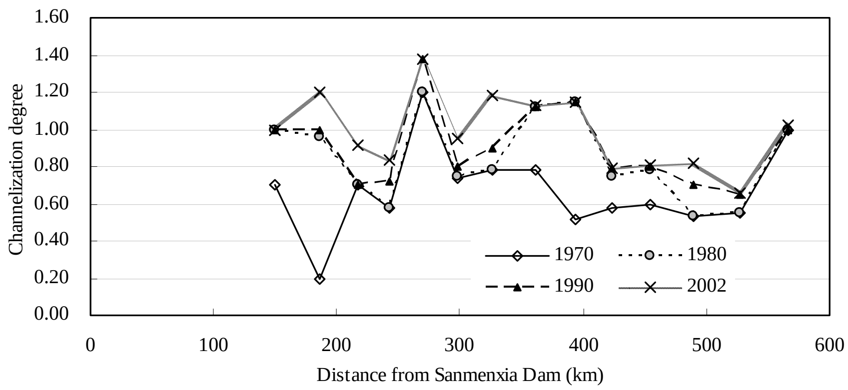


Fig. 12 Distribution of Channelization Degree Along the Lower Yellow River (= Ratio of the Length of the Spur Dykes to the Length of the Channel)

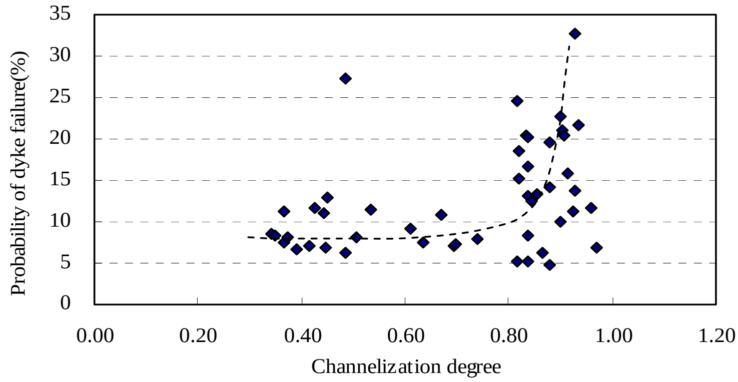


Fig. 13 Probability of Dyke Collapse as a Function of the Channelization Degree

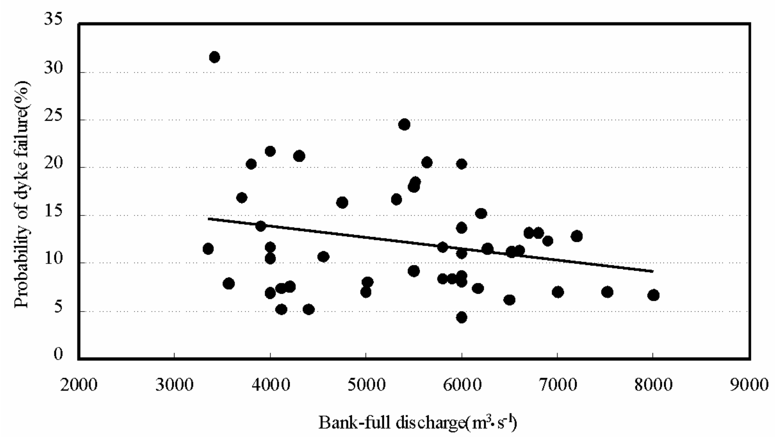


Fig. 14 Probability of Dyke Failure as a Function of Bank-full Discharge

Nevertheless, the natural fluvial process tend to break the constraint of the spur dykes, and the flow scours the dykes and causes them to collapse. Fig.13 shows the probability of collapse of each dyke as a function of the channelization degree; the probability is calculated with the total times of collapse per year over the number of spur dykes. The probability is lower when the channelization degree is lower than 0.8. If the degree is higher than 0.8, however, the probability of dyke collapse abruptly increases from 10% to 30%. The high probability of dyke collapse is due to the conflict between the natural fluvial process and the constraint of channelization. In fact the strongest conflict occurs for chnanelization degrees of 0.8-1.3, and therefore there is a corresponding high probability of dyke failure. Further chanellization may finally control the lateral motion and cause the channel motion to change from lateral to vertical. The channel will be deepened, resulting in an increase in the bank-full discharge. Fig.14 shows the probability of dyke failure against the bank full discharge. Following increase in bank full discharge the probability of dyke failure decreases.

If a river is completely channelized, or the channelization degree is equal to 2, the flow is controlled within a narrowed channel by hardened banks. In this case, few bank failures may occur. An example of this is the Rhine River, which has been channelized since the 19th century. Lateral migration of the river has been controlled, but the vertical process has caused problems. The sediment-starving flow has eroded the riverbed and caused it to be lowered by several meters. The riparian vegetation and ecology were impaired, the ground water table dropped, and navigation channels and harbor facilities were damaged. The German people adopted the strategy of feeding gravel at selected locations to increase the supply of the bedload. An annual average of 170,000 tonnes of sand and gravel are dumped on the riverbed from barges to maintain the balance of the riverbed (Kuhl, 1992). Key factors for the effectiveness of the strategy were the size composition of the sediment fed into the river and the location and time of dumping. The strategy has stopped the incision of the channel not only at the section where gravel has been dumped, but also along all of the reaches downstream.

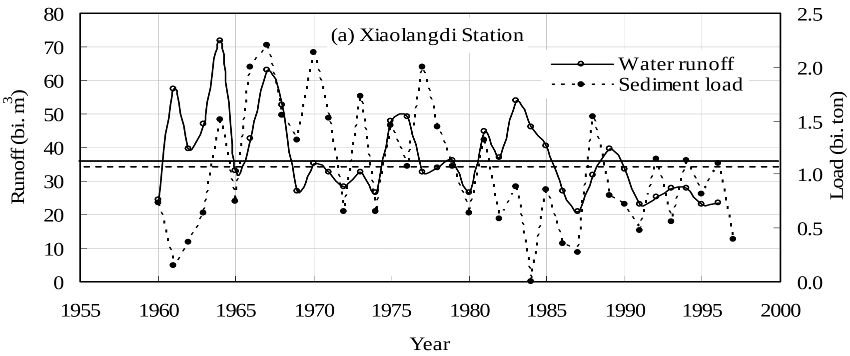
4 IMPACT OF WATER-DIVERSION PROJECTS ON FLUVIAL PROCESSES

The demand for water from agriculture, industry and urban development continues to increase. To meet the demand, increasing amounts of fresh water have to be diverted from rivers. Water diversion inevitably alters the character of streams, eco-systems, and ultimately landscapes. If more than 10% of water is diverted from a river, the fluvial process will be affected. Water diversion may even change a section of a perennial stream to an ephemeral river section (Fogg and Muller, 1999). Water diversion can have a major impact on the stream habitat by reducing flows, which in turn decreases depths, modifies flow velocities and decreases the overall stream volume. These changes can then alter the microhabitats that sustain various life-stages of fish species. The North Fork Little Snake River in south central Wyoming in the USA is presently being affected by water diversion as a result of the Cheyenne Stage II water diversion project.

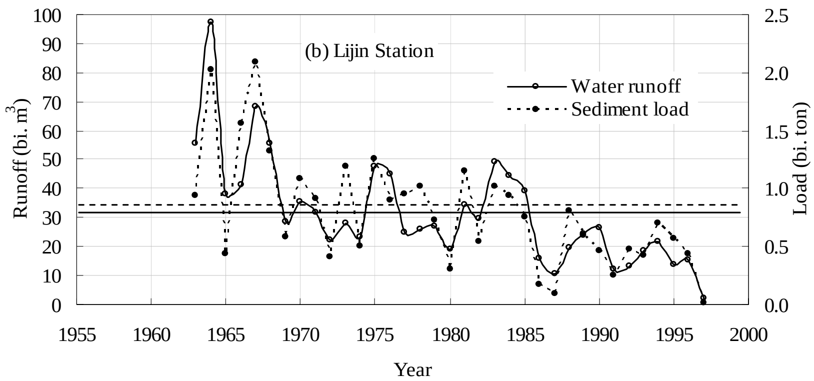
In China many water diversion projects in the past have been constructed for agricultural use. At present a continuous drought is exacerbating an already critical water shortage in northern China. More and more water has been diverted from the Yellow River for drinking water and irrigation. For the first time in its history the Yellow River failed to reach the ocean in 1972. In 1997 the Yellow River failed to reach the sea two-thirds of the year because most of the river water was diverted. To provide more water to the thirsty north China, a great inter-basin water transfer project has been launched and will be implemented within the decade. The water diversion project will create up to three separate canals from the oft-flooded Yangtze River basin to the oft-dry Yellow and Haihe River basins. The total capacity of water diversion of the three canals will be about 50 billion m^3 per year, which is almost equal to the annual amount of water in the Yellow River.

While water diversion projects have become a popular and important strategy to meet increasing water demand, the fluvial processes of rivers are increasingly affected by the diversions. The lower Yellow River is a perched river, with its riverbed 10 m higher than the surrounding land. This poses a flooding risk but also provides the potential for water diversion to farmland and numerous cities and towns within and outside of the Yellow River basin. Residents in Tianjin and Qingdao cities, which are several hundreds kilometers from the Yellow River, currently are drinking water from the Yellow River. There are hundreds of water diversion facilities along the lower Yellow River with a total capacity of about 1,500 $m^3 \cdot s^{-1}$.

Figs. 15 (a) and (b) show the variation of the annual water and sediment load from 1960 to 1997 at Xiaolangdi (130km from Sanmenxia) and Lijin (900km from Sanmenxia). 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 at Lijin than at Xiaolangdi each year because the water diversion was less than the inflow from tribuitaries. From 1970-1985, the annual water at Lijin was equal to or slightly less than at Xiaolangdi because more water had been diverted. From 1986, however, the total volume of water diverted was much more than the inflow from tributaries, and the water runoff decreased along the course. From 1970-1985, the annual water was about 10 billion m^3 less at Lijin than at Xiaolangdi. The reduction in flow volume over a long stretch of the river elicited a sharp reduction in the flow's sediment-carrying capacity. Therefore, the annual load was much less at Lijin than at Xiaolandi during this period.



(a)



(b)

Fig.15 Variation of Annual Runoff and Sediment Load in the Period From 1960 to 1997 at Xiaolangdi (130km from Sanmenxia) and Lijin (130km from Sanmenxia). The Differences Between the Two Stations are Due to the Inflow from Tributaries and Water Diversions

One of the fluvial impacts of the water diversion was the shrinkage of the channel. Fig.16 shows the bank full discharge of the lower Yellow River during different periods. Water diversion along the lower Yellow River 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 $m^3 \cdot s^{-1}$ in 1958 and 1964; it decreased to about 6,000 $m^3 \cdot s^{-1}$ in 1985 and to only 3,000 $m^3 \cdot s^{-1}$ in 1999. The shallow channel cannot accommodate floodwater as before; so the flood stage has become extremely high and the phenomenon known as the "little flood with high flooding disasters" has occurred frequently in the river basin.

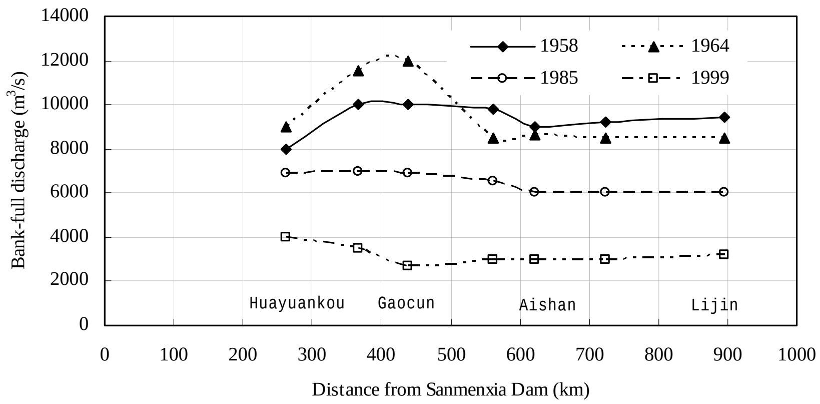


Fig. 16 Bank-full Discharge Along the Lower Yellow River Course During Different Periods

The second important impact of water diversion projects is the adjustment of riverbed profiles. According to the minimum stream power theory, the morphology of fluvial rivers develops to reach the minimum stream power (Yang, 1983). This can be described by the following equation:

$$\frac{\mathrm{d}P}{\mathrm{d}x} = \frac{\mathrm{d}}{\mathrm{d}x}(\gamma sQ) = \gamma(Q\frac{\mathrm{d}s}{\mathrm{d}x} + s\frac{\mathrm{d}Q}{\mathrm{d}x}) = 0 \quad (1)$$

in which P is the stream power, γ is the specific weight of water, s is the riverbed slope, x is the distance along the river course, and Q is the discharge. For most rivers, the discharge increases along the course due to the inflow from tributaries; thus the term $s\mathrm{d}Q/\mathrm{d}x$ is positive. According to Eq. (1), the term $Q\mathrm{d}s/\mathrm{d}x$ must be negative, or the slope of the riverbed decreases along the course; so that these rivers exhibit concave riverbed profiles.

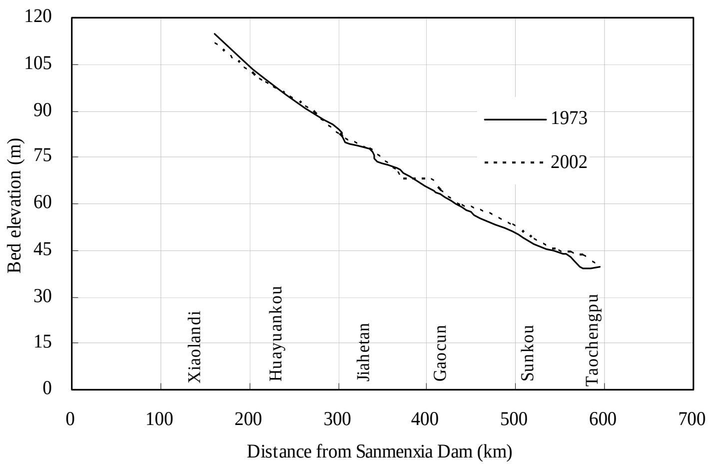


Fig. 17 Longitudinal bed Profiles of The Lower Yellow River in 1973 and 2002

A large quantity of water diverted along the course of a river, however, makes the term $s\mathrm{d}Q/\mathrm{d}x$ negative. For instance, since 1986 the average discharge has decreased along the Yellow River course in the reach below Jiahetan (Fig.17), i.e. $\mathrm{d}Q/\mathrm{d}x<0$. According to the minimum stream power theory, the rivers have a tendency to satisfy Eq. (1), and thence the term $Q\mathrm{d}s/\mathrm{d}x$ must be positive. In this case, the riverbed profiles will develop toward a convex shape, which is different from the normal concave curve. Fig.17 shows the bed profiles of the lower Yellow River. The upper section is developing toward a concave profile, and the lower section to a convex profile. The fluvial process takes a long period of time and we can predict an “s-shape” longitudinal bed profile from the development trend. In fact the bed profiles of the Weihe River has shown an “s”-shape profile (Cao *et al.*, 2001). For the same reason, the water diversion makes the slope of the lower Weihe River increase from negative to zero and positive, although the rising of the Tongguan elevation has offset some of this influence.

5 CONCLUSIONS

Damming of rivers causes not only sedimentation in reservoir but also creates additional backwater and deposition even further upstream. Sedimentation in the Sanmenxia Reservoir raised the Tongguan elevation, which acts as the base level of the bed profile of the Weihe River, a tributary stream. The ascent and descent of the Tongguan elevation have induced sedimentation and erosion in the lower Weihe River in the form of retrogressive waves. Damming can change the river patterns in upstream river sections and tributaries. Dams may change braided river sections into single thread channels, as evidenced by the effect of the Three Gorges Dam on the Chongqing section of the Yangtze River; and dams may cause meandering rivers to become less meandering and more wandering, as was the case for the Sanmenxia Dam on the lower Weihe River.

Large dams cause the following fluvial processes in the downstream reaches: (1) channel incision; (2) variation in channel width; (3) reduction in bank erosion and channel migration; and (4) changes in river patterns. The migration rate of a channel can be reduced by 50%-75% for rivers with low sediment concentration, but there is no reduction in channel migration rate for rivers with hyperconcentrated sediment. Dams change downstream river patterns from braided to wandering, or from wandering-braided to wandering-meandering.

Channelization changes river morphology from braided and meandering to single-thread and straight, which may induce secondary fluvial processes. If the channelization degree is within the range of 0.8-1.3, the highest probability of dyke failure occurs due to the conflict between the natural fluvial process and the constraint of channelization. If a river is completely channelized, the flow is controlled within a narrowed channel by hardened banks. Few bank failures may occur in this case, but vertical processes may be more active.

Water diversion has becomes an important stress causing changes in fluvial processes. Water diversion may even change a section of a perennial stream to an ephemeral river section. The lower Yellow River is a perched river, with its riverbed 10 m higher than the surrounding land. This poses a flood risk, but also provides a potential for water diversion to farmland and cities and towns. More than 10 billion m^3 of water is currently being diverted from the Yellow River, which has caused shrinkage of the channel and readjustment of the bed profiles. If the quantity of water diversions along the course is more than the inflow from its tributaries, the riverbed profiles will develop toward an s-shape longitudinal bed with a concave profile in the upper reach and a convex profile in the lower reach.

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