APPLICATIONS OF MATHEMATICAL MODELING TO SEDIMENT RESEARCH IN THE THREE GORGES PROJECT

Ying Tan[1]

ABSTRACT

Mathematical modeling has been extensively applied to sediment research of the Three Gorges Project (TGP). Since 1995 the major problems studied by mathematical modeling included: soil erosion and sediment yield, effect of reservoirs upstream on sediment load entering into the TGP, reservoir sedimentation, sedimentation in the Chongqing Reach, sedimentation in the neighborhood of dam, change of water stage below the Gezhouba dam, general degradation of downstream, fluvial processes of some key sections in the reach from Yichang to Chenglingji, impact of TGP on relationship between the Yangtze River and the Lake Dongting, and impact of TGP on the Lake Poyang, etc. A preliminary verification of 1-D mathematical models by the field data of 2003-2004 showed that the results calculated were in reasonable agreement with the measured when appropriate coefficient of sediment-carrying capacity was employed. Validity of forecast in sediment transport depends on both mathematical modeling technique and boundary conditions. Reliable field data and in-depth understanding of mechanism of sediment transport are essential for verification and improvement of mathematical modeling.

1. INTRODUCTION

The Three Gorges Project (TGP) is located at 44 km upstream of Yichang, China. The maximum height of the dam is 175 m, with a crest of 2309.5 m long on elevation 185 m. The reservoir created by the dam extends about 700 km long and has a total storage capacity of 39.3 billion m^3, of which 22.1 billion m^3 is reserved for flood control. Operation of TGP will give rise to many sedimentation issues, such as sediment yield and its control in the basin, reservoir sedimentation, sedimentation at the end of reservoir and in fluctuating backwater region, sedimentation in the vicinity of the dam, and effect of TGP on downstream, etc.

Preliminary research on sedimentation of TGP was started in the 1950s. Since the 1970s mathematical modeling has been extensively applied to sediment research and design of the TGP, achieving rich results. TGP initiated its impoundment in June 2003. After that a wide range of hydrological survey has been undertaken to obtain field data of sediment transport. These data have been used for verification of the mathematical models on prediction of sedimentation. This contribution attempts to provide an overview on applications of mathematical models to sediment research in TGP since 1995 and recent verification of the mathematical models. Some relevant issues are also raised for discussion.

[1] Secretariat General-Emeritus and Senior Engineer, International Research and Training Center on Erosion and Sedimentation, 20 West Chegongzhuang Rd., P.O. Box 366, Beijing 100044, China P.R.. Phone: 86-10-68413372 Fax: 86-10-68411174 Email: tany@iwhr.com

2. APPLICATIONS OF SEDIMENT MATHEMATICAL MODELING

Mathematical modeling has been extensively employed in studying sediment transport in TGP, including yield, transportation, distribution and management of sediment. The major problems studied by mathematical modeling and the brief computational results are as follows since 1995.

2.1 Soil Erosion and Sediment Yield

The Jinsha River (the upstream main stem of the Yangtze) and the Jialing River (the largest tributary of the Yangtze) are the major source of sediment, contributing 72.8% of sediment but only 48.6% of runoff. Since the 1980s large-scale soil conservation and river cascade development have been conducted in the Jialing River basin. Some large-sized reservoirs are being constructed on the Jinsha River now. These activities will remarkably change sediment load entering into the TGP. The hydrological survey indicated that since 1990 the sediment load entering into the TGP reservoir has displayed a decreasing trend. The reduction of sediment load in the Jialing River is particularly noticeable. The main factors bringing about the reduction of sediment load in the Jialing River are taken as follows: detention of sediment by reservoirs recently built on the river; reduction of precipitation; effect of extensive soil conservation works; and dredging of sediment from the riverbed for the local construction industries (Lin Bingnan et al., 2004). In the studies, some mathematical models were developed for estimating the effects of soil conservation works on soil erosion and sediment yield, such as:

(1) Artificial neural network model of runoff yield, soil erosion and bed load for typical small watersheds (Fang Duo et al., 2002),

(2) Model of runoff and sediment yields in the Qujiang and Xihanshui rivers (Xu Gaohong, et al., 2002), and

(3) BP (Back Propagation) neural network model of runoff and sediment yield in the Jialing River (Xu Quanxi, 2002), etc.

Combining the mathematical computation with analysis of observation data, it is concluded that about 18% of sediment reduction in the Jialing River resulted from the soil conservation works.

2.2 Effect of Reservoirs Upstream on Sediment Load Entering into the TGP

Two large hydropower projects, namely, Xiluodu and Xiangjiaba, are being constructed on the Jinsha River, with total storage capacities of 12.7 billion m^3 and 5.0 billion m^3 respectively. The Xiluodu dam locates 1180 km upstream from the TGP dam, and the Xiangjiaba dam 1023 km. Both projects will initiate impoundment in about 2013. After that the sediment load from the upper Jinsha will be firstly intercepted by the two reservoirs. The relative clear flow released from the reservoirs would immediately pick up sediment from the bed downstream, resulting in degradation of the downstream channel. Meanwhile sediment load in the flow would be gradually resumed. Three 1-D mathematical models have been employed in forecasting the sediment load entering into the TGP during the degradation processes:

(1) HELIU-2 developed by the YRSRI (Huang Yulin et al., 1997),
(2) MI-NENUS-3 developed by the IWHR (Han Qiwei, 1997), and
(3) QHXXS1 developed by TU (Yang Meiqin, 1997).

In these models armoring action on the surface of a non-uniform bed, the displacement of finer particles in the bed by the coarser deposited, the change in roughness in the process of degradation and consolidation of the deposited material have been taken into account.

The three models were tested by the natural data measured in the reach of 455 km long from Pingshan to Cuntan on the Jinsha, including sediment data in 1980-1984 for calibration, and water surface profile in 1991 and sediment data in 1985 for verification. The verification showed that the results computed tallied with the measured by and large. The error of water level at most points is smaller than +/- 0.2 m, error of annual suspended sediment load smaller than +/- 3-5% and error of annual bed load smaller than +/- 50%.

The results of mathematical modeling showed that if either of the Xiangjiaba and Xiluodu projects were completed in 2013 as planned, the sediment load entering into the TGP reservoir would be reduced by about 4.6 billion t in the former case and 10.4 billion t in the latter case, respectively, in the 30th year of operation of Xiangjiaba and the 60th year of operation of Xiluodu.

2.3 Reservoir Sedimentation

Reservoir sedimentation in the TGP has been studied numerically for a long time. In the 1970s two 1-D mathematical models, HELIU and MI-NENUS, were established respectively by YRSRI (Huang Yulin et al., 1990) and IWHR (Han Qiwei et al., 1990a). Both models are based on theory of non-equilibrium transport of non-uniform sediment. They can been employed for calculation of long-term deformation of river channel along long distance, including reservoir sedimentation and general degradation of river channel below a dam. In the 1980s both the models experienced verification by the field data from the Danjiangkou reservoir in 1967-1986 (Huang Yulin et al., 1990 and Han Qiwei, 1990b). The errors between measurement and calculation in MI-NENUS are: <1 m for water level, <11% for annual amount of deposition and <10% for accumulated deposition amount. The error for accumulated deposition amount in HELIU is 7.5%. HELIU was also verified by the field data from the Gezhouba reservoir in 1981-1987. The calculation value of accumulated deposition amount was 44% larger than the measurement. Calculations by both the models in 1988 indicated that 86% and 92% of the original flood and dry-season control storages respectively may be preserved, if an optimal operational mode, namely "Discharging the Turbid and Impounding the Clear" (DTIC), is employed. The water stage of 1% flood at Chongqing, a municipality at the end of TGP reservoir, was anticipated to be about 199 m, which would bring about a little influence on the city area. After that a series of improvement based on new results in research and observation has been employed in the both models. Now they have advanced to the HELIU-2 and MI-NENUS-3 respectively and applied to various computations in the TGP.

The above-mentioned calculations were based on the inflowing sediment load assumed in the preliminary design. Considering that the sediment influxes into the TGP reservoir will be obviously decreased by the upstream reservoirs, e.g. the Xiangjiaba and Xiluodu reservoirs as above-mentioned, the reservoir sedimentation in the TGP was recalculated recently by the HELIU-2 (Wan Jianrong, 1998) and MI-NENUS-3 (Wang Conghao et al., 1998). The computations indicated that the operation of either of the Xiangjiaba and Xiluodu reservoirs might reduce the sediment deposition in the TGP reservoir by about 2.8 billion m^3 (the Xiangjiaba, in the 50th year) and 4.1 billion m^3 (the Xiluodu, in the 60th year). And the water stage of 1% flood at Chongqing would be lowered by 1.5-2.0 m in 30th year.

Recently a 1-D mathematical model was developed by TU to study how to control reservoir sedimentation in TGP through optimizing the flood control level of the reservoir (Zhou Jianjun et al., 2004a).

2.4 Sedimentation in the Chongqing Reach

The Chongqing reach is comprised of four sequent bends and with a tributary, the Jialing river, emptying into it on the left bank. Prior to the construction of TGP, the Chongqing reach is in a state of annual equilibrium regarding sedimentation. Deposition in flood season would generally be balanced by scouring in the following dry season, so that by and large the Chongqing reach is not affected by sedimentation on yearly basis, and the port of Chongqing thus remains in substantially decent conditions as far as navigation is concerned. After TGP is operated, the reservoir would be generally filled to 175m in the end of October, causing the Chongqing reach to be impoundment area. As a result, the time allowed for erosion of the reach would be shortened. 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.

The problem is so important that four physical models and three 1-D and two 2-D mathematical models of sediment transport were concurrently adopted to study it. The mathematical models were developed by YRSRI (Huang Yue, 2005 and Zhang Jie, 2005), IWHR (Mao Jixin, 2005 and Fang Chunming, 2005) and TU (Zhou Jinajun, 2004b) respectively. Before usage these models were verified by the field data of water level, velocity and deposition of the Chongqing reach in 2003 and proved to be generally in accord with measurement. Combining the physical and mathematical modeling, the fluvial processes of the Chongqing reach under influence of impoundment were forecasted and some measures for alleviating the sediment problem in the Chongqing reach were worked out, including training works, local modification of the shore line, optimal operation scheme and dredging.

2.5 Sedimentation in the Neighborhood of Dam

The study on sedimentation in the neighborhood of dam mainly aimed at optimizing the layout of structures for navigation, flood discharging and power generation. It involves detailed flow characteristics and sediment transport under complicated boundary conditions. Importance and complexity of the problems call for the construction of three physical models for mutual checking. 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 1-D mathematical modeling (Huang Yulin et al., 1994).

Meanwhile, two mathematical models have been developed for supporting to and comparing with the physical model tests:

(1) 2-D mathematical model for suspended sediment by TU (Zhou Jianjun, 1995). It was used for calculation of unsteady flow, aggradation and degradation in the navigation channels of TGP;

(2) 3-D mathematical model for sediment transport in the dam area of TGP by NHRI (Lu Yongjun et al., 2004).

Besides, a 2-D mathematical model with consideration of density current was employed by IWHR for verifying deposition in the temporary navigation approach channel of TGP during construction period (Fang Chunming et al., 2004). The computed amounts of deposition can approximately match the measured values in 1998-2000.

2.6 Change of Water 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. Except three physical models, three mathematical models have been applied to forecasting the quantity of erosion in the river channel downstream of Gezhouba Project and the resultant changes of stages at Yichang Station, and to searching out the countermeasures:

(1) 1-D mathematical model of sediment transport in the reach of 146 km long from Gezhouba to Shashi by TU (Yang Meiqing, 2000), which was verified by the field data in 1980-1987,

(2) 2-D mathematical model of flow and sediment transport in the reach of 35.5 km long from Gezhouba to Yunchi by TRIWTE (Lu Yongjun, 2000), which was verified by the field data in

1980-1986, and

(3) 2-D mathematical model of flow and sediment transport in the reach of 22 km long from Gezhouba to Mopangxi by YRSRI (Dong Yaohua, 2000), which was verified by the field data in 1997.

Change of river channel and water stage below the Gezhouba dam was studied in the models. Some training works for the reach were proposed based on the studies.

2.7 General Degradation of Downstream

The Yangtze River extends for about 1800 km from TGP dam to the estuary. According to the results of mathematical modeling, in the first 12 years of operation of TGP, on the average, only about 30-40% of the incoming sediment load would be discharged from the reservoir. There is then a surplus of capacity for sediment transportation and the flow released would immediately pick up sediment from the bed downstream of the dam, resulting in degradation of the downstream channel. It was estimated that the degradation would spread to Datong, 1123 km from the dam (Fig.1).

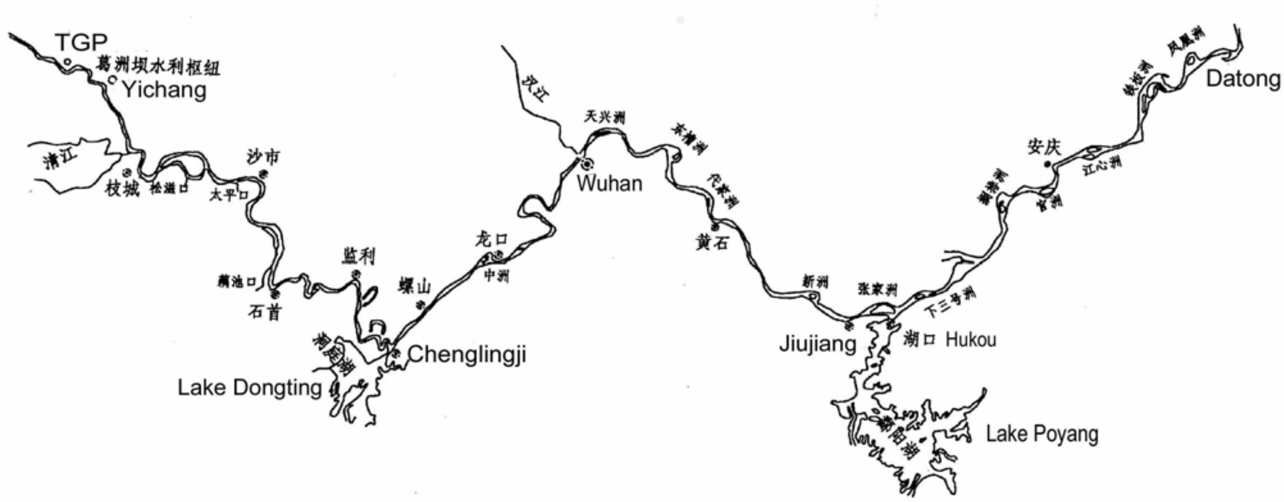

Fig.1 Downstream of TGP

The general processes of degradation downstream have been investigated by the 1-D mathematical models: HELIU-2 of YRSRI (Huang Yue et al., 2000a) and MI-NENUS-3 of IWHR (Mao Jixin et al., 1998). Before computation both models were verified by the field data of water surface profile and deposition and erosion in the middle and lower Yangtze from 1980 to 1987. The error of accumulated erosion/deposition amount in different reaches in the verification is listed in Table 1. There is the smallest error in the first reach from Yichang to Chenglingji, so the computational results in this reach would be more reliable than in others. The computation indicated that the degradation amounts in most reaches are close to each other in the two models, but the degradation processes develop faster in the HELIU-2 than in the MI-NENUS-3. The degradation processes computed by HELIU-2 (Fig. 2) showed that at a given section, degradation would reach a maximum in a certain time and then refilling of the bed would follow.

The above-mentioned results were based on the inflowing runoff and sediment load assumed in the preliminary design. Considering the effect of the upstream reservoirs (e.g. Xiangjiaba and Xiluodu), the computation of two models indicated that the amounts of degradation would increase and the duration of degradation would be prolonged. For example, the maximum amount of degradation in the reach from Yichang to Datong would be increased by 10%, and its corresponding time delayed for 10 years due to operation of either of the projects (Mao Jixin et al., 2000 and

Huang Yue et al., 2000b).

Table 1 Error of Accumulated Amount of Deposition/ Erosion in Verification

Model	Yichang-Chenglingji (393Km) Erosion	Chenglingji-Wuhan (230Km) Deposition	Wuhan –Datong (500Km) Erosion
HELIU-2	+ 4.2 %	+ 5.8 %	-15.0 %
MI-NENUS-3	+1.5 %	+ 40.3%	-19.5%

Note: $\text{Error} = \dfrac{\text{Calculation - Measurement}}{\text{Measurement}}$

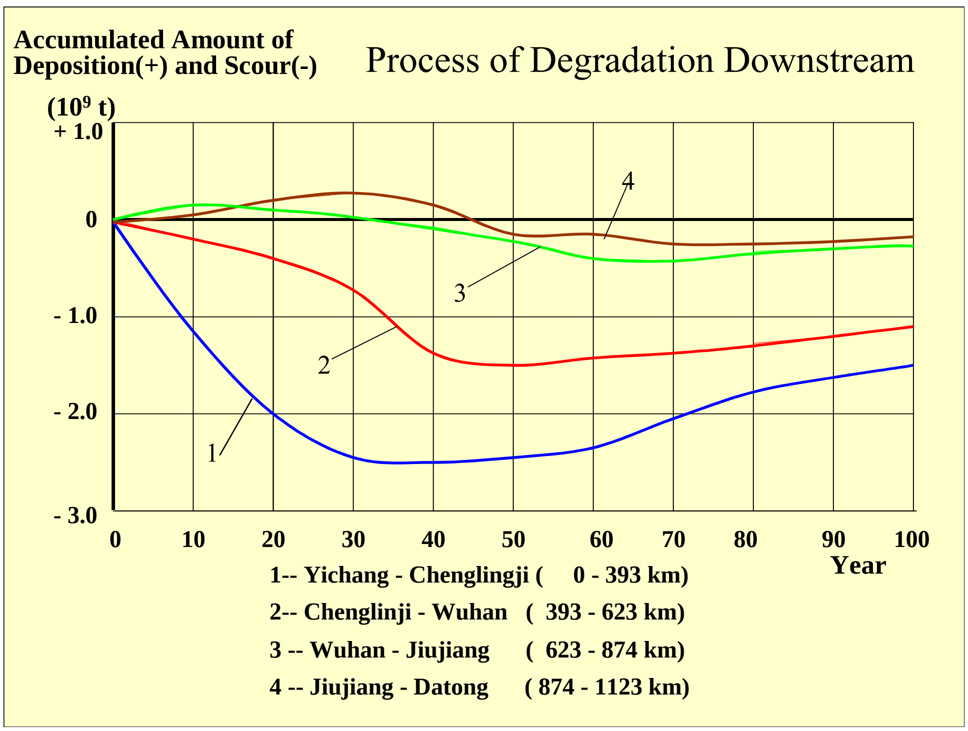

Fig. 2 Degradation Processes of Downstream

2.8 Fluvial Processes of Some Key Sections in the Reach from Yichang to Chenglingji

After impoundment of the TGP, the most significant changes of downstream channel would occur in the reach from Yichang to Chenglingji, which is close proximity to the dam and is immediately subjected to the new hydrological and sediment processes remolded by the dam (Fig. 3). These changes would give rise to great impacts on navigation and flood control security and should be researched in details. So 2-D mathematical models have been developed and employed in the studies of some key sections in the reach.

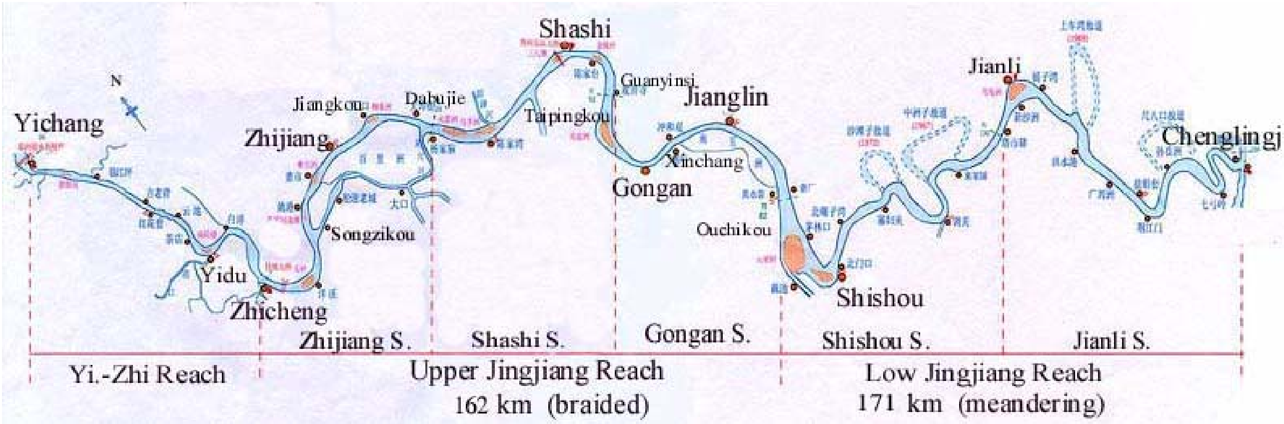

Fig. 3 The Reach from Yichang to Chenglingji

2.8.1 The section from Zhicheng to Dabujie (52 km long)

The section from Zhicheng (60 km downstream of Yichang) to Dabujie is located at the middle of the reach from Yichang to Shashi of about 150 km long. It 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, resulting in flow conditions undesirable to navigation in the transition zone: a swift flow with steep surface gradient and inadequate depth. The fluvial processes of the section from Zhicheng to Dabujie are related closely to evolution in the whole reach from Yichang to Shashi. Therefore, two coupling 1-D and 2-D models were employed in the study:

(1) Coupling 1-D and 2-D mathematical model for gravel-shoal reaches developed by CWB and WU (Gao Kaichun, et al., 2000), and

(2) Coupling 1-D and 2-D mathematical model for training of shoal reaches developed by TRIWTE (Lu Yongjun, 2000b).

In both models the 1-D model was applied to the reach from Yichang to Shashi, and the 2-D model to the section from Zhicheng to Dabujie. Before computation, the CWB model was verified by the field data in 1988, 1995 and 1999, and the TRIWTE model was verified by the field data in 1981-1987, 1988 and 1995. Calculation of the two models, combining physical model tests, predicted that in several years of operation of TGP, under a discharge of 5500 m^3/s the local surface gradient in the section situated in the said transition could reach $9\sim10\times10^{-4}$ and the velocities of flow there may reach 3.5~4.0 m/s. These all exceed the permissible limits set for navigation of 10,000-ton barge tows. Based on the results of model studies, some measures for regulation of the section were proposed.

2.8.2 The section from Jiangkou to Guanyinsi (66 km long)

The section from Jiangkou (120 km downstream of Yichang) to Guanyinsi is a slight meandering-bifurcated river section, comprising three bends and four bifurcated subsections. There is a tributary (Zuzhang River) emptying into the Yangtze on the left bank, and a distributary (Hudu River) taking off from the Yangtze at Taiping on the right bank.

A 2-D mathematical model of sediment transport was employed by YRSRI in studying channel processes in the section (Fan Beilin et al., 2000). The model was verified by the field data of water level, velocity and amount of degradation and deposition in 1986-1991. The error between computed and measured amounts of degradation and deposition in whole section was smaller than

8%. The model forecasted the alternation of main channel and branch channel, and the changes of the cross-sections and hydraulic conditions. It indicated that during the first 30 year of operation of TGP, the main channel would be eroded with average scouring depth of about 2-6 m and maximum 12 m, and the floodplain would be silted with average deposition of 1-3 m thick.

2.8.3 The section from Guanyinsi to Xinchang (55 km long)

The section from Guanyinsi (186 km downstream of Yichang) to Xinchang is comprised of two bends and one bifurcated subsection. A 2-D mathematical model of sediment transport was employed by IWHR in studying the problem in this section (Fang Chunming, 2000b). The model was verified by the field data in 1980-1987, getting a reasonable agreement between them. Calculation of the model indicated that serious degradation would occur in the channel of the section, with maximum local scouring depth of about 13 m in 30 years of operation of the TGP.

2.8.4 The section from Ouchi to Jianli (77 km long)

The section from Ouchi (222 km downstream of Yichang) to Jianli is a meandering river, comprising three sequent bends. There is a distributary (Ouchi River) taking off from the Yangtze at Ouchi on the right bank. The FLUVIAL-12 model developed and programmed by H. Howard Chang was applied by the YRSRI to studying variation of river channel in the section (Dong Yaohua et al., 2004). FLUVIAL-12 is a 1-D unsteady flow and sediment mathematical model with consideration of bank erodibility and curvature effects. Before calculation the researchers in YRSRI had made a few simple modification on some modules to adapt it to the condition in the Yangtze. Verification of the model by field data in 1987-1991 indicated that the model achieved reasonable agreements with the observation in terms of flood stage, sediment transport rates, erosion-deposition processes and river bed deformation. The computation predicted that within the 60-year period of TGP operation, the Ouchi-Jianli section would experience four sequent fluvial periods: slight deposition, substantial degradation, transient equilibrium and slow recovery. The average scouring depth would be 3-9 m, and the maximum drop in flood stage would be 3.1-4.7 m for 5,000 m^3/s and 0.4-2.8 m for 30,000 m^3/s respectively.

2.9 Impact of TGP on Relationship between the Yangtze River and the Lake Dongting

The section of the middle Yangtze from Zhicheng to Chenglingji is 333 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 Lake Dongting. The outlet of the Lake Dongting to the Yangtze is at Chenglingji (Fig. 4). 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. After operation of TGP new changes would occur in the river-lake system. Because there exists a crisscross network of rivers and lakes in this area, forming a very complicated situation of flow and sediment transport, three models of river network were established for studying variation of flow and river channel caused by TGP:

(1) 1-D flow-sediment mathematical model for coupling system of rivers and lakes developed by YRSRI (Gong Ping et al., 2000).

Calculation for a single river was implemented by 1-D model, but for river network the continuity conditions of discharge and momentum were added to the nodes. The model was verified by the field data from main hydrological stations in this area in 1995. The computed values are in general agreement with observation in terms of level-discharge relation, discharge processes in the three distributaries and annual sediment load.

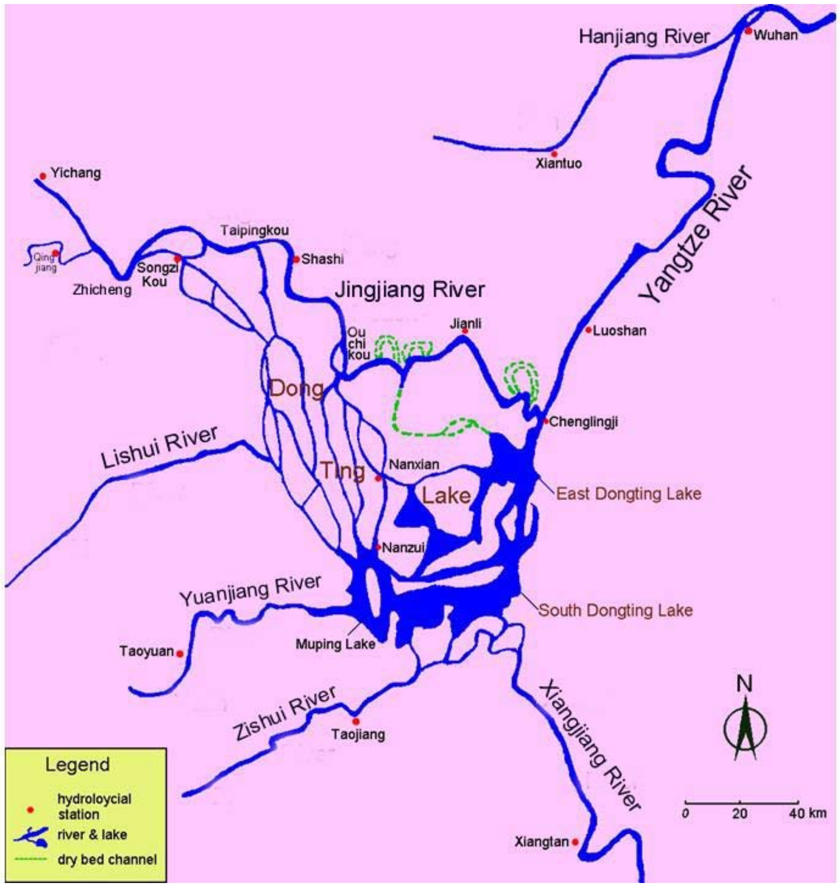

Fig. 4 The Jingjiang River and the Lake Dongting

(2) 1-D flow-sediment mathematical model for river network developed by IWHR (Fang Chunming, 2000a).

Continuity conditions of discharge and water level were added to the nodes. The model was verified by the field data of 1953-1976 in the Ouchi river system. The calculated values of water surface, discharge, amount and distribution of degradation/deposition are in general agreement with the measured.

The above two models anticipated that subsequent to the completion of TGP the degradation in the Jingjiang River would cause stages at the inlets of the distributaries leading to the Lake Dongting to gradually drop for many years. 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. In 41-50 years of operation, the annual runoff diverted into the Dongting will be reduced to $36.5\text{-}46.0\times10^9$ m^3, or 34-48% less than the annual average value of 70.0×10^9 m^3 in the period of 1981-1998, and the amount of sediment diverted will decrease to $28\text{-}38\times10^6$ t, a reduction of 60-70 %. The planned new development on the Jingsha River upstream of TGP would prolong this process for many additional years.

(3) 1-D mathematical model of unsteady flow and sediment transport in the Lake Dongting area developed by WU (Li Yitian et al., 2000).

Computational area of the model includes 64 river reaches and 44 nodes. Water level-discharge relation at hydrological stations measured in 1983 and sediment load emptying into and taking off the Lake Dongting measured in 1980-1983 were used for a preliminary verification of the model, getting a general agreement. The model predicted the degradation amount in the

Jingjiang river channel and decrease of deposition in the Lake Dongting after decades of operation of TGP.

2.10 Impact of TGP on the Lake Poyang

The Lake Poyang, with a total storage capacity of 32 billion m^3, is the largest lake of fresh water in China. It connects with the Yangtze at Hukou (about 900 km downstream of Yichang). The water flow and sediment load move from the lake to the Yangtze in most months when the water stage in the lake is higher than in the Yangtze. However, the flow may be in opposite direction during July – September when the Yangtze transports flood and has higher water stage than the lake. A 2-D mathematical model for unsteady flow and sediment transport was developed by NHRI to study this complicated flow area (She Mingfu, 2000). The model was verified by water stage measured in 1981 and deposition distribution in 1981-1987, achieving a general agreement between computation and field data. The model anticipated that the change of the Yangtze channel caused by TGP would give rise to slight impact on the Lake Poyang, especially in the first 30 years of operation of TGP. The flood discharging from the Lake Poyang, however, would be immediately influenced by regulation of runoff in operation of TGP. The pool level in TGP reservoir should be drawn down to the lowest level for preparation of storing flood during May-June, which is just the flood season of the Poyang area. The released discharge from the reservoir is larger than the natural value. As result, the water stage at Hukou in the Yangtze would be 1-2.4 m higher than the natural value, leading the flood discharging from the Poyang area to be choked up.

The above-mentioned applications show that mathematical modeling has been playing an important part in the sediment research of TGP. For certain cases, mathematical modeling is the only available predictive tool: (i) Assessing long-term sediment transport and fluvial processes along long distance. For example, the calculation of channel evolution from Xiluodu to Datong covered aggradation in reservoirs and general degradation in downstream channel, extending for about 2000 km. In so wide range it is impossible and impracticable to employ other forecasting approaches than 1-D mathematical model; (ii) Providing boundary conditions for physical model or multidimensional mathematical model of shorter river reach. For other cases, mathematical modeling is one of the effective approaches. Due to complexity and importance of the problems involved in sediment research of the TGP, it is often to study one problem by using concurrently several approaches, including mathematical models, physical models and analysis of field data, which were conducted by different researchers in different institutions. Comparison among the various possible results from different approaches could reach more reliable prediction and increase the faith in decision-making, although this may be time-consuming and involve higher cost. Among various approaches the mathematical modeling might be usually the fastest and cheapest one.

3. VERIFICATION OF MATHEMATICAL MODELS

All the mathematical models, before used for prediction of sediment transport in the TGP, have been verified by whatever field data available from the reservoirs and river channels in the nearby regions or from the natural Yangtze. Better verification should be based on the field data collected on TGP itself. The TGP reservoir initiated its impoundment in June 2003. Since then the pool level has been keeping at elevation of 135-139 m, forming a reservoir with storage capacity of about 12 billion m^3. Comparing with the natural value, the water level in front the dam has been raised by about 70 m.

A wide range of field data acquisition has been undertaken for investigating the real status of aggradation/degradation in upstream and downstream of the TGP and for verifying the mathematical and physical models. To date most of the models have been tested by the field data in 2003-2004. The following is a briefing on the preliminary verification of 1-D mathematical models (HELIU-2 and MI-NENUS-3) by the field data in 2003-2004. The 1-D mathematical models have the most extensive application and play crucial role in sediment research of TGP.

Both the models are based on non-equilibrium transport of non-uniform sediment, having the same or similar basic equations: flow continuity, flow momentum, sediment continuity (diffusion), sediment-carrying capacity, and bed deformation etc. (refer to Han Qiwei et al., 1990, 1997 and Huang Yulin et al., 1990, 1997). But for the empirical relations used in both models, some are the same, and some different, as follows.

(1) Values of parameters in suspended load transport, e.g. coefficient K and exponent m in sediment-carrying capacity and recovery coefficient α in the equation of continuity of suspended load:

$$S^* = K\left(\frac{U^3}{H\omega}\right)^m \tag{1}$$

$$\frac{\partial(QS_i)}{\partial x} + \frac{\partial(AS_i)}{\partial t} + \alpha B(S_i - S_i^*)\omega_i = 0 \tag{2}$$

where S^* is the critical sediment concentration representing sediment-carrying capacity; U is the mean velocity; H is the mean water depth; ω is the sediment fall velocity; ω_i is the sediment fall velocity of size class i; Q is the discharge; A is the cross-section of flow; B is the channel width; S_i is the sediment concentration of size class i; $S_i{}^*$ is the sediment-carrying capacity of size class i; x is the longitudinal coordinate; and t is the time. The values of K, m and α were determined by observed data in each case, as in Table 2.

Table 2 Values of K, m and α in Eq. (1) and (2)

Model	K	m	α
HELIU-2	0.02-0.03 (deposition) 0.0175-0.020 (degradation)	0.92	0.25 (deposition) 1.0 (degradation)
MI-NENUS-3	0.02-0.03 (deposition) 0.0145-0.020 (degradation)	0.92	0.25 (deposition) 1.0 (degradation)

(2) Variation of roughness during the process of degradation and deposition

HELIU-2 – linear variation between n_0 (roughness before deposition) and n_k (roughness in equilibrium).

MI-NENUS-3 – nonlinear variation between n_0 and n_k.

(3) Method for calculating sediment-carrying capacity of non-uniform sediment

HELIU-2: The gradations of suspended load and deposited material are calculated by relevant empirical equations separately for deposition and degradation cases.

MI-NENUS-3: Different equations are presented separately for three cases of sediment transport: (i) substantial deposition, (ii) substantial degradation, and (iii) slight deposition and degradation.

(4) Each model has its own empirical relation of bed load discharge.

(5) Others.

The range of verification extended from the dam to Zhutuo (740 km upstream of the dam). The content of verification included water surface profile, amount and distribution of deposition, and rate of sediment releasing from the reservoir. The following is some results of the verification.

Three groups of data in water surface under different discharges at Cuntan were selected for the verification. The differences between measured and computed water levels are listed in Table 3.

Table 3 The Maximum Differences between Measured and Computed Water Level (m)

Discharge (m^3/s)	HELIU-2	MI-NENUS-3
6500	-0.07 - +0.10	-1.53 - +0.39
15300	-0.21 - +0.14	-0.60 - +0.84
5100	-0.03 - +0.19	-0.03 - +1.03

The differences at most points were small, but at some points were larger. The larger ones might be partly attributed to that the model is for steady flow, but the flow is unsteady in practice.

In the calculation of reservoir sedimentation the values of exponent *m* and recovery coefficient α were adopted as in Table 2, but the coefficient *K* were assumed to be different values for comparison. The measured and computed amounts and distribution of deposition in the TGP reservoir, and the rate of sediment releasing from the reservoir in June – Oct. 2003 are listed in Table 4.

Table 4　Amount of Deposition and Rate of Sediment Releasing

	K	Deposition (10^6 t)			Rate of S.R. (%)
		Zhutuo–Qingxichang	Qingxichang–Dam	Zhutuo-Dam	
Measured		23.4	122.5	145.9	36.5
HELIU-2	0.03	7.0	143.8	150.8	34.3
	0.02 (above Qingxichang) 0.03 (below Qingxichang)	15.3	135.8	151.1	34.2
MI-NENUS-3	0.03	-10.2	119.4	109.2	52.5
	0.02 (above Qingxichang) 0.03 (below Qingxichang)	21.4	124.4	145.8	36.5

In former prediction of reservoir sedimentation in TGP the value *K* was assumed to be 0.03. However, Table 4 shows when *K*=0.03, the calculated amount of deposition in the reach Zhutuo-Qingxichang is obviously smaller than the measured, even occurred degradation. An analysis indicted that in June 2003 the pool level in the TGP reservoir was 135 m, and influence of the impoundment could reach in the vicinity of Qingxichang, 479 km from the dam. There occurred the natural processes of flow and sediment transport above Qingxichang. The previous study revealed that the coefficient *K* of sediment-carrying capacity in a natural river is smaller than in a reservoir. So a better choice is *K*=0.02 above Qingxichang and *K*=0.03 below Qingxichang. Under this circumstance the calculated deposition amounts in the reservoir are in better agreement with the measured. The same or similar outcome may be also drawn for the rates of sediment releasing.

It should be noted that the above-mentioned is an initial verification of mathematical models in sediment research of TGP because there were only two years of field data available for the verification. More accurate conclusion should rest upon further verifying by long term, abundant and systematic field data.

4. DISCUSSION ABOUT VALIDITY OF FORECAST ON SEDIMENT PROBLEMS

When the results forecasted by mathematical modeling were tested by the field data in TGP reservoir, it was found that the validity of the conclusion would depend on several factors, including accuracy of mathematical modeling, correctness of boundary condition and reliability of field data etc.

4.1 Accuracy of Mathematical Modeling

Mathematical modeling of flow and sediment transport is, strictly speaking, a numerical-empirical modeling. The so-called "empirical" mainly, except empirical treatments in numerical methods, embodies the relations involved in sediment transport, e.g. sediment-carrying capacity, bed load discharge, non-equilibrium adaptation coefficient (recovery coefficient), variation of roughness in the fluvial processes, armoring action on the surface of a non-uniform bed, influence of non-uniform composition of sediment, exchange between finer particles in the bed and coarser ones in suspension, etc. These relations in a mathematical model are usually determined based on experience and field data at the study site. So they should be the major objective in verification of the mathematical model. Each empirical relation will affect the last result of the model. It is, however, impossible to verify all of them by a group of field data. The attention should be centered on the most important one. In the above-mentioned verification of 1-D models the coefficient K of sediment-carrying capacity was selected as the major objective. The verification indicated that when adopting K=0.02 for the natural reach and K=0.03 for the impoundment reach in TGP reservoir, the predicted reservoir sedimentation was close to the measured. When forecasting, however, the exact position of interface between the natural and the impoundment reaches could not be known in advance. In fact the interface is indistinct and variable, especially during depositing process and in fluctuating backwater region in the reservoir. It seems there would be embodied some arbitrariness in choosing value of K. Of course, the determination of sediment-carrying capacity is not limited in choice of value K. It may be preferable to study the sediment-carrying capacity in different river reaches of the reservoir under various conditions. This will, of course, involve large amount of laboratory experiment and field observation. Similarly, other empirical relations should also be studied and validated progressively by experimental and field data to reduce the empiricism in them. There is plenty of room for improvement in the mathematical modeling, but the first important one is the betterment of understanding of sediment transport mechanism.

4.2 Boundary Conditions

Any mathematical model of sediment transport should run under certain boundary conditions, including incoming flow and sediment load (quantity and quality), original morphology and composition of river bed, stability and erosion-resistance of river bank, distributaries discharging into or from the river, etc. Even though the mathematical model is strictly correct, unreal boundary conditions may also give rise to significant error in prediction. In former prediction of reservoir sedimentation in TGP the incoming sediment load was assumed to be 523×10^6 t/year, the average value in 1950-1986. The real sediment load entering into the TGP was 211×10^6 t in 2003 and 166×10^6 t in 2004, or smaller than half of the assumed value. As a result, the real deposition amount in the TGP reservoir was much smaller than the value predicted in the past. This deviation obviously does not result from the mathematical modeling technique, but from the difference of boundary conditions.

4.3 Reliability of Field Data

The field data are usually employed as the standard to verify a mathematical model. A mathematical model without verifying by field data can not be employed in prediction calculation. So accurate field data are essential for upgrading models and theory. However, due to the imperfection of apparatus, method and procedure used in field measurement and the uncertainty of sediment transport processes, the field data itself may include some errors, leading to an embarrassment in the verification sometimes. One of the examples is dry density of deposits in terms of dry mass per unit volume. It is a crucial parameter for converting from sediment mass into a volume. This conversion is often needed in measurement and calculation of channel deformation. Field observation shows that dry density of deposits in a reservoir depends on size and texture of sediment, and compaction and consolidation of deposits, which are related to place and duration of deposition, thickness of deposits, period of deposits to be exposed to the weather etc. So the density varies with time and space. In the above-mentioned verification of 1-D models the field deposition amount was the value measured by sediment discharge method (deposition was equal to difference between sediment loads at upstream and downstream stations). This value, however, was found to differ somewhat from that by contour method or range method. This may be attributed to inaccurate density of deposits except for errors in measuring. Before verifying of a model by field data it is necessary to analyze field processes and understand reliability of field data. In order to obtain field data of high quality, a new suggestion about field measurement in TGP was proposed for deliberation recently. Besides a large scale monitoring in upstream and downstream TGP, one or two short reaches would be selected as experimental ones. In them a detailed measurement should be implemented to study the difference between different measurement methods and to get as reliable field data as possible, so that the verification can be free from all inhibitions.

It can brook no delay to establish a set of typical and reliable field data for verification of mathematical models. As G. K. Gilbert's sediment transport experiments in flumes in 1909-1914 and E. Meyer-Peter's bed load experiments in flumes in 1930s-1940s, with their systematic data of measurement, greatly advanced research in this field in the 20th century, the reliable and systematic field data of sediment transport will give an impetus to advancement of mathematical modeling in the 21st century.

5. CONCLUSIONS

1. Mathematical modeling has been extensively employed in studying various sediment problems in TGP, including yield, transportation, distribution and management of sediment. For certain cases, mathematical modeling is the only available predictive tool, and for other cases, mathematical modeling is one of the effective approaches.
2. A preliminary verification of 1-D mathematical models by the field data of 2003-2004 in TGP reservoir showed that the results calculated were in reasonable agreement with the measured when appropriate coefficient of sediment-carrying capacity was employed. Further verification is to be carried out.
3. Whether a forecast from mathematical modeling accords with field observation depends firstly on accuracy of mathematical model. Improvement of mathematical modeling relies to a large extent on in-depth understanding of mechanism of sediment transport. Boundary conditions of models also give great impact on results of forecasting, and should be defined exactly. In verification of models it is necessary to analyze field processes and understand reliability of field data. Reliable and systematic field data of sediment transport will give an impetus to advancement of mathematical modeling.

ACRONYMS AND ABBREVIATIONS

CSRTGP	Compendium of Sediment Research for the Three Gorges Project (1996-2000)
CWB	Changjiang Waterway Bureau
IRTCES	International Research and Training Center on Erosion and Sedimentation
ISRS	International Symposium on River Sedimentation
IWHR	China Institute of Water Resources and Hydropower Research
NHRI	Nanjing Hydraulic Research Institute
TGP	Three Gorges Project
TRIWTE	Tianjin Research Institute for Water Transport Engineering
TU	Tsinghua University
WU	Wuhan Unisersity
YRSRI	Yangtze River Scientific Research Institute

REFERENCES (all in Chinese except as noted)

Dong, Yaohua (2000). "2-D Mathematical Model for Training of the Reaches below TGP", CSRTGP, Vol. 6, pp. 344-359.

Dong, Yaohua et al. (2004). "Variation in a Typical Lower Jingjiang River Reach below the TGP: a Preliminary Study", Proceedings of the 9th ISRS, Vol. 2, pp. 695-700 (in English).

Fan, Beilin et al. (2000). "Computation of Sediment Transport in the Reach from Jiangkou to Guanyinsi below TGP", CSRTGP, Vol. 7, pp. 382-412.

Fang, Chunming et al. (2000a). "Numerical Simulation of Fluvial Processes in the Three Diversion Channels from the Jingjiang River after construction of TGP", CSRTGP, Vol. 7, pp. 749-774.

Fang, Chunming (2000b). "2-D Computation of Sediment Transport in the Douhudi Reach of the Yangtze", CSRTGP, Vol. 7, pp. 413-421.

Fang, Chunming et al. (2004). "Numerical Simulation of Deposition in the Temporary Navigation Channel of the TGP", Proceedings of the 9th ISRS, Vol. 2, pp. 881-885 (in English).

Fang, Chunming (2005). "2-D Mathematical Modeling of Flow and Sediment Transport in the Chongqing Reach in TGP Reservoir"

Fang, Duo et al. (2002). "Yield of Runoff and Sediment in Typical Small Watersheds", CSRTGP, Vol. 4, pp. 294-315

Gao, Kaichun et al. (2000). "Coupling 1-D and 2-D Mathematical Model for Gravel Shoal Reaches below TGP", CSRTGP, Vol. 6, pp. 486-529.

Gong, Ping et al. (2000). "Computation of Diversion of Flow and Sediment at Three Outlets of the Jingjiang River and Fluvial Processes in the Three Diversion Channels after Construction of TGP", CSRTGP, Vol. 7, pp. 775-793.

Han, Qiwei et al. (1990a). "Computation of Reservoir Sedimentation in TGP", Research Reports of Key Problems in Sediment and Navigation of TGP, Vol. 2, pp. 488-564.

Han, Qiwei et al. (1990b). "Verification of 1-D Mathematical Model for the Danjiangkou Reservoir", Research Reports of Key Problems in Sediment and Navigation of TGP, Vol. 2, pp. 616-631.

Han, Qiwei et al. (1997). "1-D Mathematical Modeling of Channel Processes in the Jinsha River below the Xiangjiaba and Xiluodu Projects".

Huang, Yue (2000a). "1-D Mathematical Modeling of Fluvial Processes in the Reach from Yichang to Datong below TGP", CSRTGP, Vol. 7, pp. 258-311.

Huang, Yue (2000b). "Computation of Channel Evolution in the Reach from Yichang to Datong after construction of the Xiluodu Project", CSRTGP, Vol. 7, pp.339-359.

Huang, Yue (2005). "Computation of Deposition in TGP Reservoir under Pool Level of 172/170 m".

Huang, Yulin et al. (1990). "Computation of Reservoir Sedimentation in TGP", Research Reports of

Key Problems in Sediment and Navigation of TGP, Vol. 2, pp. 423-487.
Huang, Yulin et al. (1994). "Computation of Reservoir Sedimentation for Hybrid Physical and Mathematical Model of Dam Area in TGP", CSRTGP, Vol. 1, pp. 206-223.
Huang, Yulin et al. (1997). "1-D Mathematical Modeling of Channel Deformation in the Jinsha River below the Xiangjiaba and Xiluodu Projects".
Li, Yitian et al. (2000). "Mathematical Modeling of Sediment Transport in the Lake Dongting", CSRTGP, Vol. 7, pp. 794-804.
Lin, Bingnan et al. (2004). "Sediment Research for the Three Gorges Project on the Yangtze River since 1993", Proceedings of the 9th ISRS, Vol. 1, pp. 29-37 (in English).
Lu, Yongjun et al. (2000a). "2-D Mathematical Modeling of Water Depth in the Navigation Channel with Movable Bed below the Gezhouba Dam", CSRTGP, Vol. 6, pp. 330-343.
Lu, Yongjun (2000b). "Coupling 1-D and 2-D Mathematical Model for Training of Shoal Reaches below TGP", CSRTGP, Vol. 6, pp.530-549.
Lu, Yongjun et al. (2004). "3-D Numerical Simulation for Water Flows and Sediment Deposition in Dam Area of the TGP", Proceedings of the 9th ISRS, Vol. 1, pp. 205-215 (in English).
Mao, Jixin et al. (1998). "Computation of Degradation in the Reach from Yichang to Datong below the TGP", CSRTGP, Vol. 7, pp. 115-148.
Mao, Jixin et al. (2000). "Computation of Channel Evolution in the Reach from Yichang to Datong after construction of the Xiangjiaba Project", CSRTGP, Vol. 7, pp. 360-381.
Mao, Jixin (2005). "Computation of Deposition in TGP Reservoir under Pool Level of 172/170 m"
She, Mingfu (2000). "Impact of TGP on Diversion of Flow and Sediment into the Lake Poyang and Flood Control in the Poyang Area", CSRTGP, Vol. 7, pp. 805-825.
Wan, Jianrong (1998). "1-D Mathematical Modeling of TGP Reservoir Sedimentation after Construction of the Xiangjiaba and Xiluodu Reservoirs", CSRTGP, Vol.5, pp. 99-114.
Wang, Conghao et al. (1998). "Effect of the Xiangjiaba and Xiluodu Reservoirs on Deposition in the TGP Reservoir", CSRTGP, Vol.5, pp. 115-141.
Xu, Gaohong et al. (2002). "Run off and Sediment Yields in Some Area of the Jialing River Basin", CSRTGP, Vol. 4, pp. 415-443.
Xu, Quanxi (2002). "Sediment Transport in the Jialing River", CSRTGP, Vol. 5, pp 59-98.
Yang, Meiqin (1997). "1-D Mathematical Modeling of Channel Deformation in the Jinsha River below the Xiangjiaba and Xiluodu Projects".
Yang, Meiqin (2000). "1-D Mathematical Modeling of the Channel Processes below the Gezhouba Dam", CSRTGP, Vol. 6, pp. 308-329.
Zhang, Jie (2005). "2-D Computation of Flow and Sediment Transport in the Chongqing Reach in TGP Reservoir"
Zhou, Jianjun (1995a). "2-D Mathematical Model for Sediment Transport in Dam Area of TGP", CSRTGP, Vol. 1, pp. 575-624.
Zhou, Jianjun (1995b). "Mathematical Modeling of Unsteady Flow and Sediment Deposition in Navigation Approach Channels of TGP", CSRTGP, Vol. 2, pp. 956-1004.
Zhou, Jianjun (2004a). "Schemes of Sediment Management Proposed for the TGP", Proceedings of the 9th ISRS, Vol. 1, pp. 250-257 (in English).
Zhou, Jianjun (2004b). "Verification and Computation of 1-D Mathematical Model for TGP Reservoir Sedimentation".