Sediment Problems and Sediment Management in Asian River Basins
(Proceedings of the Workshop held at Hyderabad, India, September 2009). IAHS Publ. 349, 2011.

Channel degradation in the Yangtze River after the impoundment of the Three Gorges Project

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Abstract The impoundment of the Three Georges Project (TGP) caused a major decrease in the sediment load downstream from the dam, and this inevitably resulted in channel degradation, which has important implications for flood control, navigation conditions and aquatic ecology in the whole river basin. Based on analysis of field data and mathematical modelling, estimates of the reduction in sediment load and the resulting channel degradation in the Yangtze River downstream from the dam are reported in this contribution. Comparison of the results of the current study with those of previous studies and with field data demonstrates that the model prediction of channel degradation in the Yangtze River after the impoundment of the TGP obtained in the current study conform more closely with the field data than previous predictions.
Key words reduced sediment load; impoundment; the Three Gorges Reservoir; channel degradation; prediction

INTRODUCTION

Channel degradation induced by damming has taken place in many rivers in the world (Gregory & Park, 1974; Petts, 1979; Knighton & Nanson, 1993; Kondolf, 1997). It is well known that both the flow of a river and its sediment load can change dramatically after the construction of a dam. Large amounts of sediment are deposited in the reservoir and the clear water released can cause long-term channel degradation and adjustment downstream over a long distance. The process of channel degradation downstream from the dam is dependent not only on the change in the flow hydrograph, but also on the reduction in sediment load and the sediment supply along the downstream reach. As a result, the flood conveyance capacity of the channel, its navigation condition, and ecological environment across the whole downstream river basin will also change due to the impact of the changes in the hydrological conditions and channel morphology. Prediction of the channel degradation process downstream of a reservoir is an important problem in the field of river management. It has been suggested that the channel degradation process that occurs downstream from a dam cannot be predicted or explained without taking account of the hydrological conditions, the reduction in sediment load, the geological setting, the geomorphic history, and other variables (Friedman *et al.*, 1998). Previous research over past decades has directed attention to changes in sediment load and channel degradation processes (e.g. Knighton & Nanson, 1993). Attempts have been made to predict channel degradation downstream from large dams, but the results have frequently proved unreliable due to the complex interaction of the numerous controlling factors and the limitations of simulation technology (Grasser & Gamal, 1994).

The Three Gorges Project (TGP) is the biggest project on the Yangtze River, and its impoundment will induce channel degradation in the downstream reaches over long distances. There are many tributaries in the Middle and Lower Yangtze River, and the river regime of the whole area reflects a network composed of multiple branching channels. How best to predict channel degradation in this complex area after the impoundment of the TGP must be seen as an important area of research. Beginning in the 1980s, predictions of the likely degradation process downstream from the TGP have been made for over 20 years. Many institutes, including the Yangtze River Scientific Research Institute (YRSRI, 2002) and the China Institute of Water Resources and Hydropower Research (CIWHR, 2002), have studied the channel degradation after the impoundment of the TGP using one-dimensional steady models. However, recent studies (Li *et al.*, 2003; Zhou, 2005, 2006), have shown that elements of the previous results conflict with the general rules of changing sediment discharge the river downstream river from the dam and do not match field data collected after the impoundment of the TGP.

Since the impoundment of the TGP in June 2003, the river channel downstream from the dam has been affected by the release of clear water. In order to understand the processes and laws of channel degradation and to solve the resulting problems related to flood control, navigation and the ecological environment, it has been necessary to devote further effort to studying the reduction in sediment discharge and associated channel degradation downstream from the TGP. In this paper, based on recent research, the process and laws of channel degradation downstream from the TGP are investigated using both analysis of field data and numerical modelling, and the reliability of the results obtained is discussed.

THE STUDY AREA

The study reach downstream from the TGP extends from Yichang to Datong over a total length of 1015 km, and represents the main stem of the Middle and Lower Yangtze River (Fig. 1). There are several tributary inputs to the main river downstream from the dam, including the Qing River, the Han River, Dongting Lake and Poyang Lake. The reach from Zhicheng to Chenglingji is commonly called the Jingjiang reach, and there are three diversion points, named Songzhikou, Taipingkou and Ouchikou, connecting this reach with Dongting Lake. The flow of the three diversions enters Dongting Lake and flows out at Chenglingji after being stored in the lake. The Jingjiang reach and Dongting Lake represent the region most affected by flood disasters. In the reach downstream from Chenglingji, the main river is dominated by braided reaches, but single thread channels and braided reaches interchange at intervals, providing a complex channel network platform.

Hydrological gauging stations were established along the Yangtze River by the Yangtze River Water Resource Committee in the 1950s and data comprising daily mean water stage, discharge and sediment load are available up to the present. The main gauging stations include Yichang, Zhicheng, Shashi, Jianli, Chenglingji, Luoshan, Hankou and Datong. Among them, the Yichang station is located immediately downstream from the dam, the Chenglingji and Hukou stations are located at the outlets of the Dongting and Poyan Lakes, respectively, and the Datong station is located at the dry season tidal limit. In this study, the analysis of field data focuses primarily on data from these stations.

ANALYSIS OF FIELD DATA RELATING TO THE REDUCTION IN SEDIMENT DIS-CHARGE AND ASSOCIATED CHANNEL DEGRADATION IN THE YANGTZE RIVER

The TGP began impounding water in June 2003. The resulting changes in the discharge and sediment load downstream of the dam have caused severe scouring in the channel downstream of

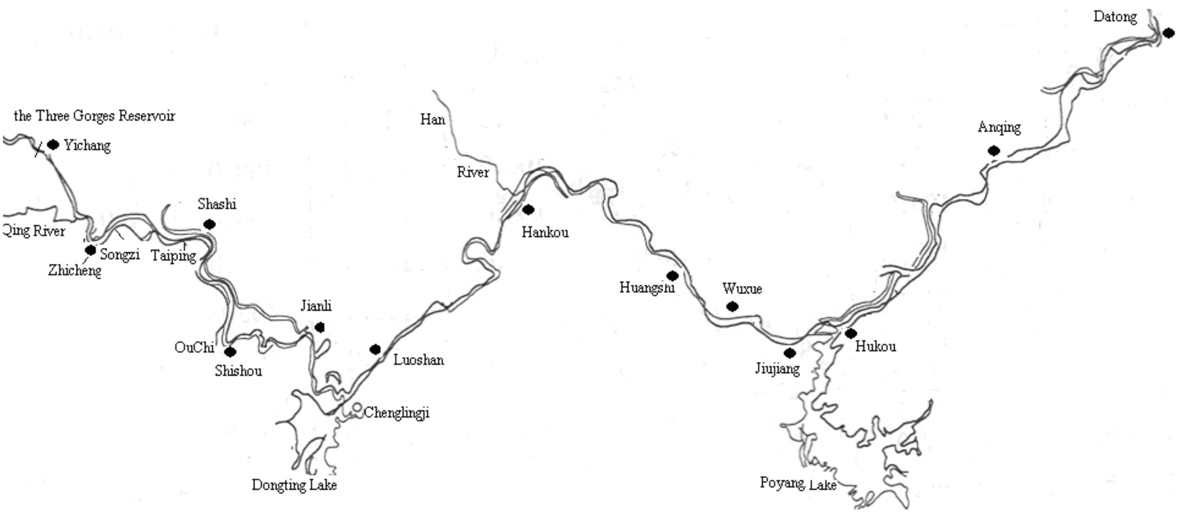

Fig. 1 A map of the Middle and Lower Yangtze River.

the dam. Based on data from the gauging stations and a long-distance topographic survey undertaken between 2003 and 2007, the changes in the sediment regime and amount of erosion or deposition in the Yangtze River were assessed.

Change of sediment regime

The change of the sediment regime in downstream reaches can be related to the analysis of channel degradation in the Yangtze River downstream of the TGP. The changes of annual sediment discharge for different stations between 2003 and 2007 are indicated in Fig. 2. Compared with that before the impoundment of the TGP, the annual sediment discharge has decreased greatly after the impoundment of the TGP. Although the extent of the decrease in sediment discharge differs between Yichang and Datong, due to sediment supply from the river bed and tributaries, it is clear the effective trapping of sediment by the TGP has resulted in significant changes in sediment discharge.

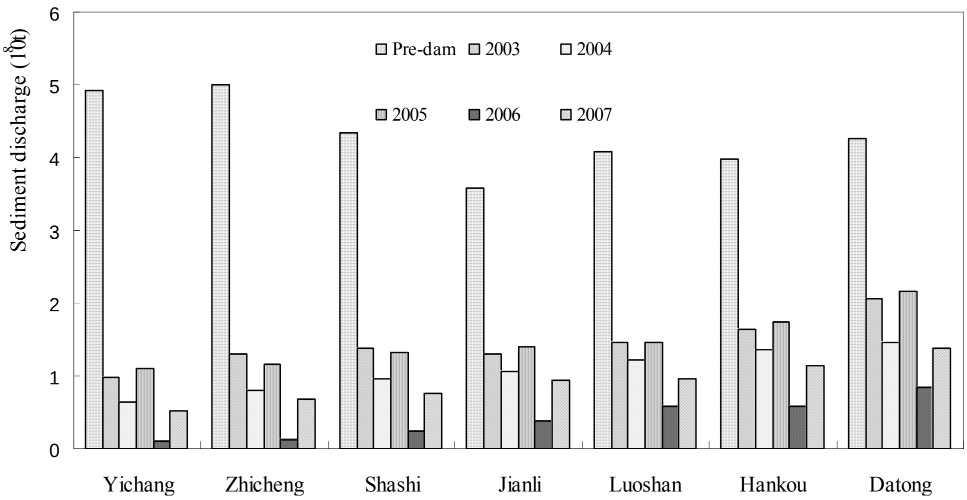

Fig. 2 Changes in the annual sediment load at different stations on the Yangtze River downstream from the TGP.

The changes in the magnitude of the sand fraction and in the median grain size shown in Table 1 indicate that the median grain size (d_{50}) of the sediment load at Yichang during the period 2003–2007 is considerably lower than that during the pre-dam period, and the contribution of the <0.031 mm fraction to the total sediment load increases to 85.5% during this period. This means that the sediment released from the dam is characterized by both a reduction in quantity and a change in its grain size composition. From Yichang to Jianli, the content of fine sand in the total load shows a decrease, but that of coarse sand increases. It can be seen that by the Jianli station, the contribution of coarse sand ($d > 0.125$ mm) recovers to the pre-dam level. From Hankou to Datong, the contributions of the different grain size fractions to the total load change less between the pre-dam condition and 2003–2007, and this reflects the reduced importance of erosion and deposition of sediment, when compared with the Jingjiang reach.

Changes in channel degradation

The reduction in sediment load of the Yangtze River downstream from the dam shown in Fig. 2 has inevitably resulted in channel degradation. The volume of sediment scoured from the channel within different subsections of the Middle and Lower Yangtze River are shown in Table 2. Because of limitations in the data collection, the most downstream location is only Hukou, the outlet of Poyang Lake. It can be seen that channel degradation occurred along the entire downstream reach of the Yangtze River from Yichang to Hukou during the period 2003–2007. The scour was focused on the low water stage channel, which accounted for about 86.9% of that associated with the channel at bank-full water stage. Comparing the different subsections, more river bed erosion occurred in the reach from Yichang to Chenglingji, whilst the erosion was less in the reach downstream from Chenglingji. The location of the channel degradation coincides with the laws of the change of sediment regime.

Table 1 Changes in the relative magnitude of different grain size fractions and the median grain size between the pre-dam period and the period 2003–2007, for several measuring stations along the Middle and Lower Yangtze River.

Size fraction	Period	Relative contribution of grain size fraction (%)						
		Yichang	Zhicheng	Shashi	Jianli	Luoshan	Hankou	Datong
D ≤ 0.031mm	Pre-dam mean	73.9	74.5	68.8	71.2	67.5	73.9	73.0
	2003–2007	85.5	69.14	54.62	43.6	56.88	61.82	77.9
0.031 mm < d ≤ 0.125mm	Pre-dam mean	17.1	18.6	21.4	19.2	19.0	18.3	19.3
	2003–2007	7.9	11.52	13.36	19.2	15.68	16.24	15.76
D > 0.125 mm	Pre-dam mean	9.0	6.9	9.8	9.6	13.5	7.8	7.8
	2003–2007	6.6	19.34	32.02	37.2	27.44	21.94	6.34
Median grain size (mm)	Pre-dam mean	0.009	0.009	0.012	0.009	0.012	0.010	0.009
	2003–2007	0.0046	0.0084	0.034	0.063	0.016	0.013	0.009

Table 2 Channel degradation in the Yangtze River from 2003 to 2007 ($10^8 m^3$).

Reach	Distance (km)	Channel of low water stage ($Q_{Yichang}$ = 5000 m^3/s)	Channel of middle water stage ($Q_{Yichang}$ = 10 000 m^3/s)	Channel of bank-full water stage ($Q_{Yichang}$ = 30 000 m^3/s)
Yichang-Zhicheng	60.8	–0.61	–0.64	–0.67
Zhicheng-Ouchikou	171.7	–1.13	–1.19	–1.33
Ouchikou-Chenglingji	175.5	–1.08	–1.19	–1.31
Yichang-Chenglingji	408	–2.82	–3.02	–3.30
Chenglingji-Hankou	251	–0.47	–0.43	–0.42
Hankou-Hukou	295.4	–0.98	–1.24	–1.20
Yichang-Hukou	954.4	–4.31	–4.73	–4.96

PREDICTION OF CHANNEL DEGRADATION IN THE YANGTZE RIVER

Methodology

As indicated above, studies of the degradation process downstream from the TGP, based on numerical models, have been undertaken by many research institutes in China. The models used are all steady 1-D models. In these models, the input flow process is treated as a number of steady flow stages. Considering the fluctuation of natural hydrographs, the precision of these models is limited for two reasons. Firstly, floods are dynamic. If treated as steady flow, the parameters in the model cannot be calibrated properly, with the result that the sediment load is likely to be over- or under-estimated. Secondly, it is during flood events that large amounts of sediment load are transported. The flood propagation process and the sediment transport capacity of the flow cannot be reflected in the steady flow models used by previous research. Furthermore, the models used in previous research have been constructed using a single channel mode, and the braided mode is dealt with using experimental formulae. Taking account of the limitations of existing numerical models, an unsteady 1-D river network model has been developed by the writer to predict channel degradation. Details of the equations and solution methods used for this unsteady 1-D river network model are provided by Li (1997).

The sketched structure of the river network of the study area is based on field information on channel morphology. Parameters in the model are calibrated by simulating a long period of operation of the fluvial processes (from 1996–2002 and 2002–2006). The time series for 1961–1970, proposed by the YRSRI to represent the typical hydrograph at Yichang, has been adopted for the post-dam upstream discharge and sediment input. The prediction aims to describe the degradation during the first 20 years after dam impoundment. The model starts with the surveyed channel topography of 2002.

Prediction results

The sediment balance for each section during different periods indicates the state of sediment recovery and the rate of channel adjustment (Fig. 3). The prediction results indicate that scour takes place immediately after the impoundment of the TGP in the near dam sections. By the 20th year, the riverbed erosion between Yichang and Shashi is finished, but the erosion process is still ongoing in the reach between Shashi and Chenglingji. The situation differs for the reach below Chenglingji, where deposition continues until the 15th year in the reach between Chenglingji and Hankou. At the end of the 20 years, the amount eroded during the most recent 5 years cannot balance the amount deposited during the first 15 years in this reach. In the reach downstream from Hankou, both erosion and deposition occur at different times, but the amounts of erosion or deposition amount are very small and similar to natural conditions.

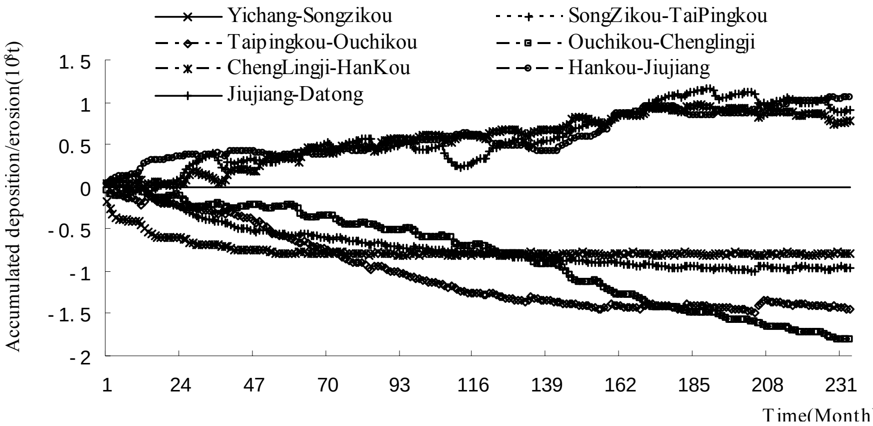

Fig. 3 Model predictions of the cumulative deposition/erosion in different sections of theYangtze River for a period of 10 years after dam impoundment.

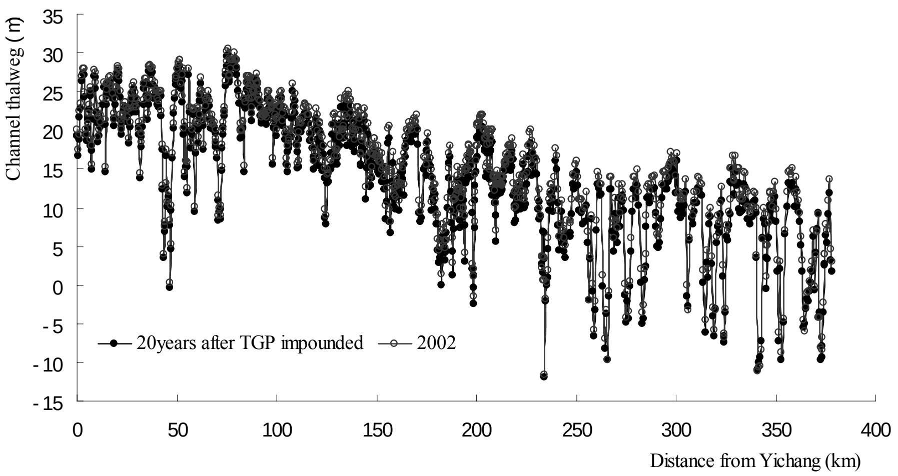

Fig. 4 The model predicted channel thalweg 20 years after impoundment of the TGP.

Table 3 Average incision depths between Yichang and Chenglingji in the 20th year after the impoundment of the TGP.

	Yichang-Shashi	Shashi-Jianli	Jianli-Chenglingji
Channel width (m)	1300	1600	1500
Average incision depth (m)	1.09	1.6	0.75

Channel degradation occurs primarily in the reaches upstream of Chenglingji. The change in the channel thalweg 20 years after impoundment of the TGP is depicted in Fig. 4. Although the thalweg lowered at some locations, there are no major changes in the long distance thalweg, even after 20 years. For each section, the mean incision depth of the channel bed is estimated using an average channel width. Based on the cumulative volume of degradation, the incision depths for the sections between Yichang and Chenglingji are listed in Table 3. This shows that the Jiangjiang reach from Shashi to Jianli undergoes the most severe channel degradation, which agrees well with the field evidence from recent years after dam closure.

DISCUSSION

Comparison with field data

Based on the topographic survey data and hydrological data from the gauging stations, the cumulative sediment erosion/deposition has been calculated using two methods (Table 4). The first is the sediment budget method and the second is the topographic method. Both methods are widely used in calculating sediment erosion and deposition. For the purpose of comparison, the model prediction results for the same period are also listed in Table 4. The results presented in Table 4 indicate that there are differences between the values of cumulative sediment erosion/deposition for each subsection of the Middle and Lower Yangtze River provided by the sediment budget and topographic methods. In the recent literature (Guo, 2009), the values provided by the sediment budget method are considered to be more reliable when compared with the pre-dam condition and the post-dam reduction in water stage. In Table 4, the model predicted sediment erosion/deposition amount conforms more closely to that calculated by the sediment budget method, which also suggests that model prediction results are reasonable.

After the TGP was impounded, the water stage at downstream gauging stations tended to decline. A comparison of the values for the decrease in water stage between 2003 and 2007 provided by the field data and the model predictions is provided in Table 5. It can be seen that the model results agree well with the field measurements and this provides further validation of the model predictions.

Table 4 Comparison of the estimates of cumulative sediment erosion/deposition (10^8 t) in the Yichang-Hankou reach for the period 2003–2007 provided by the field data with the model prediction.

	Reach	Topographic method	Reach	Sediment budget method
Field data	Yichang-Zhicheng	–1.461	Yichang-Zhicheng	–0.75
	Zhicheng-Ouchikou	–2.195	Zhicheng-Shashi	–1.06
	Ouchikou-Chenglingji	–2.871	Shashi-Jianli	–0.70
	Chenglingji-Hankou	–1.310	Jianli-Luoshan	0.15
			Luoshan-Hankou	0.17
Prediction result	Yichang-Songzikou	–0.549		
	Songzikou-Taipingkou	–0.628		
	Taipingkou-Ouchikou	–0.985		
	Ouchikou-Chenglingji	–1.599		
	Chenglingji-Hankou	0.596		

Table 5 A comparison of the values for the decrease in water stage over the period 2003–2007 provided by the model predictions and the field data.

Station	Discharge (m^3/s)	Decrease in stage (m)	
		Field data	Model prediction
Yichang	5000	0.08	0.16
Shashi		0.60	0.63
Jianli		0.18	0.20
Luoshan	10000	0.00	0.00
Hankou		0.02	0.00

Comparison with previous results

To provide a comprehensive review of existing understanding of channel degradation along the Yangtze River as a result of the impoundment of the TGP, the model predictions provided by this study have also been compared with those generated by the YRSRI and CIWHR.

The sediment transport recovery process in the downstream reach after impoundment of the TGP should conform to the general rule, based on the response of other reservoirs, that the post-dam sediment transport rate of each grain size fraction cannot exceed the pre-dam value (Li *et al.*, 2003). Figure 5 provides further information on the sediment recovery process at the Luoshan and Hankou stations after the TGP impoundment. Attention is directed to the bed material load (d > 0.1 mm). The P-Data represent the sediment transport rate in the first 20 years after impoundment of the TGP predicted by previous research, whilst the C-Data represents the equivalent sediment transport rate predicted by this study. The pre-dam observed data refers to the period 1981–1996. Figure 5 shows that the observed sediment transport in the first three years after dam impoundment was quite close to the pre-dam level at both stations. This indicates that the ongoing channel degradation occurred primarily upstream of these stations. In the case of the predicted values, the estimates generated by previous research are much larger than the pre-dam level. For the Hankou station, it is more than three times the pre-dam value. The values provided by the current study are less than the measured data both before and after the dam impoundment. Considering that sediment transport during the first three years after impoundment will reflect the availability of sediment from the channel bed, it can be expected to reduce if it is averaged over a longer period, because the sediment supply from the channel bed will decline with time. The results provided by the current study must therefore be seen as reasonable, whereas the results provided by previous research fail to conform to the general rule stated above.

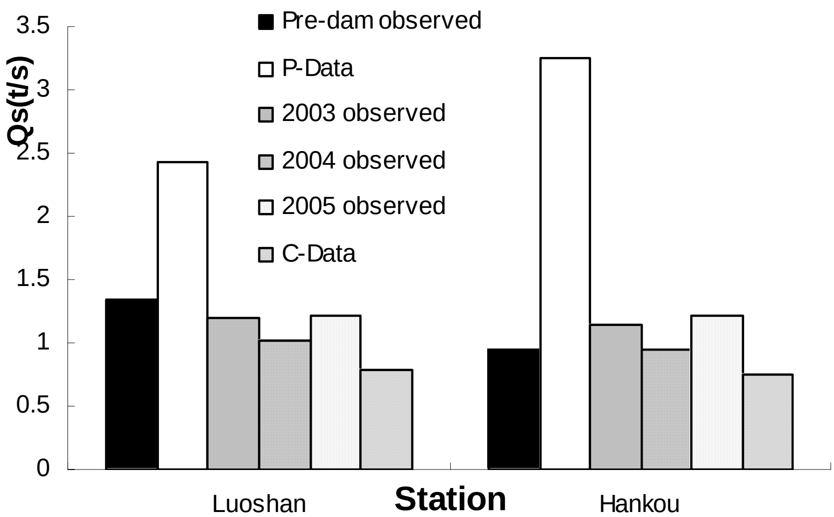

Fig. 5 Transport of sediment d > 0.1 mm at the Luoshan and Hankou stations (see text for explanation).

Table 6 provides a comparison of the amounts of erosion and deposition during the first 20 years after the impoundment of the TGP predicted by the model developed for the current study with those estimated using the models of YRSRI and CIWHR. Table 6 demonstrates that the values obtained by the present study are considerably smaller than those obtained by the previous studies. The sediment budget for the reach between Chenglingji and Hankou is shown by the present study to be close to balanced. The starting topography for the model developed in this paper is 2002 and that of the model of YRSRI and CIWHR is 1993. If the amount of erosion and deposition from 1993 to 2002 is eliminated for the reach from Yichang to Chenglingji, the degradation calculated by the present study is 8.98×10^8 m^3 less than that estimated by YRSRI and 8.5×10^8 m^3 less than the estimate of CIWHR. The reason for these differences relates primarily to the sediment transport rate, which differs considerably in each model. In the previous studies, the transport of bed material is overestimated, so that the predicted degradation process is more rapid than that estimated by the current study. Consequently, for the same period of time, the incision depths estimated by the previous studies are considerably larger than those estimated by the current study.

Table 6 A comparison of the amount of erosion and deposition in the 20 years after the impoundment of the TGP ($10^8 m^3$) estimated by the YRSRI and CIWHR studies and the present study.

Reach model	Yichang-Chenglingji	Chenglingji-Hankou	Hankou-Datong	Yichang-Datong
YRSRI	–14.68	–2.87	2.56	–14.99
CIWHR	–14.22	–3.2	5.34	–12.08
This study	–3.59	0.55	1.41	–1.64

CONCLUSIONS

The reduction in sediment transport and the associated channel degradation occurring after the impoundment of the TGP have been assessed using analysis of field data and a mathematical model. The results obtained have been compared with those obtained by previous studies. The following conclusions have been drawn:

(1) The annual sediment discharge decreased considerably after the impoundment of the TGP. The sediment released from the dam evidences not only a reduced load, but also a change in its grain size composition. During 2003–2007, channel degradation occurred from Yichang to Hukou, especially in the reach extending from Yichang to Chenglingji, and the scour primarily focused on the low water stage channel. The characteristics of the channel degradation conformed to the laws reflecting the change of sediment regime.

(2) The prediction results for the period after the impoundment of the TGP also showed that the river bed degradation occurred primarily in the reach between Yichang and Chenglingji, over a period of 20 years. The reach from Shashi to Jianli evidenced the most severe channel degradation. However, a lower rate of deposition was found in the reach from Chenglingji to Hankou over the first 15 years, and erosion and deposition alternate in the reach between Hankou to Datong.

(3) The predictions of channel degradation in the Yangtze River after the impoundment of the TGP provided by the current study are lower than those provided by previous studies and conform to the general rule on sediment transport rate after damming. The amount of erosion and the depth of channel incision depth were overestimated by previous investigations.

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