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SEDIMENT RESEARCH FOR THE THREE GORGES PROJECT ON THE YANGTZE RIVER SINCE 1993

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Abstract: This article addresses sediment research carried out for the Three Gorges Project since 1993, when the construction of the Project was formally started. Emphasis of the research has been placed on the solution of relevant problems arising from design and construction of various structures, including sedimentation problems in the Chongqing reach; layout of the upper lock approach channel and ways and means to mitigate its deposition; increasing reservoir capacity by optimizing reservoir operation; compensating depth of flow required by navigation below the Gezhouba Project caused by scouring; mitigation of adverse effects of erosion on the reach from Zhicheng to Jiangkou; and evaluating scour of the Jinjiang reach caused by releasing flows of low concentrations from TGP. In addition, reduction of the sediment load entering into the reservoir area of TGP in the recent years as well as that expected of the projected construction of large hydropower stations on the Jinsha River upstream of the TGP reservoir is also noted and discussed.

Keywords: Three Gorges Project, Sediment load, Reservoir sedimentation, River degradation

1 INTRODUCTION

Preliminary research on sedimentation for the Three Gorges Project (TGP) was started in the 1950s. Large-scale and detailed research, however, was not taken up until the 1980s. Sedimentation is one of the 8 major technical topics dealt with in the feasibility study of the project. The principal sedimentation problems investigated in the stage of feasibility study and the main findings thereof have been summed up and presented by Lin *et al* .(1989). The highlights are as follows:.

(1) Numerical simulation showed that 85% and 91.5% of the flood-control and dry-season storages respectively may be preserved by employing a mode of reservoir operation designated as “discharging the turbid and impounding the clear”.

(2) The flood stage at Chongqing, a metropolis about 602 km upstream of the TGP dam, was given by mathematical modeling to be 199 m with a range of variation of 1m to 3 m either way for a 1% flood after the reservoir is put in operation for 100 years.

(3) Physical model studies indicated that a channel permitting the passage of 10,000 t may be expected to form in the fluctuating backwater region, but some training and dredging at minor scale would be needed here and there along the channel.

(4) The pier areas of shipping terminals may be kept clear of undesirable depositions by optimizing the operation of reservoir or employing regulating structures..

(5) As sediment finer than 0.01 mm will not settle in the reservoir and as there is a good supply of fine sediment in the 1,800 km of river downstream of the TGP, no serious impact of the TGP on the estuary is anticipated.

The construction of TGP was formally started in 1993. Since then, emphasis of research on sedimentation has been placed on the solution of relevant problems arising from design of

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various structures. Recent changes in sediment yield from the basin are also noted and studied. Construction of large hydropower stations on the Jinsha River upstream of TGP is being planned. Reduction of sediment load entering into TGP reservoir is also anticipated.

2 RECENT CHANGES OF INCOMING SEDIMENT LOAD

In recent years, the sediment load entering into the TGP reservoir has displayed a decreasing trend, instead of increasing as originally predicted by some experts back in the stage of feasibility study. The reduction of sediment load in the Jialing River is particularly noticeable (Table 1). As shown in Fig. 1, Beibei is a hydrological station near the exit of the Jialing River and Zhutuo is a station on the main stem of the Yangtze River marking the gateway to the TGP reservoir. Cuntan station is at a short distance downstream of the confluence of the Jialing and the Yangtze at Chongqing. Yichang station is at a short distance downstream of the TGP reservoir (Fig. 1).

Fig. 1 The Upper and Middle Yangtze River

Table 1 Sediment Load Entering into TGP Reservoir

Period of time	Item	Unit	Beibei	Zhutuo	Cuntan	Yichang
Before 1988	Average discharge	$m^3 \cdot s^{-1}$	2,220	8,510	11,100	13,900
	Sediment load	10^6t	136	315	460	523
1990-1998	Average discharge	$m^3 \cdot s^{-1}$	1,770	8,360	10,600	13,500
	Sediment load	10^6t	49	295	375	423

The reduction of annual sediment load at Beibei station amounted to 87×10^6t in the period from 1990 to 1998. During the same period, there was also a smaller reduction in sediment load at Zhutuo, amounting to 20×10^6t. Therefore, reduction of sediment load entering into the TGP reservoir in recent years is mainly due to the reduction of sediment yield from the basin of the Jialing River.

The main factors bringing about the reduction of sediment load in the Jialing River are taken as follows:

(1) Detention of sediment by reservoirs recently built on the Jialing River. For example, the total storage capacity of the Baozhushi and Fengtan reservoirs is about 4.2 billion m^3. These reservoirs have intercepted a considerable amount of sediment. In addition, altogether 16 navigational dams are presently planned on the Jialing. Of these, four have been completed.

(2) Reduced precipitation from 1994 to 1997. The decrease in the average annual runoff at Beibei station in this period was about 20% in comparison with the data available prior to 1988.

(3) Effect of extensive soil conservation works carried out on the Jialing Basin since 1989. .

(4) Dredging of considerable amounts of sediment from the riverbed to provide for the aggregate needed by the local booming construction industries. For instance, about 3.57×10^6 t of sediment were dredged from a 114 km reach in the lower Jialing River in 2002 alone.

Further studies are needed before one may establish the comprehensive trend of future runoff and sediment yield from the basin of TGP. For the time being, in order to be on the side of safety, the original data of sediment load and runoff stipulated in the feasibility study of TGP will be upheld in all sediment studies, while keeping a close watch on any possible permanent changes in the future.

3 IMPACTS OF RESERVOIRS PLANNED ON THE JINSHA RIVER ON SEDIMEMTATION IN TGP RESERVOIR

The National Planning Commission has decided to launch soon the construction of two large hydropower projects, namely, Xiluodu and Xiangjiaba, on the Jinsha River of the upper Yangtze. The total installed capacity of the two power plants is 18,600 mW with an annual energy output of 87.2 billion kWh. The main data pertaining to the two projects are presented in Table 2.

Table 2 Main Data of the Xiluodu and Xiangjiaba Projects

Item	Unit	Xiluodu	Xiangjiaba
Normal pool level	m	600.0	380.0
Flood control pool level	m	560.0	370.0
Dead storage level	m	540.0	370.0
Total storage capacity	10^9m^3	12.67	5.00
Regulating storage capacity	10^9m^3	6.46	0.9
Dead storage capacity	10^9m^3	5.11	4.07
Installed capacity	10^6kW	12.60	6.00
Power generation	10^9kWh	57.1	30.1
Period of construction	Year	12.2	9.5
People relocated	Person	39467	89,230
Cost	10^9yuan	44.6	29.0

Operation of the two projects would reduce sediment deposition in the TGP reservoir for scores of years. The results of mathematical modeling are given in Table 3 for three cases, namely (1). no project on the Jinsha River; (2) only Xiangjiaba is built; and (3) only Xiloudu is built. It can be seen that if either of the Xiangjiaba and Xiluodu projects were completed in 2013 as planned, sediment deposition in the TGP reservoir would be reduced by about 2.8 billion m^3in the former case and 4.1 billion m^3 in the latter case, respectively, in the 50^{th} year of operation of Xiangjiaba and the 60^{th} year of operation of Xiluodu..

Table 3 Cumulative Amount of Deposition in TGP Reservoir

Operational time of reservoir (year)	Cumulative amount of deposition (10^9m^3)		
	Case (1)	Case (2)	Case (3)
20	6.100	4.935	4.943
30	8.71	6.57	6.51
40	11.13	8.30	8.03
50	13.315	10.537	9.500
60	15.05	12.86	10.94
70	16.56	14.86	12.40
80	16.975	16.000	14.101
100	17.10	16.95	16.83

4 SEDIMENTATION PROBLEMS IN THE CHONGQING REACH

Studies have been carried out on sedimentation in Chongqing reach back in the stage of feasibility.

Prior to the construction of TGP, the Chongqing reach (Fig. 2) is in a state of annual equilibrium regarding sedimentation. Deposition in flood season would generally be balanced by scouring in dry season, so that by and large Chongqing is not affected by sedimentation on yearly basis. This phenomenon is related to two topographical features. Firstly, there is the narrow gorge Tongluoxia that severely restricts the flow at the exit of the Chongqing reach. Thus the stage in the Chongqing area fluctuates greatly when the river discharge changes. Secondly, the Chongqing reach contains alternately wide and narrow sections, so that the flow path changes in different seasons. In the flood season, flow upstream of Tongluoxia would be so much backed up that the flow velocities are much reduced and heavy depositions would take place in such slag water regions as those downstream of convex banks in bends and the enlarged sections of the river channel. During the dry-season, the stage of flow would drop by a large magnitude. As a result, the flow would experience large increase in velocity on the one hand and better follow the shoreline on the other. Both would lead to the scouring of deposits left by high water in the said regions of slag flow that formerly exist in the flood season.

Fig. 2 The Chongqing Reach in the Yangtze River

Annual balance in sedimentation is thus achieved in the reach of Chongqing and the port of Chongqing thus remains in substantially decent conditions as far as navigation is concerned. When TGP is built and operated, filling of the reservoir would generally begin on October 1st and reach 175m in the end of October. As a result, the time allowed for erosion of the reach would be shortened because the stage of Chongqing would be raised as a result of impounding the TGP reservoir. Thus the deposit occurring in the Chongqing reach during the flood season could no longer be entirely scoured away and shoals left around the shipping terminals during the flood season would later hinder shipping operations in the dry season.

Studies on measures to alleviate the said deposition have been carried out in recent years. One way to accomplish this is to postpone the timing for filling of the reservoir in order to prolong the time available for scouring of the deposit. In some cases, local modification of the shore line in the neighborhood of the wharf area may help ward off undesirable effects of deposition on shipping activities around the wharf.

5 LAYOUT OF DIKE FOR UPSTREAM LOCK APPROACH AND REMOVING OF DEPOSITION IN THE CHANNELS

Different layouts of the dike embracing the upper approach channel were studied on three physical models. These models employ different scales and different model sediment for mutual checking (Table 4). Boundary conditions at the up-and downstream ends of the models were provided by routing the sediment and flow discharges assumed at the inlet of the reservoir down to the ends of the physical models with mathematical modeling. Cuntan is taken as the inlet of the reservoir. The boundary conditions at Cuntan are composed mainly on the basis of cycles of the continuous series of hydrographs of flow and sediment discharges observed at Cuntan in the years of 1961 to 1970. To be on the side of safety, the flow and sediment hydrographs of the great flood of 1954 followed by those of the conventional year of 1955 are also artificially inserted in the boundary conditions at Cuntan at prescribed intervals as follows:

(1) Three cycles of flow and sediment data for 1961 to 1970 plus flow and sediment data for 1954 and 1955, covering a total period of 32 years. This boundary condition is designated as 30+2.

(2) Two cycles of flow and sediment data for 1961 to 1970 plus flow and sediment data for 1954 and 1955 are added to the foregoing boundary condition, covering a total period of 54 years. This boundary condition is designated as 50+4.

(3) The forgoing process is repeated to form the boundary condition covering a total period of 76 years. The resulting condition is designated as 70+6.

Table 4 Physical Models for the Neighborhood of the Dam

Institute	Changjiang Scientific Institute	Nanjing Institute of Hydraulic Research	Tsinghua University
Horizontal scale	150	200	180
Vertical scale	150	100	180
Reaches modeled	20 km above dam, 11 km below dam	19 km above dam, 10 km below dam	20 km above dam ___
Model material	Hard coal, s.g. 1.33	Bakelite, s.g. 1.41	Lucite, s.g. 1.053

After comparisons of different schemes, eventually, a scheme with a long dike embracing ship lock, ship lift and sluicing gate is adopted (Fig.3).

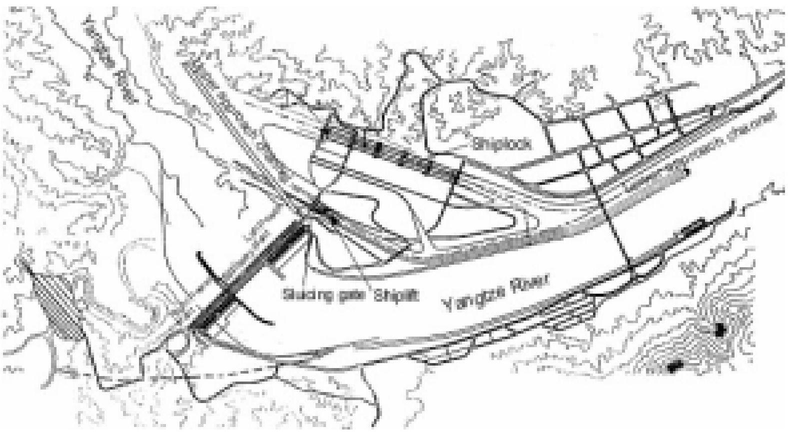

Fig. 3 Layout of the Three Gorges Project

Deposition in the approach channel (Table 5) is due to sediment carried by density currents and the reciprocating flows induced by operation of the ship lock of TGP. Model tests indicate that the amount of deposition in the approach channel increases with the operation time of the TGP reservoir, as shown in Table 5. In the years with heavy sediment load, the annual amount of deposition obstructing navigation may reach $2.0\times 10^6 m^3$-$2.2\times 10^6 m^3$, or as much as double the average value. That is more than what mechanical dredging can clean up in one season, taking into account also that placing the dredger in the path of navigation would interfere with shipping. Therefore, the scheme of hydraulic flushing with a sluice structure and two tunnels located between the ship lock and the ship lift has been studied. However, in the first 30 years of operation the amount of deposition in the approach channel is forecast to be quite small (Table 5), so that mechanical dredging should suffice to get rid of the deposition in the channel in the early stage of operation. Thus construction of the tunnels is to be postponed and only locations of the tunnels are reserved in design for the time being.

Table 5 Deposition in Approach Channel in Different Years Unit: 10^3m^3

Operation time (year)	Approach channel	Entry area
1-30+2	331	105
31-40	368	395
41-50+4	807	1,175
51-60	1,003	1,460
61-70+6	1,229	1,779

6 CONTROL OF RESERVOIR SEDIMENTATION

According to the design of TGP, its reservoir is to be maintained generally at the flood control level (FCL) of 145 m during the flood season as long as the total discharge from the dam through powerhouse and spillway does not cause the discharge at Zhijiang downstream of TGP to increase beyond 56,700 $m^3 \cdot s^{-1}$. When the flood arriving at the dam further increases, 1then the reservoir is to be impounded, but the total discharge at Zhijiang is still to be kept at 56,700 $m^3 \cdot s^{-1}$.

Recently, a new scheme for reservoir operation has been put forward by Lin and investigated in details by Zhou (Zhou, Lin & Zhang, 2000). It is proposed that as soon as a flood exceeding 40,000 $m^3 \cdot s^{-1}$is predicted at Cuntan, about 600 km upstream of the dam, the pool at the dam is to be lowered from 145 m (FCL) to 135 m at a discharge that again will keep the discharge at Zhijiang not exceeding 56,700 $m^3 \cdot s^{-1}$. The reservoir would then be scoured before the large flood arrives at the dam and raises the pool to whatever level called for by the need of flood equalization. If starting from the third year after the commission of TGP, this scheme were applied throughout the subsequent years, then mathematical modeling would show that in 100 years of reservoir operation the total deposition in the reservoir could be reduced from 16.4 to about 13.4 billion m^3, i.e. a deduction of about 3 billion m^3. This means a possible increase in effective flood control storage of about 5 billion m^3, if the storage between pool levels of 135 m and 145 m is also taken into account. This scheme is found particularly effective in reducing the deposition in the fluctuating backwater region. Thus by applying this scheme, deposition in Chongqing in 100 years of operation of TGP may be reduced by about 40%. A drawback in this scheme is that it would require suspension of the use of navigation locks for 5 to 7 days annually. As the river is impassable to the 10,000 t tows anyway when the discharge exceeds about 20,000 $m^3 \cdot s^{-1}$, suspending the use of locks at discharges exceeding 40,000 $m^3 \cdot s^{-1}$ may cause inconvenience to isolated boats only. This scheme is dubbed the DFCL or double flood control level scheme. A principle of early flushing is embodied in this scheme. For best results, it has to be employed not later than the 11th year after the commission of TGP. The later this scheme is put to use the less increase in the effective flood control storage it will result. A somewhat different scheme called the multiple flood control level scheme (MFCL) has also been proposed. Further studies on these schemes are under way.

7 CHANGE OF STAGE BELOW THE GEZHOUBA DAM

About 40 km downstream of the TGP is located the large hydropower development Gezhouba.. When the impounded reservoir of the TGP discharges flows at low sediment concentrations, the riverbed downstream of the Gezhouba dam will be subject to further erosion, causing the stage to drop, so that both the depth of flow over the sills of the lock chambers at Gezhouba and that in the channel downstream would become inadequate for navigation. Mathematical modeling has been applied to forecast the quantity of erosion in the river channel downstream of Gezhouba Project and the resultant changes of stages at Yichang Station (Table 6). Computations show that the natural stages at Yichang in various operation periods will always be lower than the values required by navigation. Measures recommended for the solution of the problem include the following:

(1) With the TGP reservoir filled to the pool elevation of 135m behind the coffer dam, the surcharge between 135m and 139m may be utilized in dry seasons to effect a temporary increase in discharge

(2) Paving the riverbed of some key reaches with artificial roughnesses may be adopted to prevent further erosion.

(3) Dredging the lower approach channel of the Gezhouba locks may be employed to increase water depth.

(4) Optimizing the operational scheme may help upgrade efficiencies of the navigation locks.

Table 6 Predicted Stages at Yichang Station

Pool level of TGP(m)	Yeas	Discharge in dry season ($m^3 \cdot s^{-1}$)	Stage required (m)	Stage predicted (m)
135	2007	3,200	38.0	37.2-37.7
156	2009	4,000	38.5	37.8-38.0
175	2012	5,000	39.0	38.3-38.4

8 EROSION IN THE REACH FROM ZHICHENG TO JIANGKOU

The reach from Zhicheng (67 km downstream of Yichang) to Jiangkou is the transition zone in which the Yangtze flowing in a hilly country with a gravel-sand bed changes to that flowing in a plain with a bed of fine sand. When the TGP is brought to operation, the scour in the reach with gravel-sand bed would be relatively slight, whereas in the reach of fine sand the degradation would be considerable. Changes to flow conditions undesirable to navigation would then take place in the transition zone where a swift flow with steep surface gradient and inadequate depth would prevail. Mathematical modeling predicts that in several years of operation of TGP under a discharge of 5,500 $m^3 \cdot s^{-1}$, the local surface gradient in the Lujiahe reach situated in the said transition could reach $(9\text{-}10) \times 10^{-4}$ and the velocities of flow there may reach 3.5 $m \cdot s^{-1}$-4.0 $m \cdot s^{-1}$. These all exceed the permissible limits set for navigation of 10,000 barge tows.

Measures proposed for the regulation of the reach are based on the results of model studies and include the following (see Fig. 4).

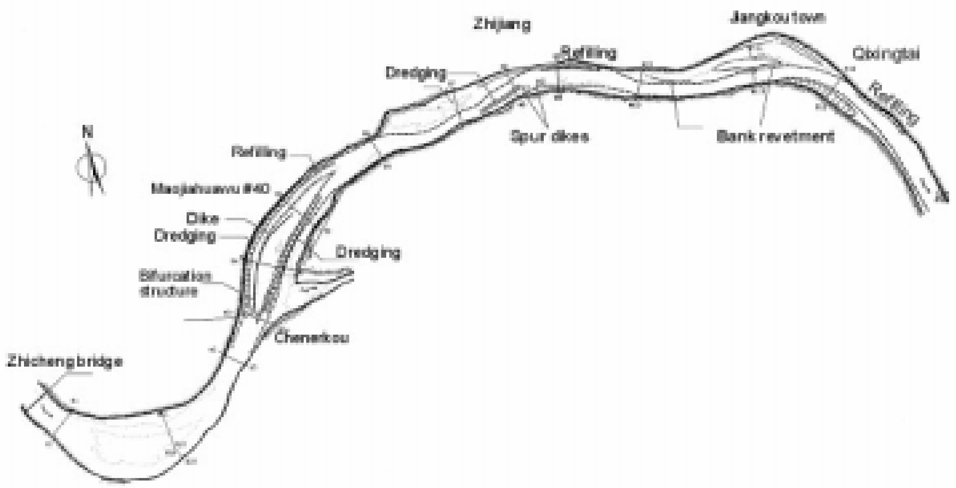

Fig. 4 Scheme of Channel Improvement in the Zhicheng-Jiangkou Reach

(1) Construction of revetment, spur dyke and others to help achieve a more stable river channel of small sinuosity.

(2) Elimination of the local steep reach of the river channel through dredging and filling so as to even out the gradient;

(3) Construction of a bifurcation structure at the entry of the reach to properly distribute the flows in the two branches in order to provide appropriate discharge and depth of flow required by navigation in each branch.

Results of physical model testing also indicate that by applying the regulating measures listed above a navigation channel 3.5m deep and 100m wide may be ensured even in the dry season and the said steep gradient and high velocities of flow may be eliminated.

9 IMPACT OF TGP ON THE MIDDLE AND LOWER YANGTZE RIVER

Operation of TGP will for a long time retain much of the sediment carried by the Yangtze in its reservoir and discharge ‘clear water’ in large quantities to the river system downstream. Flows of ‘clear’ water will naturally give rise to extensive changes in the fluvial processes downstream in the Middle and Lower Yangtze River. A large portion of the river channel downstream would then undergo cycles of scouring and refilling, accompanied by such changes in the river channel as broadening of the channel with increased incidence of bank caving and even changes in the plan forms of the river. Large riparian lakes connecting with the Yangtze, such as Dongting and Boyang Lakes, may also be affected either favorably or unfavorably. The foregoing problems are highly complicated and are still under investigation.

Assuming absence of changes in river pattern, the cumulative amounts of erosion and deposition in the reach between Yichang and Chenglingji predicted by mathematical modeling are given in Table 7.

Table 7 Cumulative Amounts of Erosion and Deposition in the Reach Between Yichang and Chenglingji

Unit：10^9t

Year	Erosion/deposition	Year	Erosion/deposition	Year	Erosion/deposition
10	-1.125	50	-2.454	90	-1.617
20	-1.981	60	-2.326	100	-1.499
30	-2.453	70	-2.025		
40	-2.504	80	-1.777		

Note: “-” signifies erosion and “+” signifies deposition.

10 IMPACT OF TGP ON RELATIONSHIP BETWEEN THE YANGTZE RIVER AND DONGTING LAKE

The section of the middle Yangtze from Zhicheng to Chenglinji is 347 km long and is usually called the Jingjiang River. There are three distributaries taking off from the mainstem Yangtze at Songzi, Taiping and Ouchi on the right bank of the Jingjiang River and emptying into the Dongting Lake. The outlet of the Dongting Lake to the Yangtze is at Chenglinji (Fig. 5). The diversion by the three distributaries may help alleviate floods in the Middle Yangtze River. However, the capacities of the distributaries have been much reduced in recent years, because of cutoffs carried out in the Lower Jingjiang River and construction of the Gezhouba Project upstream. Degradation upstream of the said cutoffs as well as that downstream of Gezhouba has led to the continuing drop of water level at the inlets of the distributaries and hence reduction in the flows they divert. Statistics indicates that, in comparison with the values in the years from 1955 to 1966, the annual flows diverted into the Dongting Lake in 1981-1998 had decreased by $64.5\times10^9m^3$ or 48.3%, while the annual sediment load diverted had decreased by 107×10^6t or 53.3%.

Subsequent to the completion of TGP, the conditions of the three distributaries with regard to diversion will be changed continuously due to erosion in the Jingjiang River. Mathematical modeling predicted the following:

(1) In the period of 30-40 years after completion of TGP, the distributary leading from Songzi will be eroded, but those from Taiping and Ouchi will be deposited.

(2) With the TGP in operation, the annual amount of water diverted into the Dongting will decrease markedly. Thus, in 41-50 years of operation, the annual runoff diverted will be reduced to (36.5-46.0) $10^9 m^3$, or 34%-48% less than the annual average value of 70.0×10^9 m^3 in the period of 1981-1998. The amount of sediment diverted will decrease to $(28\text{-}3) \times 10^6$t, a reduction of 60%-70 %.

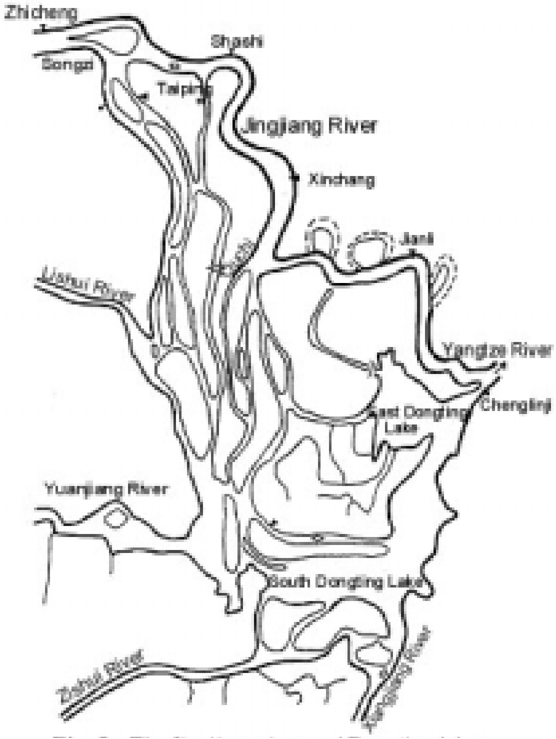

Fig. 5 The Jingjiang River and Dongting Lake

(3) The reduction in diversions by the distributaries will lead to an increase of flood flow in the Jingjiang River.

Further studies would be carried out to modify the strategy of flood control in the middle and lower Yangtze River and to work out the measures for the regulation of Dongting Lake.

11 CONCLUDING REMARKS

As was adopted in the past, an approach of combined mathematical simulation, physical modeling and analysis of field data has been employed in the studies leading to the material reported herein. Both physical and mathematical models used have been calibrated and verified by whatever field data presently available from the reservoirs and river channels in the nearby regions. Better verifications will be based on the field data collected on TGP itself, which calls for a large program of field data acquisition. For this purpose, a large sum has been appropriated. Data for the initial filling of the TGP reservoir to the elevation of 135 m has begun to flow in.

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