

# HENRY

Hydraulic Engineering Repository

Ein Service der Bundesanstalt für Wasserbau

---

Conference Paper, Published Version

**Xiao, Y.; Fu, X. H.; Tong, S. C.**

## **Temporal and Spatial Changing Trends on the Fluvial Sedimentation in the Three Gorges Reservoir, Yangtze River in China**

Zur Verfügung gestellt in Kooperation mit/Provided in Cooperation with:  
**Kuratorium für Forschung im Küsteningenieurwesen (KFKI)**

---

Verfügbar unter/Available at: <https://hdl.handle.net/20.500.11970/108523>

Vorgeschlagene Zitierweise/Suggested citation:

Xiao, Y.; Fu, X. H.; Tong, S. C. (2016): Temporal and Spatial Changing Trends on the Fluvial Sedimentation in the Three Gorges Reservoir, Yangtze River in China. In: Yu, Pao-Shan; Lo, Wie-Cheng (Hg.): ICHE 2016. Proceedings of the 12th International Conference on Hydroscience & Engineering, November 6-10, 2016, Tainan, Taiwan. Tainan: NCKU.

### **Standardnutzungsbedingungen/Terms of Use:**

Die Dokumente in HENRY stehen unter der Creative Commons Lizenz CC BY 4.0, sofern keine abweichenden Nutzungsbedingungen getroffen wurden. Damit ist sowohl die kommerzielle Nutzung als auch das Teilen, die Weiterbearbeitung und Speicherung erlaubt. Das Verwenden und das Bearbeiten stehen unter der Bedingung der Namensnennung. Im Einzelfall kann eine restriktivere Lizenz gelten; dann gelten abweichend von den obigen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Documents in HENRY are made available under the Creative Commons License CC BY 4.0, if no other license is applicable. Under CC BY 4.0 commercial use and sharing, remixing, transforming, and building upon the material of the work is permitted. In some cases a different, more restrictive license may apply; if applicable the terms of the restrictive license will be binding.

Verwertungsrechte: Alle Rechte vorbehalten



## Temporal and Spatial Changing Trends on the Fluvial Sedimentation in the Three Gorges Reservoir, Yangtze River in China

*Y. Xiao, X. H. Fu, S. C. Tong*

National Inland Waterway Regulation Engineering Research Center, Chongqing Jiaotong University  
Chongqing, China

### ABSTRACT

The impoundment of the Three Gorges Reservoir (TGR) alters the response of the hydrodynamic conditions and sediment movements, which are related to the fluvial sedimentation in the upper stream of the Yangtze River. Based on an extensive dataset of daily water discharge, sediment transport rate, and river bed level collected from 2003 to 2013 in the TGR area, this study investigated the controls of the temporal-spatial reservoir sedimentation process and their changing trends. The turning points of the TGR temporal variations in inlet and outlet boundary conditions for the relationship between inflow sediment and inflow discharge were 1990 and 2002. The response to the rapidly decreasing sediment supply reflects that the TGR operation scheme indirectly influences the runoff-sediment changing trends, and that the adjustment of the pool level at the outlet of the dam can directly influence the deposition process. As a river reservoir, the river pattern of the main deposition reaches can be classified as meander, broad-valley, and braided, indicating a key in the sedimentation process in a huge river reservoir. In the following decades, dam constructions on the upper Yangtze River and its major tributaries would lead to a further decrease in sediment discharge and alleviate the sedimentation process in the backwater area of TGR.

**KEY WORDS:** Fluvial sedimentation, Runoff-sediment discharge, River pattern, The Three Gorges Reservoir, The Yangtze River.

### INTRODUCTION

Fluvial sedimentation occurs primarily in response to interactions among natural factors such as surface material, river runoff, and sediment supply; however, with increasing population, reservoir construction, sand excavation, bank revetments, and land use alterations have significantly changed the natural dynamics of river channels (Wang et al., 2012). Human impacts on channel morphology and fluvial processes become an increasingly important influencing factor, particularly dam construction and water diversions for water and energy needs (Nilsson et al., 2005). Dams can disrupt river continuity, intercept sediment, and change the fluvial hydrology, leading to altered channel patterns (Graf, 2006; Kiss et al., 2008; Lu and Jiang, 2009).

There are more 45,000 dams in major rivers worldwide, and much progress has been made in the study of downstream river dynamics in response to the changes in climate, river runoff, and the sediment

transportation (Aleem, 1972; Batalla et al., 2004; Kummur et al., 2010; Draut et al., 2011). The Three Gorges Reservoir (TGR) is located in the middle stretch of Asia's largest river, the Yangtze River in China, and as the world's largest hydropower project, the Three Gorges Project is key to harnessing and exploiting the Yangtze River. The TGR is located at Sandouping near Yichang city, Hubei province, in the Xiling Gorges of the Three Gorges reach in the trunk of the Yangtze River, 40 km upstream of the Gezhouba Dam (Fig. 1). The completion of the Three Gorges Dam has led to a rapid and significant decrease in downstream sediment load. Recent research has focused on the changing trends of water and sediment discharge (Lu et al., 2001; Chen et al., 2001; Xiong et al., 2009; Xu and Milliman, 2009; Dai and Lu, 2014), the changes in the downstream channel patterns, and the material fluxes and water exchanges between the river and large lakes (Li et al., 2011; Yang et al., 2011; Guo et al., 2012; Sun et al., 2012; Dai et al., 2013).

The construction of the TGR alters the response of hydrodynamic conditions and sediment movements in the upper stream of the Yangtze River. The dam holds a reservoir 660 km long, stretching from Yichang to Chongqing (Fig. 1). After the pool level of TGR was raised to 175 m in 2008, the 432 km long permanent backwater zone stretched from the dam to Fuling and the fluctuating backwater region extended to Jiangjin. The TGR became fully operational in 2009 and has the largest storage capacity, 39.3 billion m<sup>3</sup>, in the Yangtze River basin, constituting about 4.5% of the Yangtze's annual discharge. In the backwater area of the TGR, more attention has been given to the environmental and land-slip impacts (Yan et al., 2008; Zhang et al., 2009; Yang et al., 2010; Wolf et al., 2013), but few studies have investigated the temporal-spatial distribution of the sedimentation process or quantified the main deposition reach sections in the backwater region, although this deposition key to navigation conditions and is closely related to the environment and fish habits in the reservoir area.

This study is based on an extensive dataset of daily water discharge, sediment transport rate, river bed level collected at representative hydraulic stations, and the field measurement of streambed topography or regular streambed cross-sections from 2003 to 2013 in the TGR area. The objectives of this study were to (1) reveal the temporal and spatial distribution of the reservoir sedimentation in the first 10 years of operation, especially focusing on the main deposited reaches along the backwater area; (2) analyze the variations in the inflow and sediment discharge on the spatial-temporal sedimentation process; and (3)

evaluate the change trends of the sedimentation pattern based on the controls analysis.

### TEMPORAL DISTRIBUTION OF THE SEDIMENTATION IN TGR

In 2008, the backwater area of the TGR reached Jiangjin town of Chongqing city, with a total length of approximately 660 km under the 175-145-155 m operation scheme. Cuntan station is the inflow control point of the upper Yangtze River into the TGR, located 608 km above the TGR. The pattern and distribution of reservoir sedimentation were obtained mainly through measurement of streambed topography or regular streambed cross-sections, a method referred to as the “volume method”.

The total reservoir sedimentation was about 1.46 billion m<sup>3</sup> after the first 10 years of operation. The annual inflow and the outflow sediment discharge from 2003 to 2013 (Fig.1a) shows that since the late 1990s, sediment volumes have been declining due to reforestation efforts and the construction of many small and intermediate-sized dams in the upper Yangtze River tributaries. The incoming sediment supply of recent years has been reduced to about 35% of the 1950-1986 levels used in the designed stage, leading to reduced reservoir sedimentation. In comparison with the sediment load predicted during the design phase of the TGR, the actual sediment deposition dropped to about 40% of the predicted value. The highest deposition of 0.19 billion m<sup>3</sup> occurred in 2010 as a response to high sediment supply (Fig. 1a). The sedimentation accounted for ~60-80% of the inflow sediment after the TGR became operational. Owing to the low sediment supply from the upper catchments in 2006, 2011, and 2013, the annual sediment deposition was < 0.1 billion m<sup>3</sup> during these dry years.

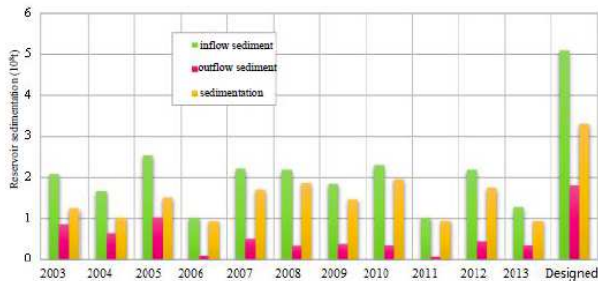


Fig. 1a Sediment inflow, outflow, and deposition in Three Gorges Reservoir

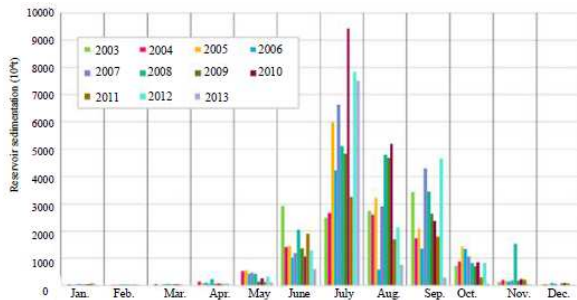


Fig. 1b Monthly sedimentation in the Three Gorges Reservoir area

The mean monthly sedimentation during the first 10 years of operation

(Fig. 1b) indicates that the sediment entering the TGR was trapped in the backwater region, primarily during the flood period with high discharge and incoming sediment (June to September), comprising 90% of the annual sediment deposition. Because drier years could reduce the percentage of the wet season’s sediment load, the sediment deposition in 2006, 2011, and 2013 was lower than the other years, especially during the flood period, leading to a decrease in the annual sedimentation (Fig. 1a).

### SPATIAL DISTRIBUTION OF THE TGR FROM 2003 TO 2013

In general, the contribution of the water depth increase and the velocity decrease caused a loss in the transporting capacity of the stream and deposition of the sediments after the reservoir filled. Since the impoundment of the TGR in 2003, approximately 0.0156 billion m<sup>3</sup> of sediment erosion has occurred in the fluctuating backwater region, and serious sediment deposition has occurred in the permanent backwater region of the TGR, up to about 1.476 billion m<sup>3</sup> after the first 10 years of operation. More research is needed to determine the deposition locations and understand the mechanics of the sedimentation processes that play a vital role in the navigation and management of the TGR area. By comparison with the river bed level changes between 2003 and 2013, the variation of the thalweg profile in the permanent backwater region of the TGR (Fig. 2a) indicates that the closer to the dam area, the greater the amount of sedimentation. The maximum thickness of deposits along the thalweg was 64.7 m (5.6 km upstream of the dam). Changes of the thalweg profile in other areas of the TGR were modest (Fig. 2a), mostly within the range of 5 m, except in some reach sections where the thickness of the deposits reached about 50 m. Over time, the fluctuation of the thalweg became less pronounced than that in the initial operation years.

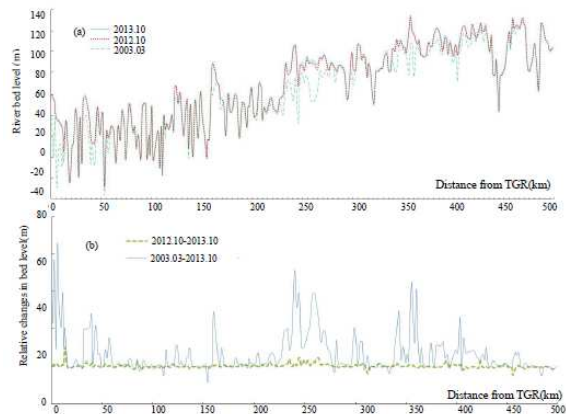


Fig. 2 The thalweg profile changes in the permanent backwater region of TGR

Generally, a typical sedimentation process of a reservoir (known as aggradation) continues progressively until a delta forms (Sloff, 1991; Fan et al., 1992). The relative deposition/scouring values in the permanent backwater region of the TGR were compared (Fig. 3b): unlike a sand or gravel delta, alternation of erosion and accretion processes occurred along the reservoir river reaches, indicating that serious sedimentation may not only be related to the distance from the dam, but is also independent of the river reach patterns; the second

maximum deposition thickness was 52 m, located 250 km upstream from the TGR, negatively influencing navigation conditions during the flood period. The relative deposition/erosion values between 2012 and 2013 were less variable, with the exception of some deposition near the dam area, indicating that the sediment deposition rate could gradually decrease over time (Li et al., 2011).

Table 1 Main sedimentation position in the permanent backwater region  $10^9\text{m}^3$

No	Reach section	Channel pattern	Amount of sedimentation ( $\times 10^9\text{m}^3$ )
1	Nearby dam	Broad-valley	1.529
2	Xiling Gorge	Broad-valley	1.42
3	Daning River	Broad-valley	0.309
4	Chouzi Qi	Broad-valley	0.818
5	YunYang	Meander	1.949
6	Wanzhou	Meander	0.459
7	Zhongzhou	Braided	1.89
8	Lanzuba	Braided	1.603
9	Fengwei Bar	Braided	0.198
10	Yuanyang Pan	Braided	0.209
Total			10.5

Field measurements for the topography map were collected in the permanent backwater region between 2003 and 2011 to indicate the main deposition reach sections; the entire river channel survey was based on a 1:5000 scale. Sediment deposition in the meandering, broad-valley, and braided reaches of the permanent backwater region reached 1.0 billion  $\text{m}^3$ , accounting for 84% of the total sedimentation (Table 1). The spatial distribution of the main sedimentation along the TGR area (Fig. 3) shows that, in addition to the nearby dam, the river pattern of the reach section is an important control on the deposition location in the TGR.



Fig. 3 Main sedimentation reach sections in the Three Gorges Reservoir area

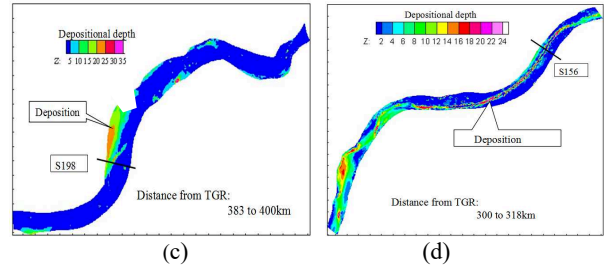
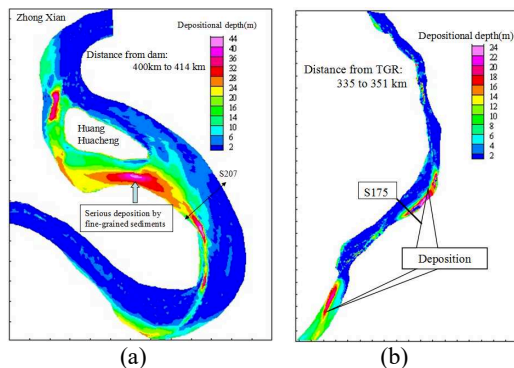


Fig. 4 Typical deposition reaches in the permanent backwater region of TGR

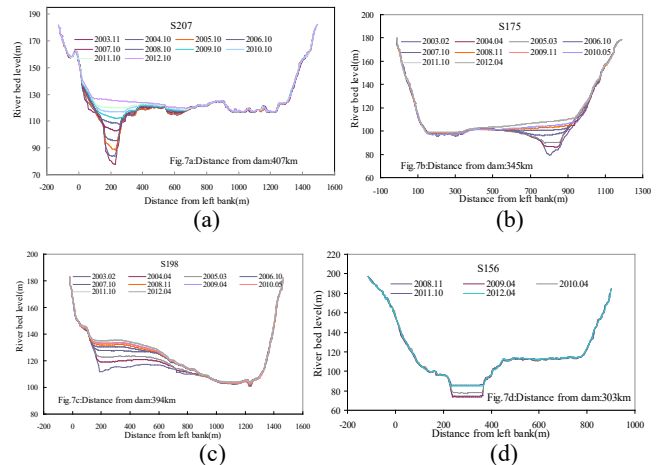


Fig. 5 Changes of the river bed level in the typical cross sections

The relative changes of the river bed level between 2003 and 2011 for typical, main deposition reach sections in the permanent backwater area show that the convex banks of the meander reach sections accounted for about 50% of the depositions (Fig. 4). Here, the central gravel bar in the Zhongxian reach causes the major flow to move from one side of the bar to the other with varying flow stages (Fig. 4a), creating an unstable condition that influences the sediment transport through this reach, not achieving equilibrium; the highest deposition thickness was up to 52 m on the left course. In general, bends form dynamically, constantly shifting positions through erosion of the concave banks and deposition along the convex banks of a bend, which correspond with the distribution of the deposition in the backwater reach sections of the TGR.

Pattern trends of typical selected cross-sections show that, in terms of the lateral distribution of deposits over the cross-section in the typical broad-valley section, a large part of the deposition occurred in the main channel, accounting for 79% of the total deposition (Fig. 5). In the meander channel with the central bar in the Zhongxian reach, the serious deposition occurred on the left side of the bend, which is dictated primarily by its hydrodynamic power for the capacity of sediment transport (Fig. 5a). Field measurements on the river bed in the serious sedimentation reach sections showed the medium grain size of sediment deposits has reached 0.008 mm (Li, 2013), composed of significant fractions of fine-grain material in the silt and clay sizes that have greater resistance to entrainment than coarser sediments consisting only of sands (Fig. 3).

## ANALYSIS ON THE CONTROLS OF THE TEMPORAL AND SPATIAL SEDIMENTATION PROCESS

Xiangjiaba station is located on the upper Yangtze River; Gaochang and Fushun stations are the control points for the main tributary of the Min and Tuo rivers that join to the upper Yangtze River; Zhutuo station is located above the Chongqing reach section; Beibei station is the control for the Jialing River that joins to the Yangtze River; Cuntan station is the inflow control point of the upper Yangtze River into the TGR; and Wulong station is the control of the major tributary of Wujiang River in the TGR area.

The patterns of variation in averaged runoff over the past 30 years (Fig.6a) at these typical hydrological stations show that the average runoff in the first 10 years of operation from 2003 to 2013 was the same as the long-term runoff over the past 20 years. Compared with the 1980 levels, the control points for the major tributaries of the Yangtze River (Min River, Tuo River, Jialing River, Wujiang River) slightly decreased by ~3-5%, accounting for 50% of that at Cuntan station. By comparing the data set of 2003-2013 with that of 1990-2002, the average runoff of Tuo River and Jialing River had increasing trends by about 28% and 2%, respectively. Water and soil conservation measures in the upper stream have contributed to the reduction of the inflow control point of the upper Yangtze River into the TGR. The mean monthly runoff (Fig. 6b) is high in the wet season and low in the dry season, with a decreasing trend in the flood period during the first 10 years of operation compared to the 1990s level. The monthly pattern trends are similar to the temporal sedimentation distribution (Fig. 1).

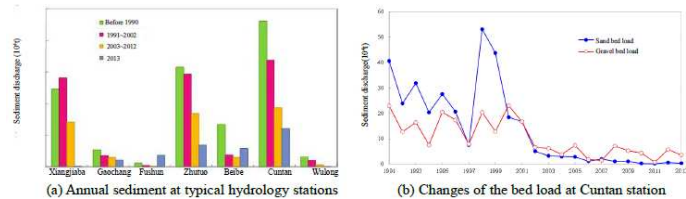


Fig. 6 Changing trends of the runoff into the TGR

As the inflow control point of the upper Yangtze River into the TGR, the accumulated curve of annual sediment load at Cuntan station versus year was used to test the inconsistency of the sediment discharge by the existence of an obvious change on the relationship curve, which began to bend slightly in 1991 and then leveled off in 2002 (Fig. 7a). These phenomena indicated that there were two stages in the reduction process of the sediment discharge in the past 30 years; 1991 and 2002 can be regarded as the turning point for the reduction of the sediment supply into the TGR. The rating curves of annual water discharge versus sediment discharge at Cuntan station for the three time series divided by the turning points of 1991 and 2003 (Fig. 7b) shows that the correlation of the water-sediment regression line declined with the three time series of 1953-1990, 1991-2002, and 2003-2013. The positive correlation decreased over time, which can be ascribed to anthropogenic activities such as dam construction, water and soil conservation, and sand excavation in recent years.

To test the sensitivity of the reservoir sedimentation response to the sediment discharge and the runoff into the TGR, the correlations of the sedimentation-sediment discharge and the sedimentation-runoff relationship were examined (Fig. 8). Regression lines indicate that the sedimentation is more dependent on the sediment discharge ( $R^2=0.7064$ ,

larger than the value with the runoff change trends  $R^2=0.4043$ ). Anthropogenic activity has been recognized as the dominant factor in the sharp decrease in the sediment load of the Yangtze River in recent years. After reservoir operations on the upper Yangtze River (Jinsha River) and the main tributaries over the next decades (Fig. 9), the sediment discharge could decrease more rapidly, leading to a reduction in the sedimentation process.

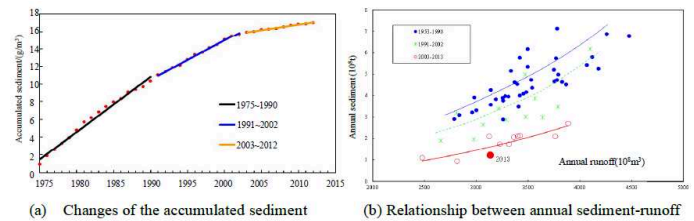


Fig.7 Turning year of the annual water discharge versus sediment discharge at Cuntan station

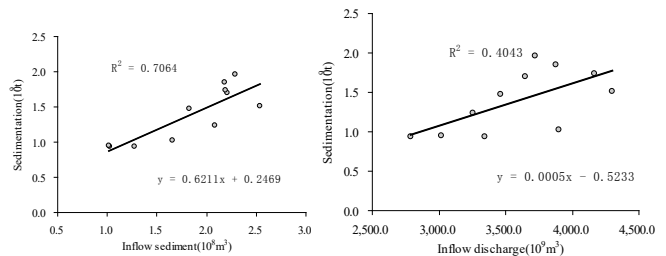


Fig. 8 The relationship between the control factor and the reservoir sedimentation



Fig. 9 Dam constructions on the upper Yangtze River

## CONCLUSIONS

Human impacts on channel morphology and fluvial processes include both indirect and direct influences. With the impoundment of the Three Gorges Reservoir on the upper Yangtze River, the alteration of the hydrodynamic conditions and sediment transport characteristics not only occurred in the downstream, but also in the backwater area of the TGR. The sedimentation reached 1.46 billion  $m^3$  after the first 10 years of operation in 2013. Few studies have attempted to determine the main deposition reach sections or the controls for the reservoir sedimentation process. Based on field data from 1990 to 2013, the temporal variation in the relationship of sediment-runoff shows the two turning points for the decreased stage in the inflow sediment occurred in 1990 and 2002, illustrating that the inlet condition is not influenced by the operation of TGR, and the reduction of the sediment supply would lead to a decreasing trend of the sedimentation process. As the outlet condition, the operation scheme relating to the water level fluctuations in the



backwater area directly affects the sedimentation: deposition increases with the raising of the pool level at the dam. According to the field measurements of the river bed map in the backwater area of TGR, the main deposition reach sections can be divided into three patterns: meandering, broad-valley, and braided, accounting for about 84% of the total sedimentation. The response of the channel pattern to the sedimentation can be regarded as a vital factor in controlling the spatial distribution of the deposition. The relationship of inflow to discharge-sediment, operation scheme, and the channel pattern contributes to the temporal and spatial distribution of the sedimentation in the Three Gorges Reservoir.

## ACKNOWLEDGEMENTS

This research is supported by the National Natural Science Foundation of China (51409027), Chongqing Research Program of Application Foundation and Advanced Technology (cstc2016jcyjA0121).

## REFERENCES

- Aleem, A. A. (1972). Effect of river outflow management on marine life. *Marine Biology*, 5, 200-208.
- Batalla, R.J., Gomez, C.M., Kondolf, G.M. (2004). Reservoir-induced hydrological changes in the Ebro River basin (NE Spain). *Journal of Hydrology*, 290, 117-136.
- Chen, Z., Li, J., Shen, H., Wang, Z. (2001). The Yangtze River of china: historical analysis of discharge variability and sediment flux. *Geomorphology*, 41, 77-91.
- Dai Zhijun, Liu James T. (2013). Impacts of large dams on downstream fluvial sedimentation: A example of the Three Gorges Dam (TGD) on the Changjiang (Yangtze River). *Journal of Hydrology*, 480, 10-18.
- Fan, J. and Morris, G.L. (1992). Reservoir sedimentation, II: Reservoir desiltation and long-term storage capacity. *Journal of Hydraulic Engineering*, 118, 370-384.
- Graf, W.L. (2006). Downstream hydrologic and geomorphic effects of large dams on American rivers. *Geomorphology*, 79, 336-360.
- Guo, H., Qi, H., Zhang, Q., Feng, S. (2012). Effects of the Three Gorges Dam on Yangtze River flow and river interaction with Poyang lake, China: 2003-2008. *Journal of Hydrology*, 416, 19-27.
- Kiss T., Fiala K., Gy, Sips. (2008). Alterations of channel parameters in response to river regulation works since 1840 on the lower Tisza River (Hungary). *Geomorphology*, 98, 96-110.
- Kummu, M., Lu, X.X. Wang, J.J., Varis, O. (2010). Basin-wide sediment trapping efficiency of emerging reservoirs along the Mekong. *Geomorphology*, 119, 181-187.
- Li Qiongfang, Yu Meixiu, Lu Guobin, Cai Tao. (2011). Impacts of the Gezhouba and Three Gorges reservoirs on the sediment regime in the Yangtze River, China. *Journal of Hydrology*, 403, 224-233.
- Lu, X.X., Higgitt, D.L. (2001). Sediment delivery to the Three Gorges 2: local response. *Geomorphology*, 41, 157-169.
- Lu X., Jiang T. (2009). Larger Asian rivers: Climate change, river flow and sediment flux. *Quaternary International*, 208, 1-3.
- Nilsson, C., Reidy, C.A., Dynesius, M., Revenga, C., 2005. Fragmentation and flow regulation of the world's large river systems. *Science*, 308, 405-408.
- Sun, Z.D., Huang, Q., Opp, C., Henning, T., Marold, U. (2012). Impacts and implications of major changes caused by the Three Gorges Dam in the middle reaches of the Yangtze River, China. *Water Resources Management*, 26, 3367-3378.
- Sloff, C.J. (1991). Reservoir sedimentation in reservoirs: literature review. Report No. 91-2, Civil Engineering Department, Delft University of Technology, Delft, The Netherlands
- Wang Suiji, Yan Yunxia, Li Yingkui. (2012). Spatial and temporal variations of suspended sediment deposition in the alluvial reach of the upper Yellow River from 1952 to 2007. *Catena*, 92, 30-37.
- Wolf A., Bergmann A., Wilken Rolf-Dieter, GaoX. (2013). Occurrence and distribution of organic trace substances in waters from the Three Gorges Reservoir, China. *Environmental Science and Pollution Research*, 20, 7124-7139.
- Xu, K., Milliman, J. (2009). Seasonal variations of sediment discharge from the Yangtze River before and after impoundment of the Three Gorges Dam. *Geomorphology*, 104, 276-283.
- Xiong, M., Xu, Q.X., Yuan, J. 2009. Analysis of multi-factors affecting sediment load in the Three Gorges Reservoir. *Quaternary International*, 208, 76-84.
- Yang, S.L., Milliman, J.D., Li, P., Xu, K. (2011). 50,000 dams later: erosion of the Yangtze River and its delta. *Global and Planetary Change*, 75, 14-20.
- Yan Qingyun, Yu Yuhe Feng Weisong. (2008). Plankton community composition in the Three Gorges Reservoir Region revealed by PCR-DGGE and its relationships with environmental factors. *Journal of Environmental Sciences*, 20, 732-738.
- Yang ZhengJian, Liu DeFu, Ji DaoBin, Xiao ShangBin. (2010). Influence of the impounding process of the Three Gorges Reservoir up to water level 172.5 m on water eutrophication in the Xiangxi Bay. *Science China Technological Sciences*, 53, 1114-1125.
- Zhang Jixian, Liu Zhengjun, Sun Xiaoxia. (2009). Changing landscape in the Three Gorges Reservoir Area of Yangtze River from 1977 to 2005: Land use/land cover, vegetation cover changes estimated using multi-source satellite data. *International Journal of Applied Earth Observation and Geoinformation*, 11, 403-412.