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Comparison of Physical Model Predictions and Prototype Measurements of Fluvial Morphodynamics in the Yangtze River Downstream of the Three Gorges Project

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ABSTRACT: The Three Gorges Project (TGP) began to operate since June 2003. So far the hydrological regime and the features of river channel erosion/deposition change significantly in the Yangtze River downstream of the TGP. In this study, the recent variation of the flow and sediment conditions and the erosion/deposition in the river channel downstream of the TGP are briefly analyzed first. Then the predictive results of physical model tests on the morphodynamics of the river channel downstream of the TGP are briefly presented. Comparisons between the model predictions and the prototype measurements are made. The comparative results show that the model tests predict well the development of typical bars in the river, the development of typical cross-sections, and the tendency of river regime variation, etc.

Keywords: Physical model predictions, Yangtze River, Three Gorges Project, Fluvial morphody-namics, Hydrological regime.

1 INTRODUCTION

The Three Gorges Project (TGP), as the key project for the improvement and development of the Yangtze River, started operation since June 2003, and so far already bring large economic and social benefits in terms of flood protection, electricity generation, irrigation and navigation, etc. The successful protection of the big floods in 2010 and 2012 specially highlights the significant importance of the TGP in the flood protection system of the Yangtze River Basin. Yet, the operation of the TGP changes the flow and sediment conditions (i.e. the hydrological regime) of the downstream river channel as well, and consequently brings far-reaching impacts to the fluvial process of the river channel. In particular, the Jingjiang River (also called the Jingjiang Reach, from Zhicheng to Lianhuatang, about 347 km long, see Figure 1), closely downstream of the TGP, is affected relatively earlier and significant. According to relevant research (see e.g. Xu et al., 2013; CRSRI, 2011; and Guo et al., 2010), significant erosion and deposition already occurred in the Jingjiang River since the operation of the TGP, and the river regime at some river subreaches adjusted clearly.

Relying on the Changjiang River Flood Protection Physical Model (see Zhu et al. 2014, and the Changjiang River was formerly named the Yangtze River), study with physical model tests has been done to predict the erosion and deposition of the downstream river channel from Yangjianao to Luoshan after operation of the TGP (see Figure 1), and to predict the tendency of river regime development. The Changjiang River Flood Protection Physical Model is a physical model covering the Yangtze River from Zhicheng to Luoshan (380km long, including the Jingjiang Reach from Zhicheng to Lianhuatang), the Dongting Lake, the downstream ending reach of the four main tributaries of the lake (i.e. rivers of Xiang, Zi, Yuan and Li, see Figure 1), and the three outlets (i.e. Songzikou, Taipingkou and Ouchikou) and the many small channels connecting the Yangtze River and the Dongting Lake. The horizontal scale of the physical model is 1:400, and the vertical one is 1:100. For more details (including the model verification) readers are referred to Zhu et al. (2014) and CRSRI (2011).

In this study, first the change of the flow and sediment conditions of the river channel downstream of the TGP and the channel erosion and deposition are briefly analyzed. Then the physical model predictions are presented, and then comparisons between the model predictions and the prototype measurements are made.

Figure 1. Sketch map of the Yangtze River downstream of the TGP and the Dongting Lake

2 VARIATIONS OF HYDROLOGICAL REGIME OF DOWNSTREAM RIVER CHANNEL AFTER THE TGP OPERATION

Since the operation of the TGP in 2003, the flow and sediment conditions (i.e. the hydrological regime) of the river downstream of the TGP already changed significantly so far. Operation of the TGP reduces the peak of big floods and increases the flow rate for dry season. Generally, the flow process is flattening within the year. According to statistics, comparing with the situations before the project operation, the annual runoff at most hydrological stations downstream of the TGP is about 5%~10% less after the operation. Yet, the sediment load decreases dramatically (>70%), and the degree of this decrease declines in the streamwise direction (mainly due to the recovery of sediment concentration caused by erosion along the channel). The stations of Zhicheng, Shashi and Hankou are control hydrological stations for the river channel downstream of the TGP. The average annual sediment loads after the TGP operation (2003-2012) for the above three stations are 0.585×10^8t, 0.693×10^8t and 1.143×10^8t, respectively. Comparing with those before the TGP operation, the sediment loads decreased by 88%, 84% and 71% for the three stations, respectively.

After the operation of the TGP, most of the coarse sediment particles are stopped in the reservoir, resulting in fine down of the suspended load discharged from the reservoir. The clear flow discharged from the reservoir causes significant erosion along the downstream river channel, and the suspended load is coarsened distinctly, especially that at the Jianli Station, where d_{50} is coarsened from 0.009mm before the TGP operation to the averaged 0.042mm for the years of 2006-2010, and then to 0.065mm of 2011, and 0.211mm of 2012.

Due to the significant erosion of the downstream river channel (especially the low water channel, see Section 3) after the TGP operation, water levels at the same flow rates decline clearly, see e.g., Table 1 for the Shashi Hydrological Station. From 2003 to 2011, the decline of water level at the same flow rate of 6000m^3/s is 1.07m at the Shashi Station. Then along with the increase of the flow rate, this decline of water level tends to getting smaller. At some hydrological stations, as far as the prototype observational data of recent several years is concerned, the water level even shows a little upward trend at high flow rates (e.g. 30000m^3/s for the Shashi Station, see Table 1).

Table 1. Variation of water level at same flow rate after operation of TGP (Shashi Station, unit: m)

Period / Flow rate(m^3/s)	2003-2008	2008-2010	2010-2011	2003-2011
6000	-0.34	-0.53	-0.2	-1.07
10000	-0.34	-0.22	-0.11	-0.67
20000	0.07	0.02	-0.21	-0.12
30000	0.06	0.21		

The three outlets, i.e. Songzikou, Taipingkou and Ouchikou (see Figure 1), formed mainly due to historical big floods, divert flow and sediment from the Yangtze River to the Dongting Lake. During the last a few decades, under natural conditions the quantity of flow and sediment diverted via the three outlets decreases gradually (Figure 2). Since the operation of the TGP, except 2006 and 2011 which are special low flow years, in which both the flow and sediment diversion has a very significant reduction, in the other years during 2003-2013 the flow diversion shows just slight decrease, while the sediment diversion decreases dramatically.

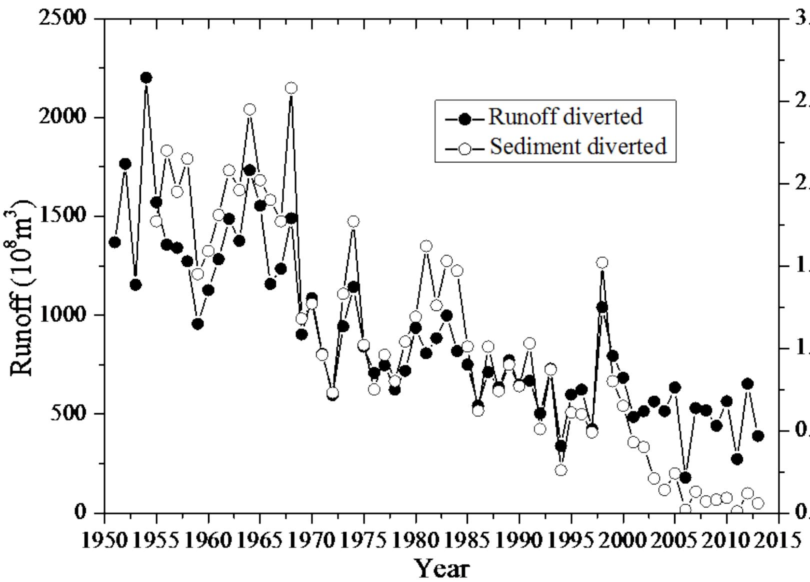


Figure 2. Variation of flow and sediment diversion via the three outlets from Yangtze to Dongting Lake (1951-2013)

3 EROSION AND DEPOSITION OF DOWNSTREAM RIVER CHANNEL AFTER THE TGP OPERATION

Based on analysis of the prototype topographical survey data of the river channel, since the operation of the TGP (2002-2012), the quantity of erosion occurred in the bank full channel for the downstream river reach from Zhicheng to Lianhuatang (i.e. the Jingjiang River) amounts to $6.21\times10^8m^3$, while this quantity amounts to $5.38\times10^8m^3$ for the low water channel (see Table 2). It is therefore indicated from Table 2 that the erosion occurs mainly in the low water channel after the TGP operation, and the averaged erosion intensity is about $0.15\times10^6m^3/km\cdot a$. Among the 10 years (2002-2012), the quantity of erosion occurred in the low water channel in the first 5 years (i.e. 2002-2007) is $2.86\times10^8m^3$, occupying a 53.1% portion of the whole, which is slightly larger than that of the last 5 years.

Table 2. Quantity erosion of river channel from Zhicheng to Lianhuatang after the TGP operation (10^6 m^3)

	2002-2003	2003-2004	2004-2005	2005-2006	2006-2007	2007-2008	2008-2009	2009-2010	2010-2011	2011-2012	2002-2012
Low water channel	-64	-90	-63.8	-18.7	-49	-6.9	-76.1	-49.3	-79.4	-40.5	-538
Bank full channel	-98.2	-130	-73.7	-26.6	-33.6	-1.7	-82.5	-49.8	-75.4	-49.4	-621

Note: "+" indicates deposition, "-" indicates erosion.

4 PHYSICAL MODEL PREDICTIONS OF THE FLUVIAL PROCESS OF THE JINGJIANG RIVER

4.1 *Brief introduction of the physical model tests*

To predict the fluvial process of the river downstream of the TGP after the project operation, study with physical model tests has been done in 2009 with the Changjiang River Flood Protection Physical Model (see e.g. CRSRI, 2011; Huang et al., 2011). In the tests, the modeling river reach is from Yangjianao to Luoshan (about 300km long, see Figure 1). The initial topography of the river bed for the movable bed model adopts the prototype topographic data measured in October 2008. The modeling flow and sediment boundary conditions are provided by the simulation of the long river channel and long period 1D mathematical model of the CRSRI, which was applied for the justification of the TGP decades ago and is improved continually ever after. The prediction period of the physical model tests is from October 2008 to December 2022 (altogether 14years plus 2months). In the tests, the process of river channel erosion and deposition and the adjustment tendency of the river regime are predicted (Zhu et al., 2014).

4.2 *Summary of the model test results*

4.2.1 *Quantity and distribution of channel erosion and deposition*

According to the physical model predictions, when the TGP operates to 2012, and then to 2017, and then to 2022, erosion occurs mainly in the low water channel for the whole modeling river reach, and among which, the intensity of erosion decreases after 2012 for the river reach from Yangjianao to Yanchuantao (see Figure 1). It is also observed that different river sub-reaches have different intensities of erosion. If sub-divide the modeling river reach into four sub-reaches (see Table 3), it can be seen that the most upstream sub-reach (i.e. Yangjianao~Beinianziwan) has the largest intensity of erosion ($2.58\times10^6 m^3/km$); the most downstream sub-reach (Lianhuatang~Luoshan) has the smallest intensity of erosion ($0.77\times10^6 m^3/km$); while the second downstream sub-reach (Yanchuantao~Lianhuatang) has the second largest intensity of erosion ($2.52\times10^6 m^3/km$). Due to the relatively small channel width, the second upstream sub-reach (Beinianziwan~Yanchuantao) has the largest averaged depth of erosion (2.42m), though the intensity of erosion for this sub-reach only ranks the third.

Table 3. Physical model predictions of erosion and deposition during 2008-2022 in Yangjiannao~Luoshan Reach

River sub-reach	Yangjianao~ Beinianziwan	Beinianziwan ~Yanchuantao	Yanchuantao ~Lianhuatang	Lianhuatang ~Luoshan
Quantity erosion (10^8 m^3)	3.15	1.54	1.16	0.24
Intensity erosion (10^6 m^3/km)	2.58	1.97	2.52	0.77
Depth erosion (m)	2.19	2.42	2.18	0.68

4.2.2 *Variations of thalweg and alongshore scour pits*

Physical model predictions indicate that, when the TGP operates to 2022, the river channel from Yangjianao to Luoshan shows a general tendency of erosion and downcutting. The planar variation of the thalweg embodies in mainly, the downstream shift of the section with the thalweg closely nestling against the bank, the downstream shift of the facing point of the thalweg at bending channels, and the swing of the thalweg at transitional river sections. Due to the reduction of sediment load in the flow, the part of channels with the thalweg closely nestling against the bank are generally scoured down, with local low-elevation scour pits formed and developed.

4.2.3 *Comparison of development of typical bars between physical model predictions and prototype measurements*

In the physical model tests, some of the typical bars in the river, such as the Sanba Central Bar, the Taipingkou Point Bar, have been modeled with movable bed. Following the Sanba Central Bar is taken as an example to make a comparison between the physical model predictions and the prototype measurements for the development of typical bars (Figure 3).

The Yangtze River Waterway Bureau started the protection for the Sanba Central Bar in March 2004, then to October 2008 the protection for the upstream part of the bar was basically finished. However, in recent years the downstream part of the bar (downstream of the Yangtze Bridge) is washed to shrink gradually. From July 2004 to November 2011, the area of the bar above 30m elevation decreased from 1.932km^2 to 0.186km^2. At the same time, at the right side river bank, the downstream part of the Taipingkou Point Bar is silted up and extends to the central river (see the left in Figure 3). The physical model predictions indicate that, when the TGP operates to 2012, the downstream part of the Sanba Central Bar is washed away to almost vanished; correspondingly the Taipingkou Point Bar is silted up and extends to the central river (see the right in Figure 3). It can be seen from the figure that the physical model predictions are in good agreement with the prototype measurements.

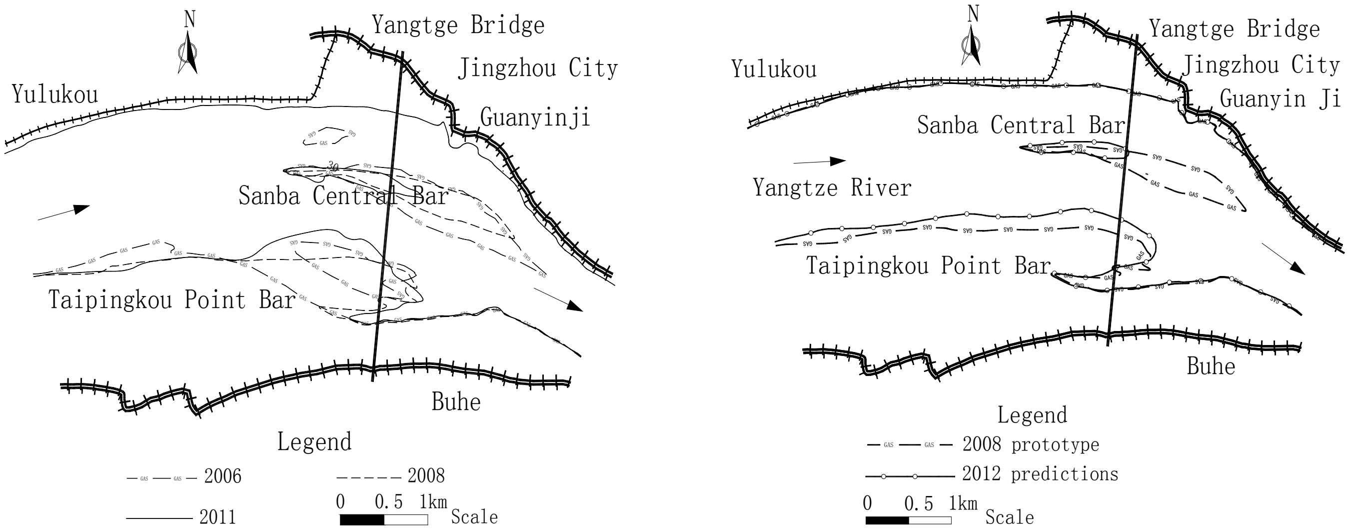


Figure 3. Recent variation of Sanba Central Bar and Taipingkou Point Bar (Left: prototype measurements; Right: model predictions)

4.2.4 *Comparison of development of typical cross-sections between physical model predictions and prototype measurements*

Following the cross-sections of J56 and J81 are taken as examples to make comparisons between the physical model predictions and the prototype measurements for the development of typical cross-sections (see Figures 4 and 5). Both the two cross-sections are parts of the conventional cross-sections of the Jingjiang River whose section configuration is measured regularly yearly. The J56 section locates at a bifurcated channel (Figure 4). With the operation of the TGP, the right-side channel (i.e. the main channel) is scoured down and develops to the left, while the left-side channel is silted up. For the J81 section (Figure 5), after the TGP operation, the left-side channel changes only slightly from 2002 to 2011, and the right-side river bed is silted up clearly, yet, close to the right-side bank, the channel shows a light degradation. As can be seen from Figures 4 and 5, the physical model predictions (year 2012) are in basic agreement with the prototype measurements (year 2011).

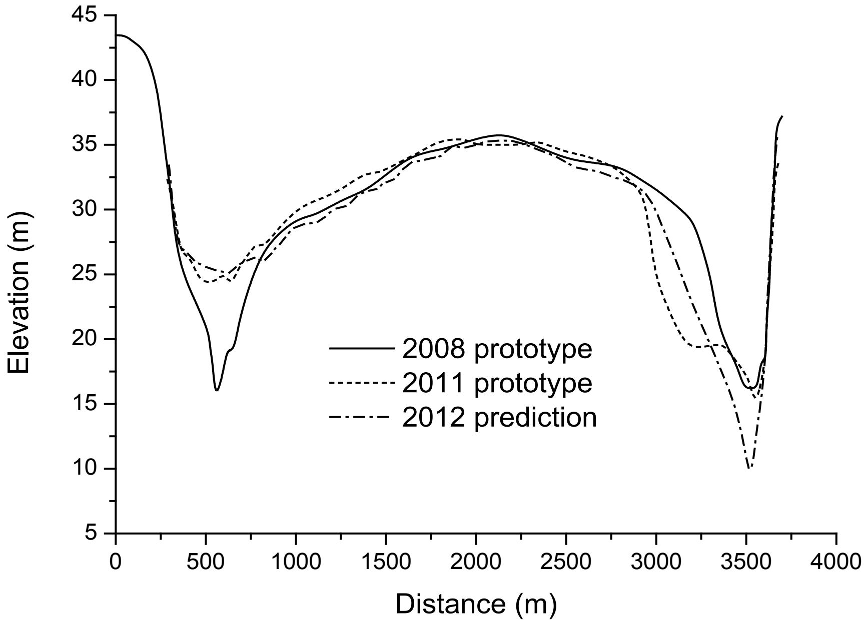


Figure 4. Variation of J56 Section (comparison between model predictions and prototype measurements)

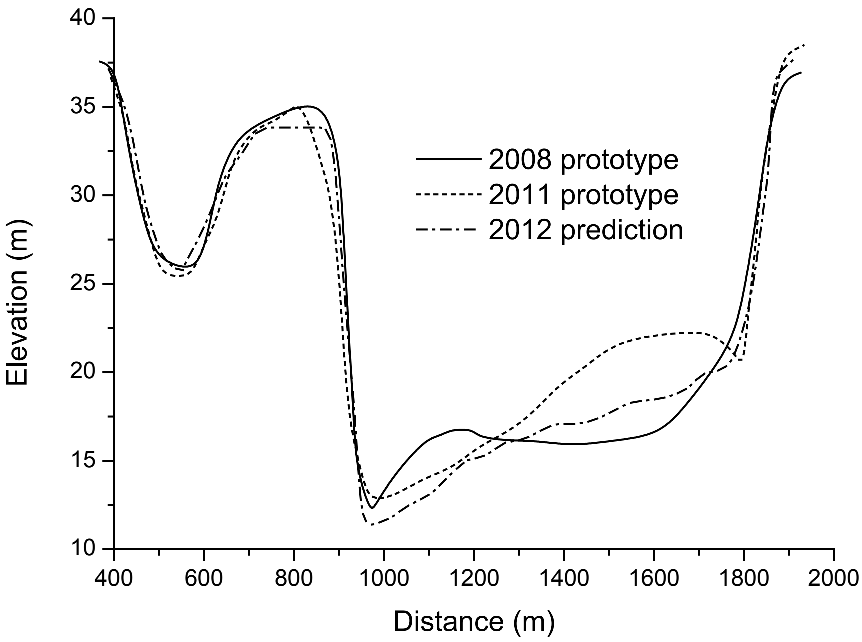


Figure 5. Variation of J81 Section (comparison between model predictions and prototype measurements)

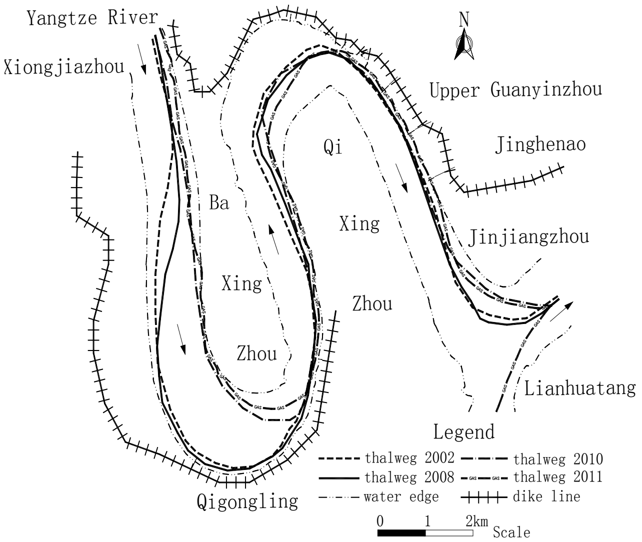
4.2.5 *Comparison of tendency of river regime variation between physical model predictions and prototype measurements*

The physical model predictions show that when the TGP operates to 2012, and then to 2017, and then to 2022, the overall river regime of the investigated river reach (Yangjianao~Luoshan) has no strong variation comparing with that in October 2008 (i.e. the initial conditions of the model tests), despite significant erosion and deposition occurs to the channel. With the lengthening of the operation period of the TGP, in general the river channel is incised down; the thalweg at transitional river sections swings and moves downstream integrally. However, at certain river sub-reaches, e.g. the curved reaches of Qigongling and Tiaoguan, and the bifurcated reach of Shashi, quite significant variation of the river regime occurs locally.

From the point of view of the general tendency of river regime variation, the above physical model predictions conform well to the prototype measurements. Analysis of prototype measurements shows that, since the operation of the TGP, generally the downstream river channel does not change much in the planform. The riverbed deformation is mainly marked with the riverbed downcutting, and the bed form evolves gradually towards a narrow-deep shape. On the whole, no big change occurred in the general river regime of the downstream channel, however, at some river sub-reaches, such as some bifurcated reaches with poor stability, and some curved reaches, relatively remarkable adjustment of river regime took place, a good example is the river sub-reach from Xiongjiazhou to Lianhuatang (in which the curved reach of Qigongling is covered).

Following the river sub-reach from Xiongjiazhou to Lianhuatang is taken as an example to illustrate the comparison between the physical model predictions and the prototype measurements in terms of river regime variation. According to the prototype measurements (see the left in Figure 6), in 2002 (and the years before), the thalweg transits from the left in the river at Xiongjiazhou to the right at the entrance of the Qigongling curved reach, and then the main current flows downstream closely along the right bank (concave bank) until to the exit of the curved reach. Then along with the operation of the TGP, the river channel is incised down, and the thalweg at the entrance of the Qigongling curved reach moves downstream gradually. To October 2010 the thalweg does not transits from the left to the right side of the river anymore, instead, the main current flows downstream closely along the left bank (convex bank) until to the lower part of the curved reach, with chute cut-off occurred. Later to 2011 the chute cutoff develops further (see the left in Figure 6).

The physical model predictions indicate that (see the right in Figure 6), when the TGP operates to 2012, the Qigongling curved reach is generally scoured continually. Compared with the initial conditions (in 2008) of the physical model, the position of the thalweg changes dramatically in 2012. The main current flows downstream closely along the left bank (convex bank) until to the lower part of the curved reach, instead of transiting from the left to the right at the entrance of the curved reach. The right side thalweg in the upper part of the curved reach is silted up gradually, to the contrary, the left side channel is scoured down and broadened and develops into the thalweg, i.e. chute cutoff occurred in the curved reach. It is concluded from the comparison between the physical model predictions and the prototype measurements that, the physical model tests predicted well the chute cutoff and the adjustment tendency of the river regime in the Qigongling curved reach, though there is slight difference in terms of quantity between the predictions and the prototype measurements.



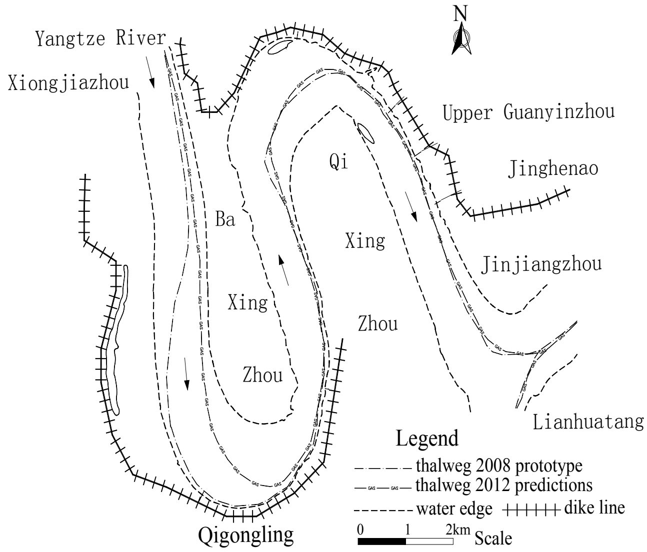


Figure 6. Variation of thalweg from Xiongjiazhou to Lianhuatang (Left: prototype measurements; Right: model predictions)

5 CONCLUSIONS

The Three Gorges Project, as the key project for the improvement and development of the Yangtze River, started operation since June 2003, and so far already brings large economic and social benefits. Yet, the operation of the TGP also changes the flow and sediment conditions of the downstream river, and consequently brings significant impacts to the fluvial process of the channel. According to statistics, the annual runoff at most hydrological stations downstream of the TGP is about 5%~10% less after the project operation. Yet, the sediment load decreased by at least 70%. Since the operation of the TGP (2002-2012), the quantity of erosion occurred in the low water river channel from Zhicheng to Lianhuatang (i.e. the Jingjiang River) amounts to $5.38\times10^8 m^3$. Due to the significant erosion of the downstream river channel (especially the low water channel), water levels at the same (medium and low) flow rates decline clearly after the TGP operation. According to prototype measurements and observations, relatively remarkable adjustment of the river regime at some sub-reaches occurred since the operation of the TGP (e.g. the

Qigongling curved reach), though generally the river regime for the downstream channel as a whole does not change too much.

Relying on the Changjiang River Flood Protection Physical Model, study with physical model tests has been done to predict the erosion and deposition of the river channel from Yangjianao to Luoshan after operation of the TGP, and to predict the tendency of river regime development. Comparisons between the physical model predictions and the prototype measurements show that the model tests predict well the development of typical bars in the river, the development of typical cross-sections, and the tendency of river regime variation, etc.

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REFERENCES

CRSRI. (2011). Evolution and Regulation of the Jingjiang River in the Early Operation Phase of the Three Gorges Project. The Changjiang River Scientific Research Institute, Wuhan, China. (in Chinese)

Guo X.H., Zhu, Y.H. and Qu, G. (2010). Research Progress on Relationship between the Yangtze River and Dongting Lake after the Three Gorges Reservoir Regulating. Water Resources and Power, Vol. 28, No. 12, pp. 33-35, 132. (in Chinese)

Huang, L., Zhu, Y.H. and Yao, S.M. (2011). Physical Modeling of Fluvial Process and River Regime Control in Shishou Reach of Yangtze River at the Initial Stage of Three Gorges Project. Journal of Yangtze River Scientific Research Institute, Vol. 28, No. 9, pp. 81-86. (in Chinese)

Xu, Q.X., Zhu, L.L. and Yuan, J. (2013). Research on Water-Sediment Variation and Deposition-Erosion in Middle and Lower Yangtze River. Yangtze River, Vol. 44, No. 23, pp.16-21. (in Chinese)

Zhu, Y.H., Lu J.Y., Fan B.L. et al. (2014). On the Progress of Research of the Changjiang River Flood Protection Physical Model. Proceedings of 2013 IAHR World Congress, Chengdu, China.