Reservoir Sedimentation Management in China

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1 Introduction

There are numerous rivers in China, among them over 1,500 have a watershed area larger than 1,000 km^2 each (Fig. 1.1). These rivers with total runoffs of 2,700 billion m^3 in a normal year provide tremendous water resources and hydropower potential. Up to now, over 80,000 hydroprojects have been constructed in China for flood control, irrigation, hydropower, navigation, water supply, fishery, etc.

Many rivers in China carry a large amount of sediment load owing to serious soil erosion. Sediment problems are very conspicuous in the development and regulation of rivers, and induce much trouble to the water conservancy and hydropower works, which force Chinese scientists and engineers to pay high attention to and make great efforts in the research of sediment problems. In recent decades, sediment problems in many key hydroprojects have been successfully solved. This paper describes briefly the experience in preservation of reservoir storage in China.

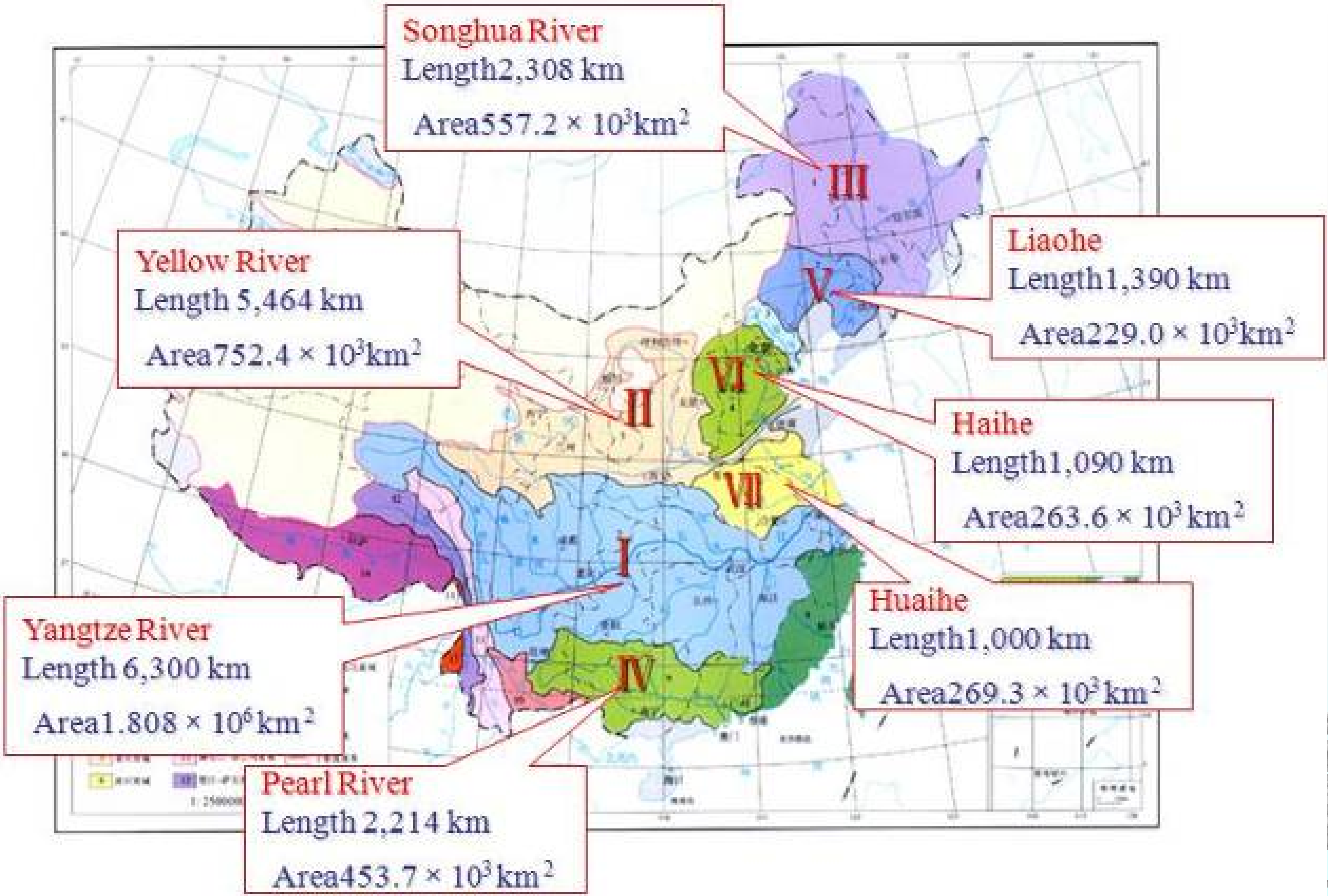


Fig. 1.1 River systems in China

1.1 River Sediment in China

In China soil erosion is very serious in some areas. A recent survey by remote sensing technique shows that the total eroded area of China is 3.67 mil. km^2, 38% of the whole territory. Over 40 rivers carry an annual sediment load larger than 10 mil. tons each. According to incomplete statistics of seven largest rivers of China, rivers in Southwest and Southeast China and inland rivers, the average annual sediment load totals 2.687 billion tons. Among them the Yellow River carries 1.6 billion tons, accounting for 60% of the total, while the Yangtze River carries 530 mil. tons, 20% of the total.

There are 430,000 km^2 of loess plateaus in the Yellow River Basin, where the soil is so loose that it can be easily eroded. In some of the gullies, the average rate of erosion is as high as 19,200 $t/km^2.a$ (Huangpu River), and the maximum rate reached 34,500 $t/km^2.a$. In some tributaries of the Yellow River the maximum sediment concentration reaches around 1,600 kg/m^3.

There are 13 large rivers in the world, each of them carries an annual suspended load over 100 mil. tons. Among them, the Yellow River stands first and the Yangtze third. The Yellow and Yangtze contribute about 29.3% of the total sediment load carried by the 13 rivers as mentioned above. Table 1.1 and 1.2 show the sediment load of the rivers in China and large rivers in the world, respectively.

In China, river sediments have obvious characteristics as follows. (1) The temporal distributions of river runoff and sediment load are quite uneven, 60-80% of the total annual runoff are concentrated in the flood season of a period of about 4-5 months. The sediment load is more concentrated in the same period. In some rivers 90% of the total annual sediment load are concentrated in the flood season.

The sediment load is even more concentrated in a few sediment peaks. For example, the sediment load in five days in the flood season at Sanmenxia Station on the Yellow River accounted for 19% of the annual load and the maximum was 31.3%. Such a phenomenon is more prominent in the tributaries of the Yellow River.

(2) The annual sediment load carried by many streams with heavy concentration differs greatly from year to year. For instance, the maximum annual sediment load of the Yellow River was 3.91 billion tons (in 1933), and the minimum was only 488 mil. tons (in 1928), one eighth of the maximum. The annual sediment loads at Yichang Station on the Yangtze River were 750 mil. tons in 1954 and 361 mil. tons in 1986, respectively. The value in 1986 was less than 50% of that in 1954.

Table 1.1 Sediment Load Carried by Large Rivers in China

River	Station	Drainage area(km²)	Length (km)	Avenge runoff ($10^9 m^3$)	Annual sediment load (10^6 tons)	Sediment concentration (kg/m^3)	Max. Sediment concentration (kg/m^3)	Rate of erosion (t/km^2a)
Yellow	Sanmenxia	752400	5464	43.2	1640	37.6	933	2480
Yangtze	Datong	I807200	6300	921.1	478	0.54	3.24	280
Haihe (1)		318800		14.26	151.9	(10.7)	436	1944
Huaihe (2)	Bangbu, etc.			29.63	27.1	0.91	11.0	153
Liaohe (3)	Tielin			11.89	60.9	(5.12)	142	240
Songhua	Jiamusi			67.80	10.0	0.16		
Pearl (4)				284.4	8l.l	0.35	4.08	260
Rivers in Southwest (5)				175.1	136.3	(0.78)		
Rivers in Southeast (6)				164.3	30.1	(0.18)		
Inland rivers (7)				30.51	59.9	(1.98)		
Total					2687			

1.2 General Situation of Reservoir Sedimentation Problems in China

At present there are over 80,000 dams in China totaling storage capacities of 410 billion m^3. Among them 18,000 dams are high dams (higher than 15 m). In the early 1980s, a survey of 231 large (each storage capacity larger than 100 mil. m^3) and medium-sized (10 to 100 mil. m^3) reservoirs showed that the sediment deposit amounted to 11.5 billion m^3, 14.3% of the total storage capacity of 80.4 billion m^3. The average annual loss of reservoir storage capacity in China was 2.3%, the highest in the world, in comparison with 1.8% of Algeria, 1.02% of Japan, and 0.24% of the USA. Moreover, the annual loss of reservoir storage in Shanxi, Shaanxi, and Gansu Provinces were even higher (Table 1.3).

Table 1.3 Annual Loss of Reservoir Storage in Some Provinces (Regions)

Province (Region)	Shanxi	Shaanxi	Gansu	Ningxia	Inner Mongolia	Hebei	Shandong	Hubei
Annual loss (%)	3.02	2.9	2.4	2.0	2.1	1.1	0.44	0.20

Table 1.5 shows the rate of loss of reservoir storage capacity in the Yellow River Basin and the rate of erosion of the catchment area where the reservoirs are located. In the areas with rate of erosion larger than 1000 $t/km^2.a$ the annual rate of loss of reservoir storage was larger than 0.5%. Special consideration to deal with reservoir sedimentation should be emphasized in those areas

Table 1.5 Relationship between Loss of Reservoir Storage and Rate of Erosion in the Yellow River Basin

Rate of erosion($t/km^2.a$)	Rate of loss of reservoir storage(%)
20000-30000	52.6
15000-20000	51.2
10000-15000	41.1
5000-10000	43.1
2000- 5000	41.0
1000-2000	20.1
500- 1000	15.4
200- 500	14.0
100- 200	11.7
< 100	3.8
Total	26.5

2. Lessons Learned in the 1950s

2.1 Underestimation of Seriousness of Sediment Problems

2.1.1 Selecting Dam Sites

Although reservoir sedimentation problem is not always an important issue in the selection of dam site, it may be of significant importance in such a selection. The Liujiaxia Project may serve as an example.

The Liujiaxia Dam is the first large multipurpose hydroproject on the upper Yellow River for power generation, flood and ice jam control, and irrigation with the first priority of power generation. The first power came in 1969 and the entire project was commissioned in 1974. Some pertinent data are shown in Table 2.1. The main dam is a concrete gravity dam. Characteristics of the outlet works are given in Table 2.2.

Table 2.1 Characteristics of Liujiaxia and Sanmenxia Projects

Project	Liujiaxia	Sanmenxia
Reservoir capacity (10^9 m^3)	5.74	
Reservoir length (km)	56	
Dam height (m)	147	106
Pool level fluctuation (m)	41	
Catchment area (10^3 km^2)	181.8	688.4
Annual runoff (10^9 m^3)	26.3	45
Annual sediment load (10^9 t)	0.087	1.6
Average sediment concentration (kg/m^3)	3.31	35.6
D_{50} of suspended load (mm)	0.025	0.038
D_{50} of topset deposit (mm)	0.02	0.02
Installed capacity (MW)	1225	250

Table 2.2 Outlet Works of Liujiaxia Dam

Outlet	Invert elevation (m)	Openings	Dimensions (m)	Discharging capacity (m^3)	
				El.1694 (m)	El.1735 (m)
Spillway	1715	3	10x8.5		3800
Spillway tunnel	1675	1	8x8.5	930	2140
Sluicing tunnel 1	1665	2	3x8	880	1488
Sluicing tunnel 2	1665	1	2x1.8	68	105

Up to 1989, 1.41 billion m^3 of sediment was deposited in the reservoir, accounting for 24.6% of the initial storage capacity. Of this deposit, some 70% were in the inactive storage, accounting for some 45% of the initial inactive storage, and only some 8% of the initial active storage.

In flood seasons incoming sediment load was deposited first in the gorge near the head of the reservoir. When the pool level was drawn down during dry seasons, the deposits on the topset of the delta were eroded and transported, then deposited in the inactive storage.

The pivot point of the delta is still far away from the dam. Thus, sedimentation in the main reservoir has not caused any trouble to the project so far.

Liujiaxia Reservoir has two small arms in the valleys of the Taohe and Daxia Rivers. The storage capacities in these two tributaries were only 2% and 4% of the total storage capacity, respectively. The Taohe River joins the main stream at a point l.5 km above the dam and carries annually 28.6 million tons of sediment or 33 % of the total sediment income to the Liujiaxia Reservoir. The large and rapid deposition resulted from the large incoming sediment load in the relatively small Taohe River has led to serious problems in Liujiaxia Reservoir (Fig. 2.1.)

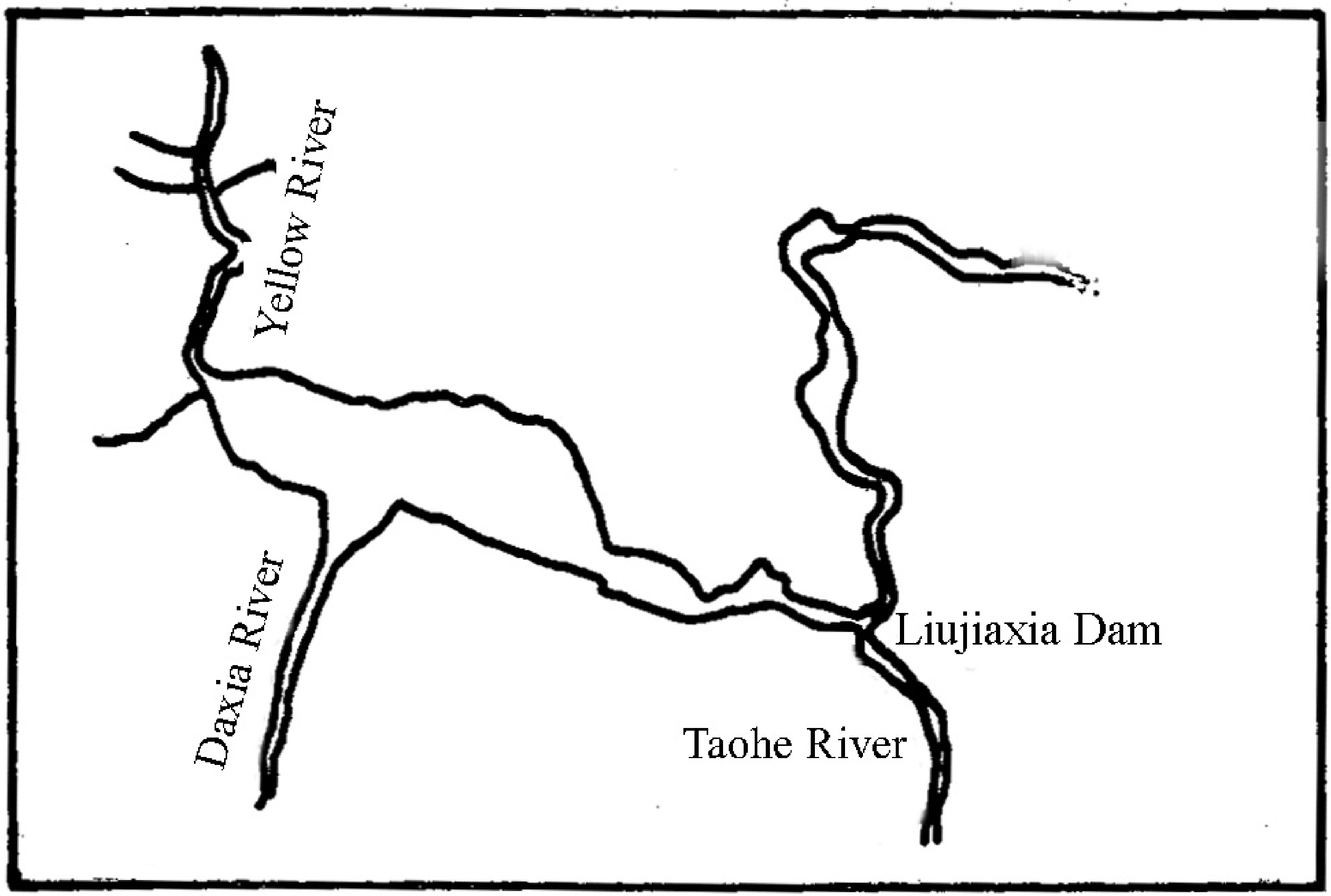


Fig. 2.1 Plan of Liujiaxia Reservoir

The major sediment problem is the formation of a mouth bar at the confluence of the two rivers. By 1979, the inactive storage of the Taohe River was filled up and the mouth bar has risen to the minimum pool level. Proximity of the mouth bar resulted in a rapid increase in the amount of sediment passing through the turbines. In June 1980, when more flow was required to meet an abrupt increase in power demand, the pool level in front of the dam suddenly dropped by large amplitude because the mouth bar impeded the flow of water to the dam from the upstream part of the reservoir.

Abrasion of turbine blades and the lining of the outlet tunnels during sediment sluicing was very serious. The annual amount of sediment passing through power unit 2 is given in Table 2.3. The amount reached its peak in 1978 and 1979, when the top of the mouth bar was the highest. After sediment sluicing in 1981, 1984 and 1985, the amount was reduced.

Table 2.3 Annual Amount of Sediment Passing Through Power Unit 2

Year	1974	1975	1976	1977	1978	1979	1980	1981	1982
Amount (10^3)	141	287	1290	1800	11600	11900	5840	3520	588
Year	1983	1984	1985	1986	1987	1988			
Amount (10^3)	919	4810	2820	1090	5310	6350			

Abrasion of turbine blades and the lining of sluicing tunnels required a great amount of repair. For example, power unit 2 was damaged so much that it had to undergo repair for 125 days. It was found that the maximum depth of abrasion was 50 mm, and the area abraded was as large as 28.9 m^2. The consumption of welding rod was 3.5 t.

During the planning stage of the Liujiaxia Project an alternative of the dam site was considered, i.e. a dam site above the confluence of the two rivers. Finally, this alternative was abandoned owing to the consideration of fully usage of the runoff of the Taohe River. If the dam site of the Liujiaxia Project had been selected above the confluence of the Yellow River and Taohe River, sediment problems of the Liujiaxia Project would have not been so serious in the initial operation stage of the project. The decrease of the benefit of the project would have not been large if remedial measures (to use the annual runoff of the Taohe River {Q_m= 178 m^3/s}) had been found to increase its benefits.

2.1.2 Selecting an Operating Rule

In the 1950s when a large number of dams were built in China, almost all reservoirs were designed to adopt the operating rule of impoundment. However, such an operating rule is mainly appropriate for reservoirs built on clear rivers. For reservoirs built on heavily sediment-laden rivers it induces much trouble in reservoir sedimentation. Two examples are given below.

2.1.2.1 Sanmenxia Project-for Large Reservoirs

The Sanmenxia Project is the first large multi-purpose hydroproject built on the middle Yellow River, where the catchment area is 0.688 mil. km^2, accounting for 91.5% of the total, and the annual runoff and annual sediment load account for 89% and almost 100% of the totals, respectively (Table 2.1) (Fig. 2.2).

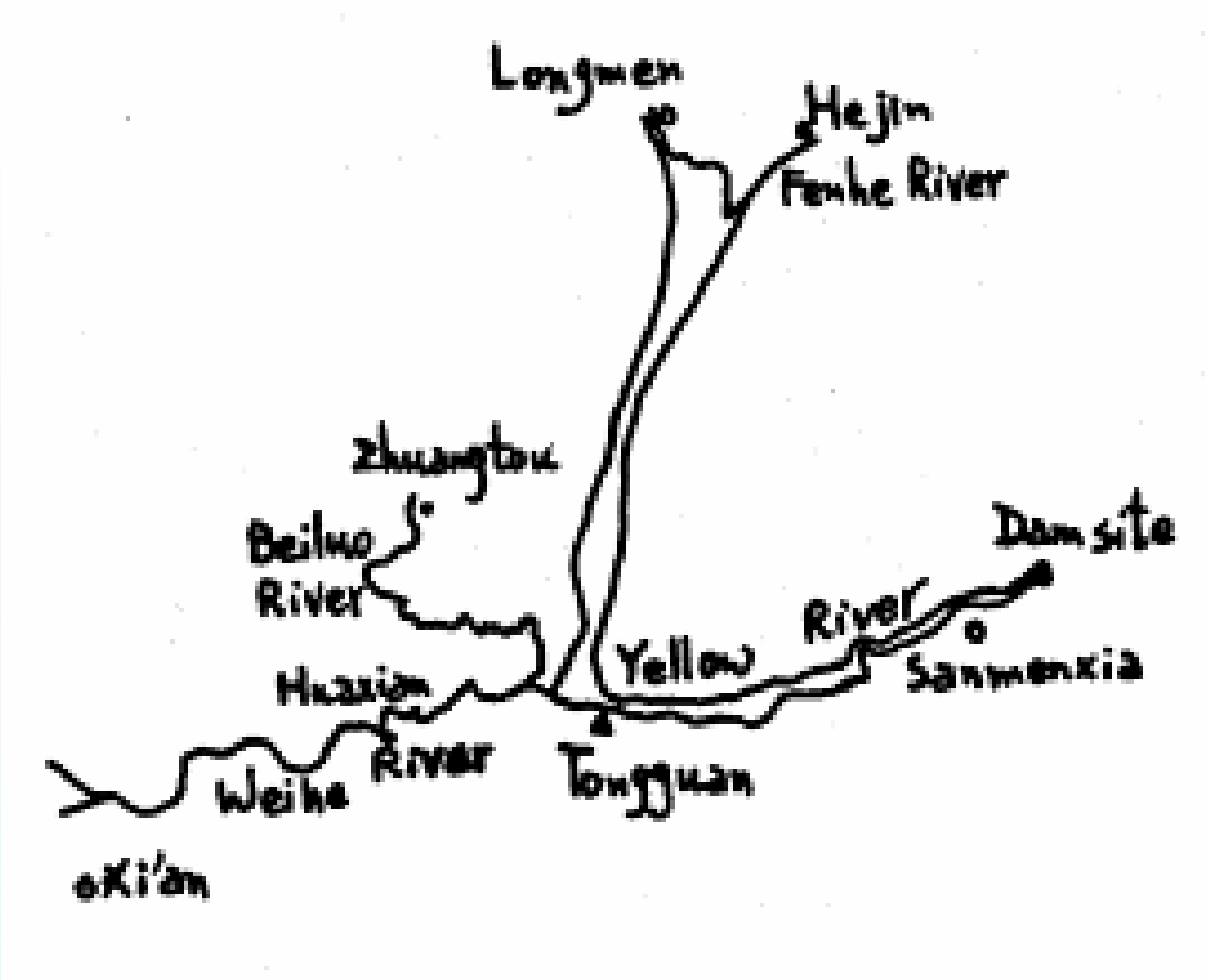


Fig.2.2 Plan of Sanmenxia Reservoir

2.1.2.1.1 Original Planning and Design

The objectives of the Sanmenxia Project in the original planning including flood control, reduction of sediment deposition in the Lower Yellow River, power generation, irrigation, navigation, and others. The planning and design of the Sanmenxia Hydrosystem was affected to a large degree by the opinion of " Large reservoir storage capacity has to be gained by large inundation". In the Preliminary Design made by the former Soviet Union in 1956, the normal pool level (NPL) and the dead pool level (DPL) were 360 m and 335 m, respectively; the total storage capacity was 64.7 billion m^3 and the inundated farmland was 0.217 mil. ha; the flow depth in the downstream channel should be no less than 1 m to meet the requirement of navigation; the resettled population was 0.87 million;

the installed capacity was 1,160 MW; the irrigation area was 2.67 mil. ha; and the 1000-yr flood of 35,000 m^3/s would be reduced to 6,000 m^3/s. In 1958, China decided to select 360 m as the NPL in the design, but at the first stage of construction 350 m and 325 m were adopted as the NPL and DPL, respectively; the dam crest elevation was 353 m; the total storage capacity was 35.4 billion m, among them 14.7 billion m^3 was reserved for sediment deposits;

the installed capacity was 900 MW. The main goals of the reservoir were to reduce the 1000-yr flood of 35,000 m^3/s to 6,000 m^3/s, eliminating the flood threat in the Lower Yellow River; to store all incoming sediment load and stop sediment deposition and bed rising in the downstream river channel; to manage the water resource of the Yellow River and irrigate 1.48 mil. ha at the first stage and 5 mil. ha at the second stage; to improve navigation in the downstream reaches. Under this planning, the reservoir would inundate 0.138 mil. ha of farmland, and 0.6 mil. people would have to be resettled when NPL was 350 m.

It was expected that the reservoir life could be 25-30 years, in combining with soil conservation works in the upstream reaches, the reservoir life could increase to 50-70 years. It was estimated that the sediment load in 1967 would reduce 50% due to soil conservation works and reservoirs on the tributaries.

2.1.2.1.2 Period of Impoundment- September 1960 to March 1962

The Sanmenxia Project was put into operation in September, 1960. The operating rule in this period was to impound water and to trap all incoming sediment loads. The highest pool level was 332.58 m (Feb. 9, 1961). During this period, a total flow volume of 71.7 billion m^3 and sediment load of 1.736 billion tons entered the reservoir.

Only 7.1 % of the total sediment load was vented out of the reservoir by density current, 1.7 billion m^3 of reservoir storage below 335 m were occupied by sediment deposits. Tongguan is at the confluence of the Yellow River and the Weihe River, the largest tributary of the Yellow River. The Yellow River has a maximum width of 18 km at the confluence zone but contracts downstream to about 1 km at Tongguan.

Thus, the pass at Tongguan serves as a local base level to the Weihe River and the Yellow River upstream. The bed elevation at Tongguan rose by 4.5 m from September 1960 to March 1962. It induced a new problem, namely the upstream extension of backwater deposits, which would cause very serious impacts on the Guanzhong Plain in the Lower Weihe River Basin, a very important agriculture zone, and Xian City, capital of Shaanxi Province.

As sedimentation in the reservoir was so serious, in March 1962 it had to be decided to change the operating rule from impoundment to flood detention and sediment discharging in order to reduce the rapid sedimentation in the reservoir.

The planning and design of the Sanmenxia Project in the 1950s had several fatal defects. First, the target of the project was too high to achieve, such as the targets for power generation and navigation. Second much attention was paid to retain sediment in the reservoir to avoid aggradation in the lower Yellow River, but the impacts of reservoir sedimentation in the upstream area and reservoir area were neglected.

Third, the opinion of "reservoir storage capacity has to be gained by inundation" made the reservoir scale too large. The NPL was determined as 360 m in the original planning, and 870,000 population would have to be resettled and 217,000 ha of farmland be inundated, which were inconsistent with China’s situation of high population and less farmland.

In fact, 3,189,000 and 403,786 people were resettled from the reservoir area until 1964 and 1982, respectively. Among them, 42% have moved back to the reservoir area because the reservoir pool level was descended later, which not only wasted a large amount of fund, but also greatly impacted those migrated people.

Fourth, the benefits of soil conservation were overestimated as that in 1967 the incoming sediment load would decrease 50%. Actually the goal has not reached. Only in one and half years the operating rule of the reservoir had to be changed and the project had to be reconstructed later several times.

2.1.2.2 Heisonglin Project-for Small Reservoirs

The Heisonglin Project is a small hydroproject on a small river of Yeyu. The initial reservoir storage was 8.6 mil. m^3, controlling a catchment area of 370 km^2. The dam is 45 m high and a bottom outlet (2x1.5 m^2) with a discharge capacity of 10 m^3/s is installed at the dead pool level. The average annual runoff at the dam site is 14.2 mil. m^3 (Qm=0.45 m^3/s) and the mean annual sediment load is 0.70 mil. t.

The average annual sediment concentration is 49.3 kg/m^3 while the average sediment concentration in July and August is 113 kg/m^3 and the maximum concentration was 801 kg/m^3. The suspended sediment is fine with a D_{50} of 0.025 mm. The D_{50} of the original bed material was 18 mm. The runoff in the flood season accounts for 45% of the whole year while the sediment load in the flood season, 98%. The reservoir is of a gorge-type.

The project was commissioned in 1959 and the adopted operating rule was impoundment. During the first 3 years (May 1959 to June 1962) reservoir sedimentation was very serious with a cumulative amount of deposition of 1.62 mil. m^3, 18.8% of the total storage capacity. If such an operating rule had been continued, the reservoir would have been silted up in 16 years. Therefore, the operating rule of the reservoir had to be changed in 1962.

2.2 Overestimation of Benefit of Soil Conservation

In the planning and design of hydroprojects in the 1950s the benefit of soil conservation was not estimated on the basis of practice. On the contrary it was estimated on imagination and the benefit of soil conservation was overestimated as mentioned in the example of the Sanmenxia Project. As a result of overestimation the planning and design pertinent to reservoir sedimentation were not coincident with practice. Consequently, a number of problems of reservoir sedimentation occurred.

3. Universality of Reservoir Sedimentation

In Fig. 3.1 reservoirs are classified according to ϕ and ψ with sediment concentration as the third parameter. Here ϕ and ψ denote the ratios of reservoir capacity to annual sediment load (in volume) and water runoff, respectively. It can be seen that points can be classified into three groups. All the points fall close to one of the three lines representing different types of rivers. The first group represents the reservoirs built on clear rivers with sediment concentration less than 1 kg/m^3. The third group represents the reservoirs built on heavily sediment-laden rivers with concentration greater than 10 kg/m^3. The second group represents the reservoirs built on rivers with medium concentration of 1 to 10 kg/m^3. For the first group reservoir sedimentation is not a problem while for the third group it is very serious.

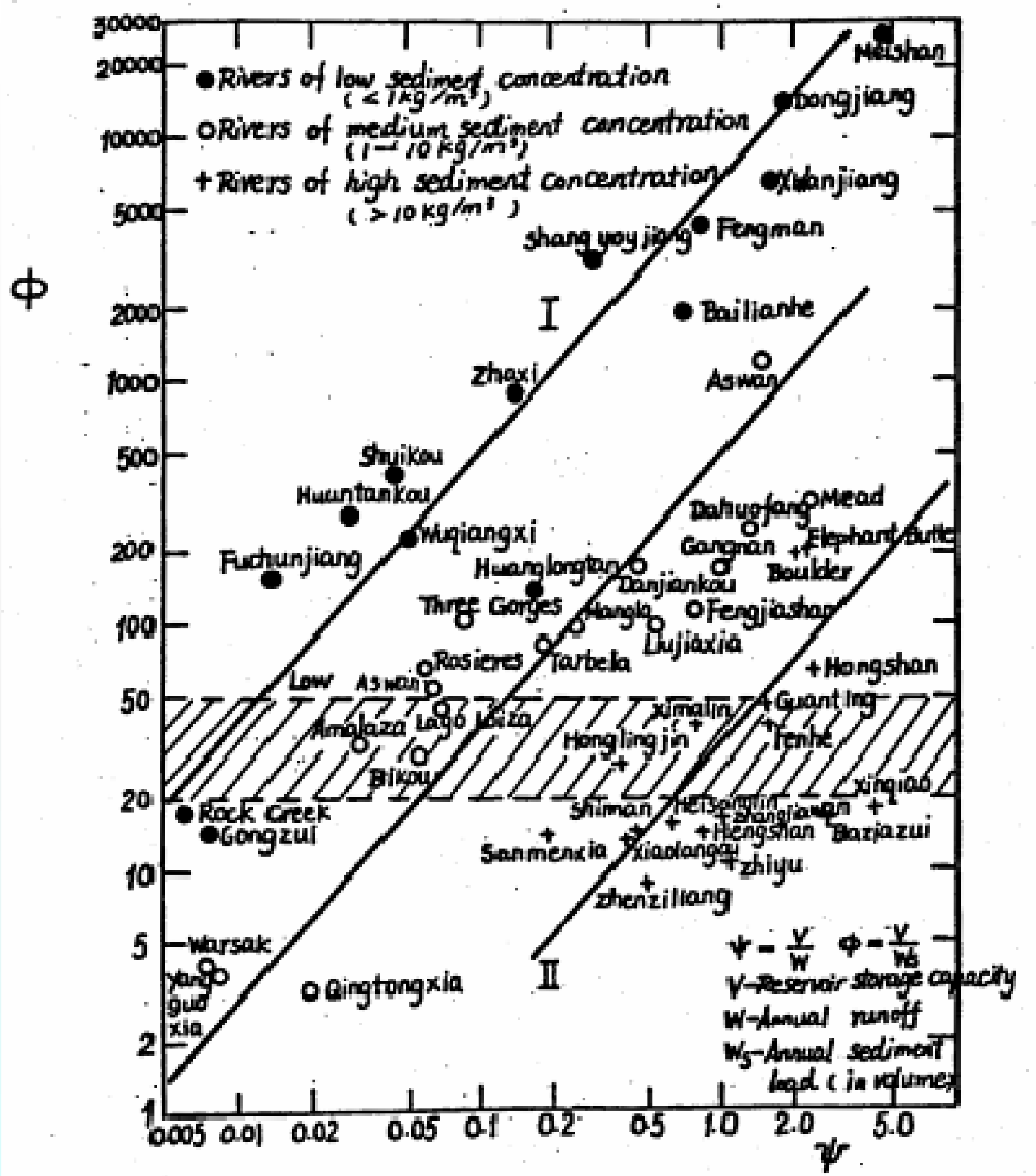


Fig. 3.1 Relationship between φ and ψ

The features of deposition and experience of reservoir sedimentation management of the reservoirs are more valuable of reference to those in the same group, though the general law of reservoir sedimentation is the same.

4.States of Distress of Reservoir Sedimentation

In China a norm for sediment management of hydroprojects has been issued. This norm is stipulated based on the practice in the past four decades in China. In this norm, the states of distress caused by sediment problems of hydroprojects are classified into two grades according to the degree of seriousness at which sediment problems affect safety and benefit of the project, namely serious and non-serious.

When one of the following situations occurs, the states of distress are considered serious.

•The ratio of reservoir capacity to annual sediment load (in volume), ϕ , is smaller than 50-100.

•Upstream extension of backwater deposits is so serious that the safety of cities, industrial areas, etc. and the normal operation of existing large or medium-sized hydroprojects are affected.

•A mouth bar may occur at the confluence of a tributary with the main river, which may affect the function of regulation of the reservoir.

•Deposition at a dam area may affect normal operation of the inlet of intakes or the outlet structures.

•Fluvial processes induced by reservoir sedimentation (aggradation or degradation) may affect safety of existing works on the river.

Sedimentation may impede navigation on the river.

5. Operating Rules

Operating rules of reservoir operation have decisive influence on reservoir sedimentation as mentioned above.

Three basic types of operating rules have been adopted in China, namely impoundment, impounding the clear and discharging the muddy (I&D), and flood detention. The first two types are often adopted. In Table 5.l, some basic characteristics of reservoir operating rules are listed.

Table 5.1 Operating Rules of Reservoirs

No.	Operating rule		Regulation of sediment	Method of sediment sluicing	Period of sediment sluicing
A1	Impoundment	Sediment totally trapped	None	None or dredging	None
A2	Impoundment	Sediment partly trapped	None	Density current venting, sluicing	Beginning of flood season
B	Impounding clear and discharging muddy		Yearly or seasonally	Discharging sediment during detention, density current venting, etc.	Flood season
C	Detention			Discharging sediment during detention, reservoir emptying	Flood season

In Table 5.2 the annual rate of capacity loss of some reservoirs are shown. For the top five reservoirs built on sediment-laden rivers the rates were quite high during the impoundment stage. Therefore, the operating rule has been changed into I&D. Subsequently, the annual rate of capacity loss was reduced significantly. This shows how important the influence of reservoir operating rule is.

Table 5.2 Influence of Reservoir Operating Rule on Reservoir Sedimentation

Reservoir	Operating rule			
	Impoundment		I&D	
	Trap efficiency (%)	Annual rate of capacity loss (%)	Trap efficiency (%)	Annual rate of capacity loss (%)
Sanmenxia	92.9	6.7	0	0
Qingtongxia	64	17.4	0	-1.1
Zhengziliang	100	11.1	10	1.1
Heisonglin	100	6.3	21	1.3
Zhiyu	99	9.3	13	1.2
Liujiaxia	85	1.14		
Danjiangkou	100	0.26		

6 A Method of Increasing Sediment Sluiced through a Dam

6.1 Operating Rule of “Impounding the Clear and Discharging the Muddy (I&D)”

In the past many reservoirs built on heavily sediment-laden rivers were seriously silted up when they were operated under the operating rule of impoundment, as mentioned earlier.

When a reservoir is designed to be built on a heavily sediment-laden river, there exists an acute contradiction between keeping a large effective storage and sediment deposition in the reservoir. If the effective storage is designed too large and the reservoir is often operated under impoundment at high pool levels, reservoir sedimentation will develop fast and encroachment of the effective storage will be serious until the reservoir is silted up by sediment deposit.

If an appropriate portion of the effective storage of a reservoir is to be preserved, the reservoir is not only necessary to regulate the runoff but also to regulate the incoming sediment load to reduce the rate of sedimentation in the reservoir. Whether the effective storage of a reservoir could be preserved permanently should be considered as a key index to judge the success or failure of the planning and design of a dam built on a heavily sediment-laden river.

The main condition to fulfill this requirement is to draw down the pool level to a certain level in the flood season to facilitate sluicing the incoming sediment load. In most heavily sediment-laden rivers, the sediment load is more concentrated in the flood season than the runoff, as shown in Table 6.1. In the flood season the sediment load accounts for almost 90% of the annual sediment load, while in July and August the percentage may be as high as 80-90%.

This character makes sediment sluicing in the flood season possible. In the dry season when the sediment load is scarce, water is impounded for usage. This operating rule is called "Impounding the clear and discharging the muddy" (I&D).

Table 6.1 Percentage of Runoff and Sediment Load in the Flood Season (%)

Reservoir	Flood season		July and August	
	Runoff	Sediment load	Runoff	Sediment load
Liujiaxia	58		90	
Sanmenxia	59		84	
Guanting	55.9		85.7	
Naodehai	63	93		
Fenhe	61.4	96.3	39.8	78.0
Heisonglin	45	98	25.0	93.8
Zhenziliang	47.8	97	30.2	81.0

The prerequisites to adopt such an operating rule are as follows.

*Drawn down of the pool level in the flood season

For regulating sediment load the pool level has to be drawn down for sediment sluicing in the flood season. A specific pool level, sediment sluicing pool level, should be designed. In most cases, this pool level is set as same as the flood control level (FCL) of a reservoir. To achieve this goal adequate low outlets with enough discharge capacity should be built. Fig. 6.1 shows the hydrologic curves of the Honglingjin Reservoir. It shows that from June to August the pool level was lowered to El. 1110 for sediment sluicing. In this period not only the incoming sediment load was sluiced out of the reservoir but also previous deposits of 300×10^3 m^3 was eroded and flushed out of the reservoir.

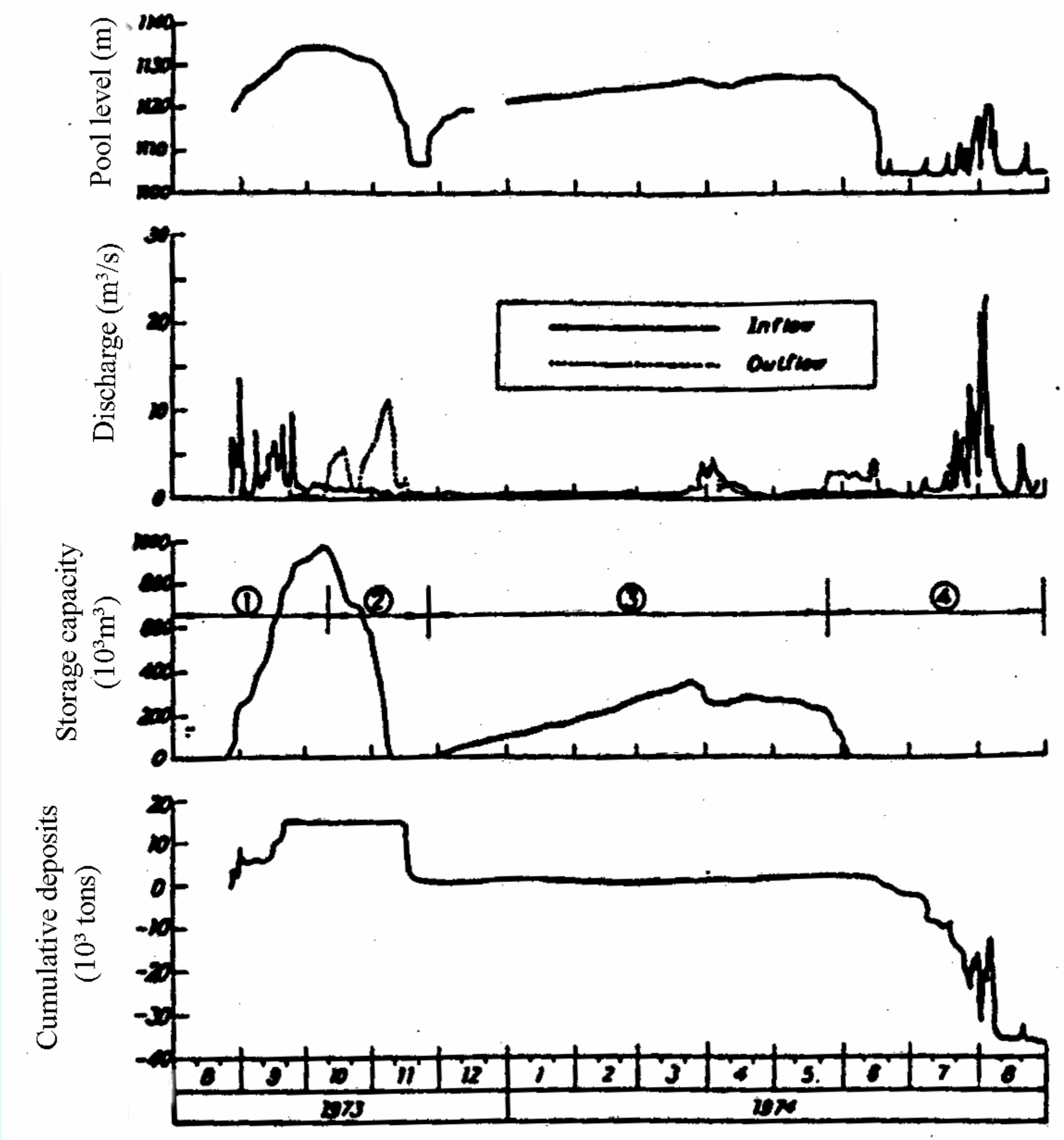


Fig. 6.1 Coordinated hydrographs of Honglingjin Reservoir

As the pool level is drawn down a certain amount, the regulation storage coefficient of a reservoir (the ratio of the effective storage to mean annual runoff) is inevitable small. For a long-period storage reservoir it is impossible to regulate the reservoir under such an operating rule. However, along with the development of reservoir sedimentation and the loss of a certain portion of the effective storage, the long-period reservoir may be finally turned into a reservoir of annual regulation. At this time the operating rule of the reservoir may be changed to the said one.

* Large difference between the natural river bed slope and the equilibrium slope of the alluvial channel eventually formed in the reservoir

During the sediment sluicing period, the whole or a part of the flood season, the annual sediment load should be sluiced out of the reservoir, so that a quasi-balance of deposition and erosion in the reservoir may be achieved. This requires that a difference between the natural river bed slope and the equilibrium slope of the alluvial channel eventually formed in the reservoir exists.

This difference originates from the surplus of sediment transport capacity of the river under natural conditions. If a river does not have such a surplus, then it is difficult for the reservoir to adopt the operating rule of I&D. An index of this prerequisite is the ratio of the equilibrium slope of the alluvial channel eventually formed in the reservoir (J) to the natural river bed slope (Jo).

The smaller the ratio, the larger the surplus of sediment transport capacity under natural conditions, the easier to adopt I&D operating rule. For the Sanmenxia Reservoir the ratio is 0.63-0.66 while for the Sanshenggong Reservoir in the upper reaches of the Yellow River the ratio is 0.91. Practice has shown that sediment sluicing of Sanmenxia is more feasible than that of Sanshenggong.

*This operating rule of reservoirs is particularly desirable for reservoirs of gorge-type. Under such a condition the equilibrium width of the alluvial channel eventually formed in the reservoir may be the same dimension as the natural river width. Thus, the percentage of the long-term preserved storage capacity may be large.

6.2 Essence of I&D Operating Rule

The essence of the I&D operating rule is to sluice the sediment load out of a reservoir in the flood season as much as possible by lowering the pool level to a designed level. In such a way a certain percentage of the reservoir storage can be preserved indefinitely. This is an old practice in the Aswan Dam on the River Nile, completed in 1902. As remarked by J. C. Stevens, "by this method of operation silting of the Aswan reservoir has been so far, and probable will be, entirely avoided" (Stevens, 1936).

Unfortunately, such an operating rule of reservoirs has almost been neglected for half a century. Only after reservoir sedimentation problem became acute in reservoirs built on heavily sediment-laden rivers, this operating rule has been seriously reconsidered as a possible measure to alleviate reservoir sedimentation.

6.3 Long-term Storage of a Reservoir

When equilibrium is reached, i.e. the incoming sediment load and the outgoing sediment load in a reservoir is equivalent, there will be no further deposition. The remaining reservoir storage is the long-term storage, which can be preserved indefinitely, as shown in Fig. 6.2.

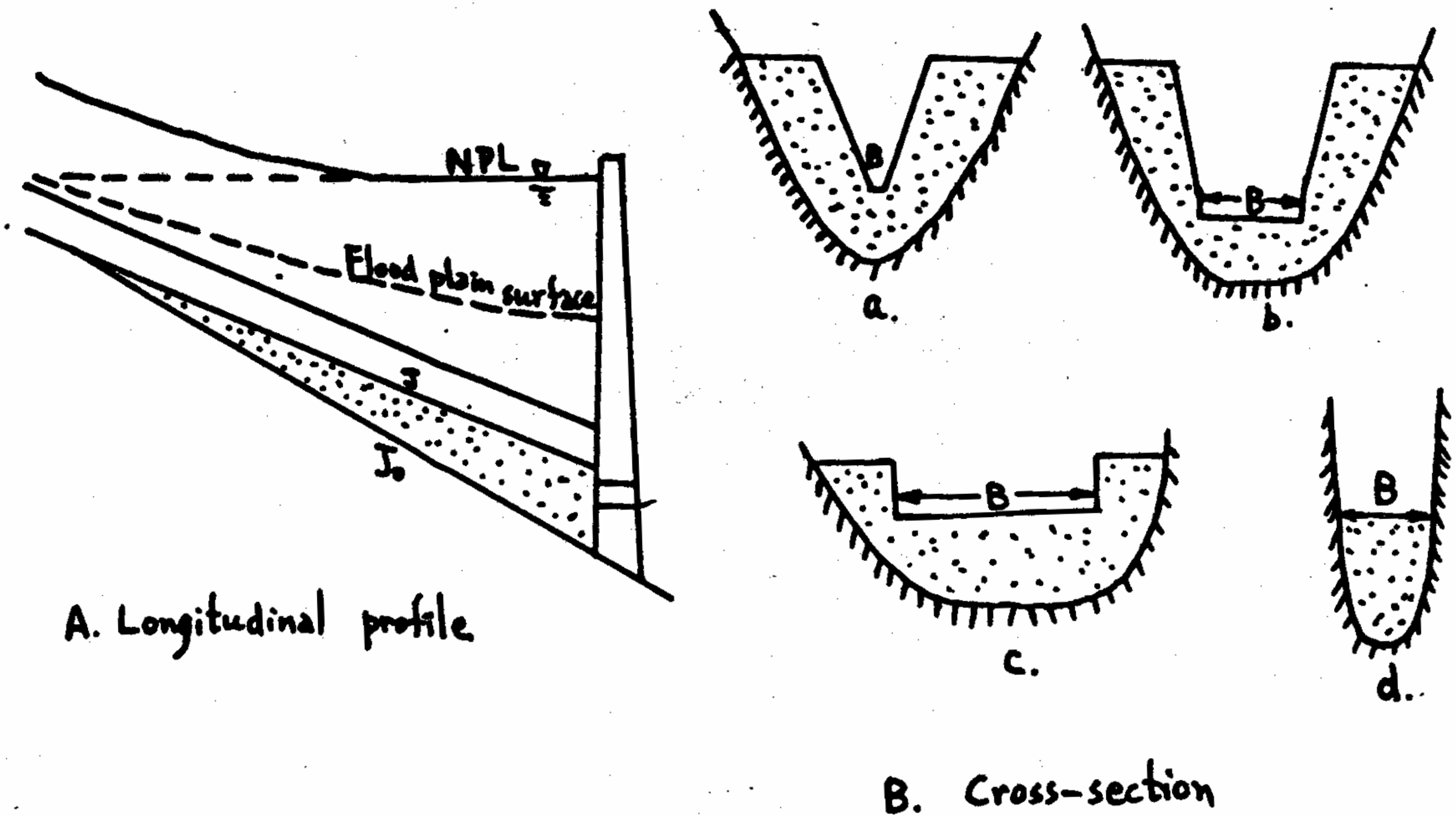


Fig.6.2 Sketch of terminal morphology in reservoirs

Adopting the operating rule of I&D, the ultimate morphology of the alluvial channel formed in the reservoir is a deep main channel and high flood plains. Deposition on the flood plains can not be recovered, but that in the main channel may be recovered and preserved. The long-term storage of a reservoir is mainly that in the main channel.

Fig. 6.3 shows the change of a cross-section in the Heisonglin Reservoir after heavy deposition of sediment during a large flood of 460 m^3/s on August 20, 1971. The main channel was fully deposited with sediment. However, after sediment sluicing the main channel was not only totally recovered, but also was deepened somewhat.

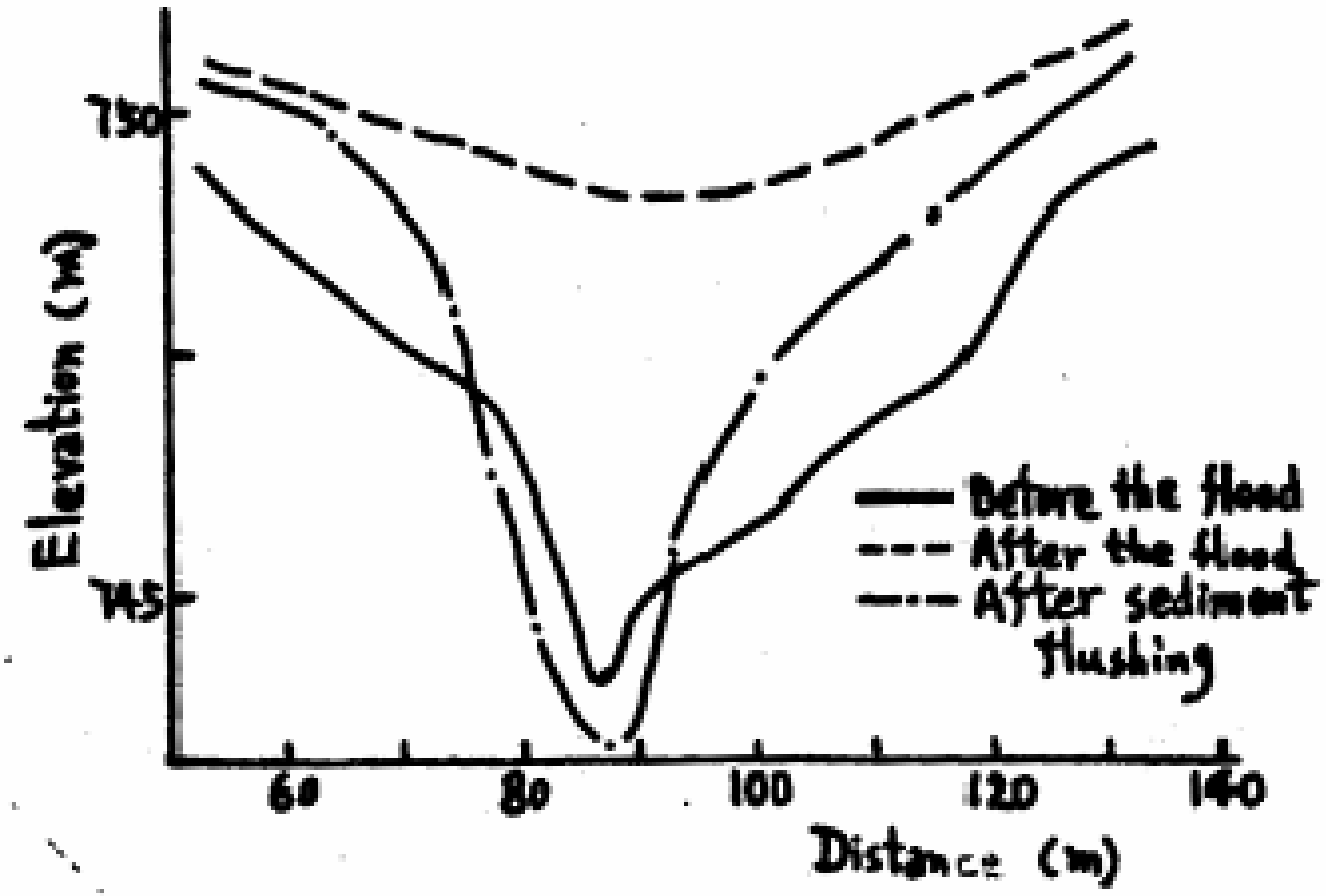


Fig. 6.3 Variation of a cross-section before and after a flood, Heisonglin Reservoir

Table 6.2 Long-term Storage of Reservoirs

(1)	(2)	(3)	(4)
Reservoir	Original storage ($10^6 m^3$)	Long-term storage (10^6 m^3)	(3)/(2) (%)
Sanmenxia	5930	2300-2600	39-44
Yanguoxia	220	60	27
Naodehai	168.3	100-120	59-71
Zhenziliang	36	4-5	11-14
Heisonglin	8.6	2.5-3	30-35
Baojixia	5.1	1.0	20
Honglingjin	16.6	3-4	18-24

Fig.6.4 shows plans of Naodehai and Zhenziliang Reservoirs. The long-term storage of the former accounts for (59-71)% of the original while the latter only (11-14)%. It is obvious that the topographic character of the former favors a large percentage of long-term storage capacity.

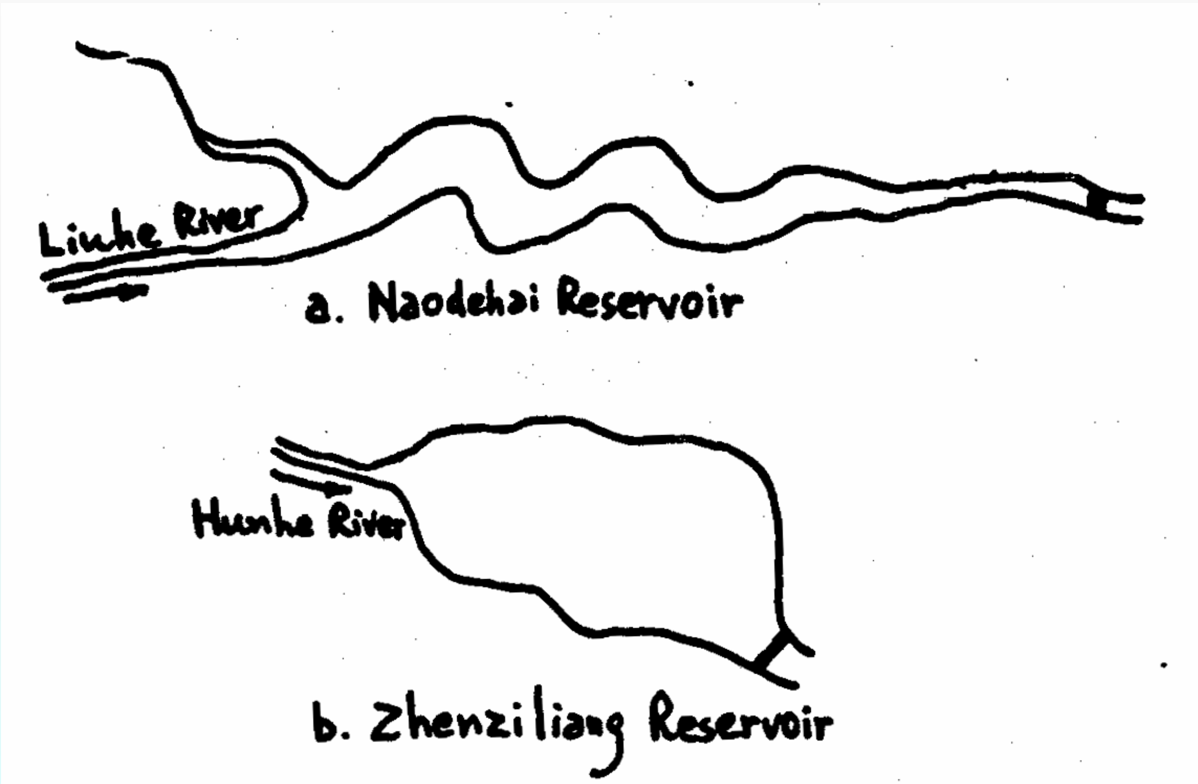


Fig. 6.4 Plans of Naodehai and Zhenziliang Reservoirs

6.4 Discharge Capacity of Outlets

For implementing the I&D operating rule and keeping a long-term storage capacity of a reservoir, low-level outlets with sufficient capacity are needed. Some empirical formulas have been derived for determining the capacity of outlets based on the practice in China. For example, Tsinghua University proposed the following formula for Q_s.

$Q_s=(30\text{-}50)\ Q_{fm}$

where Q_s-the discharge capacity of outlets,

Q_{fm}- the average discharge in the flood season.

There are also some formulas proposed by other institutes.

6.5 Limitations

The basic operating rules of reservoirs (Table 5.1) have their own field of application. If the operating rule of impoundment is adopted for a reservoir suitable for adopting the operating rule of I&D, the benefit of the reservoir may be high in a short term, but the long-term benefit of the reservoir will be reduced along with the loss of reservoir storage.

For a reservoir adopting the operating rule of I&D, there are some contradictions between various functions of the reservoir.

* Contradiction with power generation. To fulfill the demand of sediment sluicing, the pool level fluctuates significantly, resulting some problems. (1) Although the total energy output is larger in a long run, the annual energy output of a project will be reduced somewhat. (2) The water head in the flood season is reduced, so it is necessary to design a turbine with large discharge capacity to compensate the reduction of water head. (3) The variation of the water head in the reservoir is quite large, so the design of the turbine is more difficult than that under normal conditions. (4) As water flows with high sediment concentrations may pass the turbine, abrasion of the blades may be serious, resulted in the reduction of efficiency of turbines and life-span of the blades. (5) Choking of cooling water system by sediment particles may occur.

* Contradiction with irrigation. As sediment sluicing needs a certain amount of water, contradiction between sediment sluicing and irrigation may exists.

* Changes in the downstream channel. Reservoirs under I&D operating rule will alter the relationship between water flow and sediment load released from a reservoir, but the degree of alteration is not as large as that under the operating rule of impoundment. Almost clear water will be released from impounding reservoirs, resulted in channel degradation. If a reservoir is operated in two stages, impoundment in the first stage, followed by I&D in the second stage, the discharged sediment load will induce new problem in the river channel which has suited the conditions of clear water release.

7 Case Study—Three Gorges Project

From over 30 years operation and reconstruction of many projects built on heavily sediment-laden rivers, valuable experience in dealing with reservoir sedimentation has been gained. It indicates that even on heavily sediment-laden rivers such as the Yellow River, a certain reservoir storage capacity can be preserved permanently for multipurpose usage, if proper sediment sluicing arrangements and rational operating rule are adopted. The Three Gorges Project is selected as an example to elucidate the above-mentioned content.

The Three Gorges Project, located at Yichang on the Yangtze River (Fig. 7.1), is designed for flood control, power generation and navigation improvement with the priority of flood control. The construction started in 1994. After commissioned in 2009, it will be the largest multipurpose hydrosystem in the world. The main features of TGP are listed in Table 7.1 and its plan is shown in Fig. 7.2.

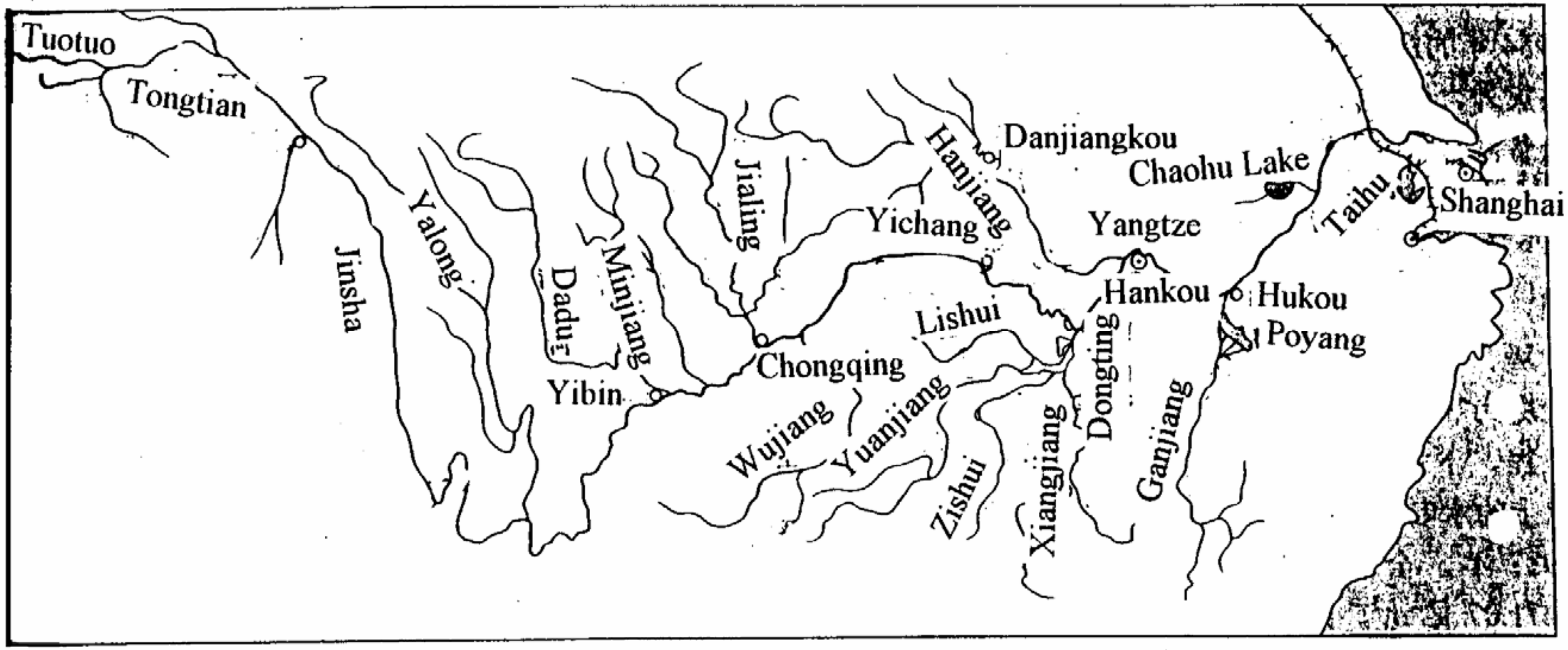
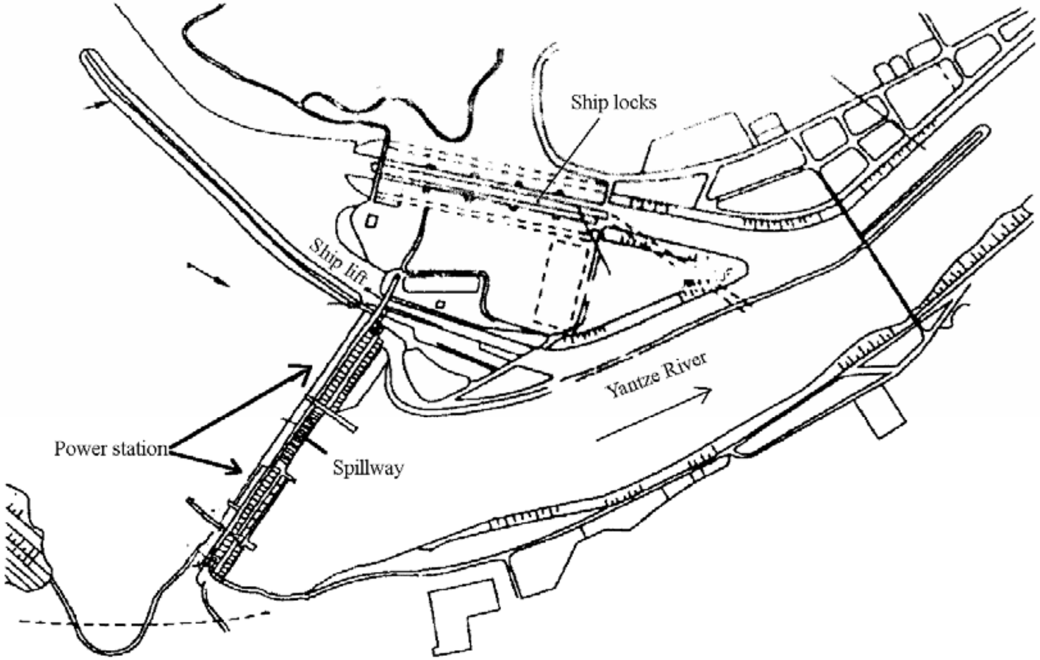


Fig. 7.1 Map of Yangtze River



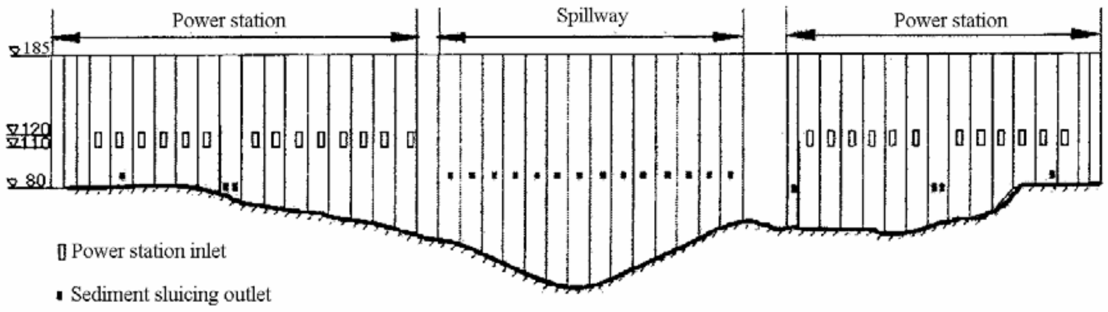


Fig. 7.2 Plan and sectional view of TGP

Table 7.1 Main Features of TGP

Item	Index
Dam height (m)	175
Crest elevation (m)	185
Reservoir	
NPL (m)	175
FCL(m)	145
DCL*(m)	155
Storage capacity (10^9 m^3)	39.3
Flood control capacity (10^9 m^3)	22.15
Surface area (km^2)	1084
Length (km)	700
Power station	
Installed capacity (MW)	26x700=18200
Average annual output (TWh)	84.68
Shiplock	
Dimensions of chamber (m)	280x34x5

*DCL- the dry-season control level

Although the sediment concentration is not large, the annual sediment load of the Yangtze is quite large due to the abundant runoff, standing as the third largest in the world. Table 7.2 shows the long-term averages of hydrological parameters of the Yangtze.

Table 7.2 Hydrological Parameters of the Yangtze

Station			Yichang*	Cuntan**	Wulong***
Catchment Area (10^2 km^2)			1006	867	83.0
Annual runoff (10^9 m^3)			439	350	49.0
Annual sediment load	Suspended load (10^6 t)		523 (d_m=0.023 mm)	460 (d_m=0.036 mm)	30.4
	Sediment concentration (kg/m^3)		1.20	1.32	0.638
	Bed load	Gravel (d>10 mm) (10^3 t)	758 (d_m=239 mm)	277 (dm=50 mm)	
		Sand (d=1-10 mm) (10^3 t)	250	10-30	

* 44 km downstream of the dam site

** At the upstream end of the reservoir

*** On the tributary, Wujiang River, joining the main stem in the reservoir region.

It is noted that during the flood season from July through September, the Yangtze carries 61 % of the annual runoff and 88.3 to 90% of the annual sediment load. Due to the large quantity of sediment load of the Yangtze, sediment problems are one of primary concerns in the planning and design, including preserving the long-term storage capacity. After extensive study the operating rule of I&D has been adopted.

According to this operating rule 3 pool levels have been determined and the rule curve of the TGP is shown in Fig. 7.3. The pool level of the reservoir will be lowered to the FCL during the flood season. This will provide storage for flood control and allow the incoming sediment load to be sluiced out of the reservoir.

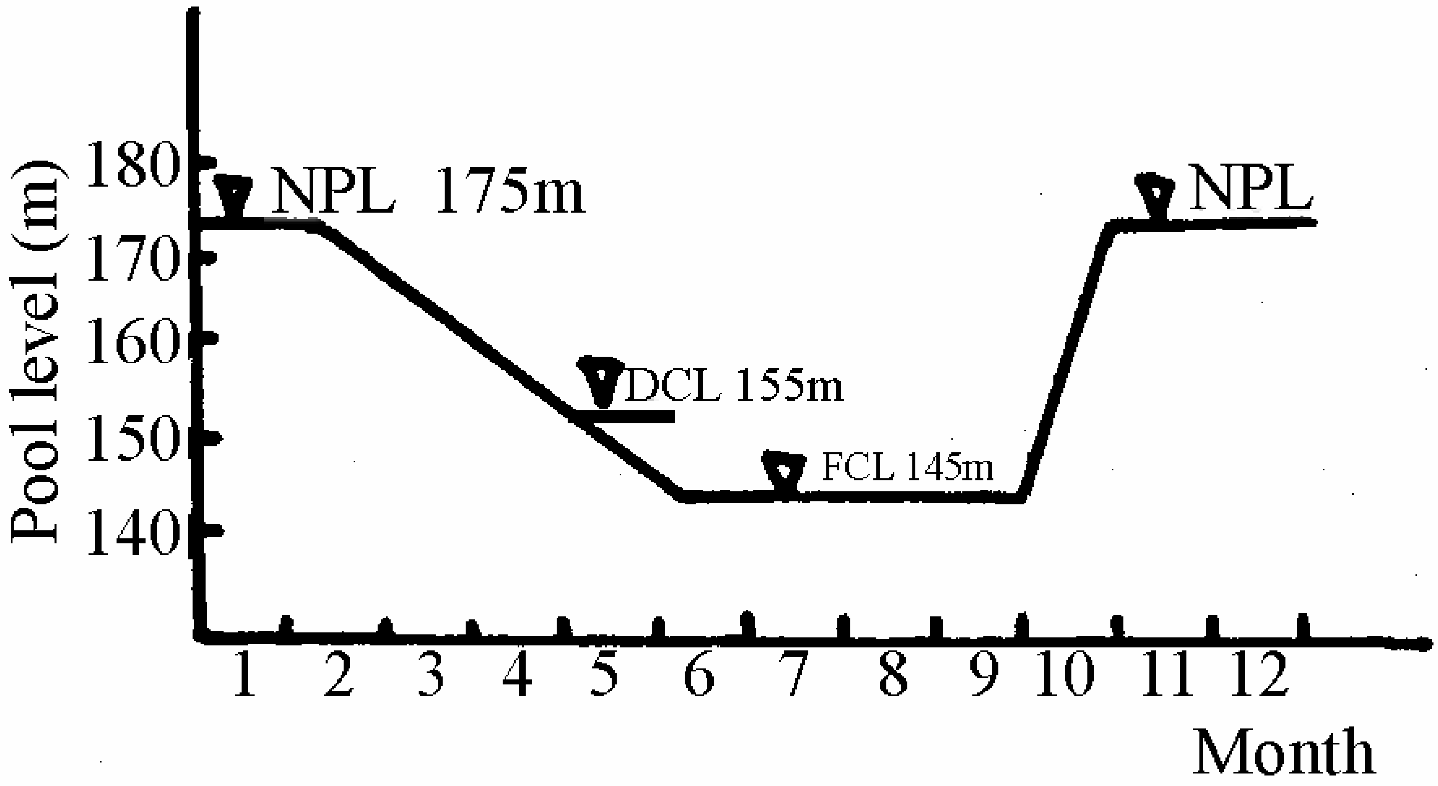


Fig. 7.3 Operating rule curve of Three Gorges Project

As mentioned earlier, a prerequisite for maintaining low pool levels during the flood season is an adequate discharge capacity of the outlet works. The TGP is equipped with many mid-level and bottom outlets that they possess great capacity of discharge at pool levels below the crest of the spillway set at El. 156. The discharge capacities at different pool levels are given in Table 7.3.

Table 7.3 Discharge capacities of TGP

(1)	(2)	(3)	(4)	(5)
Pool level (m)	Outlet	Spillway	Power plant	90% of [(2)+(3)
	(m^3/s)	(m^3/s)	14 sets (m^3/s)	+ (4)] (m^3/s)
130	37380		14400	46600
135	41400		14830	50610
140	44560		15340	53910
145	44990		15910	54810
150	47620		16420	57640
155	50100	0	16920	60320
165	52450	9470	16020	70150
175	558930	29060	14490	92230

The deposition process in the TGP reservoir has been investigated numerically by several 1-D mathematical models. The computed results of one schedule are shown in Fig. 7.4 and Table 7.4.

Table 7.4 Predicted Development of Deposition in TGP Reservoir

Item	Amount (10^9 m^3)	Percentage of storage capacity (%)	Trap efficiency (%)
Storage capacity	39.3		
Flood control capacity	22.15		
Trap efficiency			
in 10 yr			70.1
in 50 yr			47.3
in 100 yr			10.3
Volume of deposition			
in 10 yr	3.05		
in 50 yr	12.9		
in 100 yr	16.7		
Estimated at equilibrium	17.3	44.0	
Estimated preserved			
storage capacity	22.0	56.0	
Flood control storage		85.0	
Dry-season control storage		91.5	

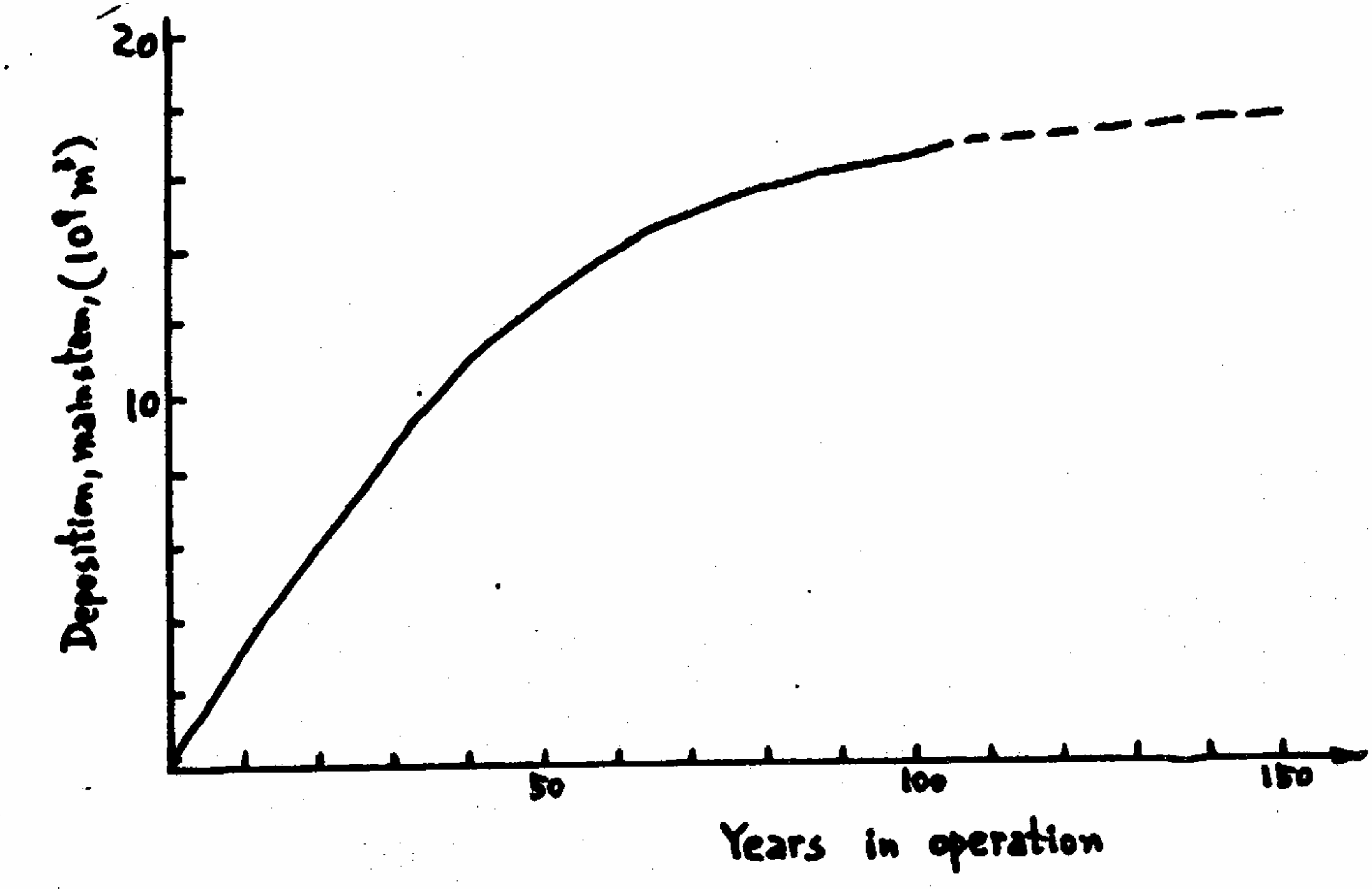


Fig. 7.4 Predicted development of deposition in TGP reservoir

From Fig. 7.4 one can deduce that deposition in the reservoir will approach its relative equilibrium state in some 150 years. Then, about half of the storage capacity will be preserved. As most of deposition will take place in the storage below FCL, which lose 72% and 79% of its original capacity in 100 and 120 years, the percentages of preserved flood control storage and dry-season control storage will be 85% and 91.5% of the initials, respectively. In other words, most of the flood control storage and dry-season control storage will be indefinitely preserved. From the same figure one can also noted that 90% of deposition takes place in the first 80 years.

The TGP has some special features in favor of adopting the operating rule of I&D. (1) The TGP reservoir looks like a ribbon in plan. The 700 km long reservoir is quite uniform in width and is less than 1000 m wide for most parts. Since the estimated width of the equilibrium channel corresponding to the hydrological conditions of the TGP is 1300 m, little flood plain is expected to form along the main channel in the reservoir. Thus, a large percentage of both the flood control and dry-season regulation storages may be preserved indefinitely. (2) Abundance of the runoff' of the Yangtze (ψ=0.098) provides surplus water in the flood season, which can be used for sluicing sediment and also provides enough water to be impounded in the dry season for power generation and navigation. (3) Fine suspended sediment of the Yangtze makes sluicing sediment easier than coarse one.

Since adopting such an operating rule, the power station of the TGP is to be functioned as a run-of-river power station in the flood season. It seems power generation will be affected. However, if the TGP adopted the operating rule of impoundment, sediment deposition would encroach the useful storage in some 70-80 years, then the power station will function as a run-of-river power station all the year round. In a long run adopting the operating rule of I&D is more favorable for power generation as the power station may be used permanently.

On June 1, 2003 the TGP started to impound water. On June 10 the pool level raised to 135 m from 70 m before the construction. Then, the pool level was kept at 135m (flood seasons) to 139 m (non-flood seasons) for about 3 years. The storage capacity was about 12-14 billion m^3 and the length of the backwater region was about 500 km. On Sept. 20, 2006 the pool level was raised up and reached 156 m on Oct. 20, 2006.

During the period of impoundment of the reservoir from June 2003 to the end of 2005 the incoming sediment load to the reservoir reduced significantly, the average annual sediment load was only 0.21 billion tons, accounting for 41% of the design. Thus, reservoir sedimentation was correspondingly reduced, only 0.377 billion tons of sediment deposited in the reservoir. Almost all the deposits were in the dead storage, no effect on the effective storage. Meanwhile, the trap efficiency was 60%, a little bit smaller than the predicted value (70%). The surface of deposits near the dam was raised to 47.7 m, faster than predicted and the thickness of the deposits was about 50 m. Although it is still far below the intakes of power stations, attention should be paid to its future development.

In summary, the TGP is a successful project in planning, design and construction. As a huge hydroproject there are still many problems to be studied and solved in order to make it functioned well.

Thanks!