Estimating sediment trapping efficiency from Landsat images: a case study of the Yellow River basin

LISHAN RAN & XIXI LU

Department of Geography, National University of Singapore, 117570 Singapore

ranlishan@gmail.com

Abstract This paper is concerned with the man-made reservoirs constructed in the Yellow River basin. Given the shortcomings of conventional approaches to assessing reservoirs constructed in large river basins, remote sensing techniques offer several benefits. Remote sensing data can provide high-resolution synoptic and repetitive information at short time intervals. Based on the results of reservoir delineation and storage capacity estimation, in this study the Yellow River basin was divided into 12 sub-basins for which the water residence time and potential sediment trapping efficiency were explored. Water cycling in the basin has been greatly regulated and its residence time increased to 3.97 years during 2006–2009. The basin-wide sediment trapping efficiency is 95.2%, indicating that most sediment entering the channels would be trapped by the reservoirs. With more reservoirs to be completed, it is expected that flow regulation will become much more important and that the sediment flux reaching the ocean will further decrease.

Key words water residence time; sediment trapping efficiency; Landsat; Yellow River basin

INTRODUCTION

To meet the increasing human need for water resources and energy, a large number of reservoirs have been constructed around the world, especially in recent decades. By altering the spatial and temporal distribution of water discharge, reservoirs provide regulated water supply to meet a range of social, economic and environmental requirements, greatly reducing human reliance on the natural availability of water. Recent statistical reports indicate that globally about 70% of rivers are intercepted by large reservoirs (Nilsson *et al*., 2005), and that more than 45 000 dams of over 15 m height have been commissioned since the beginning of the 20th century, representing nearly an order of magnitude increase in the number of dams since 1950 (World Commission on Dams, 2000). Many dams have been constructed in developing countries, such as China, to meet the demands of growing populations in both riparian and more distant urban communities. According to Zhang *et al.* (2008), more than 85 000 reservoirs have been constructed in China to exploit the available water, to serve various conservation purposes and to control flooding. In view of the limited availability of good storage sites, due to topographic constraints, it is important to preserve the “live” storage capacity of constructed reservoirs as much as possible. There is therefore an important need for ongoing evaluation of the loss of storage caused by sediment deposition in reservoirs and to update control measures at both the reservoir and basin level.

Traditionally, surveys of reservoir distribution and estimation of their storage capacity are based on topographic maps and *in situ* hydrographic surveys with an electronic planimeter, which provide both overwater and underwater topographic surveys (Onikienko, 1995; Peng *et al*., 2006). Most often, an acoustic device is used for underwater topographic surveys, while overwater topographic surveys involve field or aerial photogrammetric surveys. This traditional approach is usually labour intensive, costly and time-consuming. In addition, owing to the complexities of terrain variability and potential discrepancies between the results provided by different equipment used in reservoir surveys, an accurate assessment of the reservoirs constructed in larger basins is often hard to obtain. In contrast, monitoring reservoirs using satellite images has become more convenient and far less expensive (Wang *et al*., 2004). Satellite real-time technology permits large-scale observation and assessments at different scales. The spatial, spectral and temporal attributes of remote sensing data provide valuable and timely information for reservoir operation and management (Liebe *et al*., 2003). However, it has rarely been used for reservoir delineation and studying the spatial distribution of reservoirs. Equally, it has rarely been applied to support detailed quantitative assessment of reservoir storage capacity, residence time and sediment trapping efficiency (Propastin, 2008). The few existing studies have focused on individual reservoirs or relatively small watersheds and, as a result, only preliminary applications have been reported in the literature (Magome *et al*., 2002). Applications to groups of reservoirs or to large basins are relatively rare.

In the Yellow River basin, large-scale reservoir construction began in the 1960s (WaterPub, 2007). The current total storage capacity of all registered reservoirs is estimated to be about 72 km^3, which is ~116% of the natural annual water discharge (Li & Yang, 2004). However, most of these reservoirs have not been accurately mapped for management and research purposes. Given that the Yellow River is characterized by a high suspended sediment load and that a substantial proportion of that sediment is deposited in reservoirs, reservoir sedimentation and the resulting loss of storage capacity have adversely affected water availability and the operation of river regulation schemes. The objectives of this study are therefore to evaluate impacts of reservoirs on water cycling and sediment delivery. This paper is based on the results presented by Ran & Lu (2012).

DESCRIPTION OF THE STUDY AREA

The Yellow River originates on the Qinghai-Tibet Plateau and has a length of 5464 km (Fig. 1). It drains a large basin of about 752 000 km^2 with a wide spectrum of climatic and geological characteristics. The mean annual precipitation is highly variable across the basin, varying from ~700 mm in the southeast to ~250 mm in the northwest. In addition, the climate is characterized by significant seasonality. Approximately 85% of the annual precipitation falls during the wet summer (June–September) (Wang *et al*., 2007). Most of the river basin experiences semi-arid conditions and the multi-year mean annual runoff is 77 mm (Wu *et al*., 2008). Geologically, the upper part of the basin is located on the uplifted Qinghai-Tibet Plateau, the middle part on the Loess Plateau and the lower part on the North China Plain (Fig. 1).

Water discharge in the basin has decreased sharply in recent decades, in response to both climate change and anthropogenic influences. For the whole basin, the mean annual discharge for the period 1950–1959 at Lijin, the lowest gauging station on the river, was about 47.4 km^3, but in the past decade (2000–2009) it has declined to 14.1 km^3. To examine the influence of human activity on water resources and the hydrological cycle, several studies have tried to reconstruct the natural water discharge (e.g. Zhao, 1996; Li & Yang, 2004). According to Li & Yang (2004), the natural mean annual water discharge at Toudaoguai station, located in the upper reaches of the basin, was 35.77 km^3 and the equivalent value for the whole basin was 62.23 km^3.

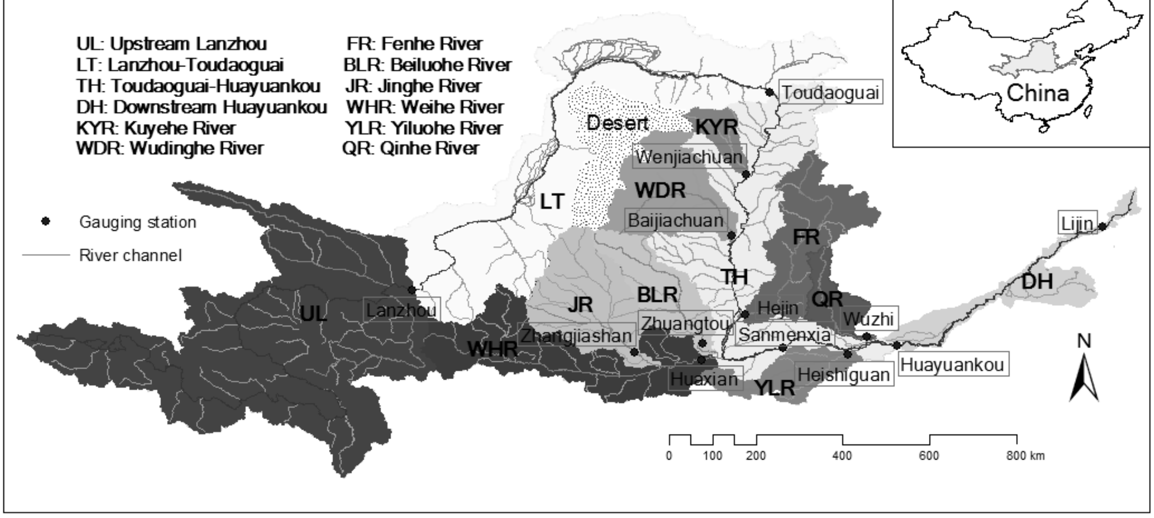

Fig. 1 Sketch map of the Yellow River basin. The 12 sub-basins are also shown.

The mean annual suspended sediment load at Sanmenxia station was about 1.6×10^9 t prior to the 1950s (Zhao, 1996), of which 9% originated from the upper basin (above Toudaoguai) and 89.7% from the middle reaches of the basin (Xu & Yan, 2005), and especially the Loess Plateau which is well-known for severe soil erosion and high sediment yields. The spatial sources of water and sediment in the Yellow River basin are quite different (Xin *et al*., 2011). Although most of the sediment load is supplied by the area below Toudaoguai, ~57% of the water comes from the upper reaches. The high sediment yield coupled with the low transport capacity of the runoff makes the Yellow River distinctive from other large rivers in the world.

Due to limitations imposed by the geological conditions, almost all the large- and medium-sized reservoirs are located in the upper basin or on the channels of the middle reaches of the basin (Ran & Lu, 2012). In the lower reaches, high sediment deposition in the channel causes major problems for the local population, since the river channel is at a higher level than the surrounding land. In addition, a large number of small reservoirs have been constructed within the Loess Plateau, in order to reduce sediment delivery to the main rivers.

MATERIALS AND METHODS

Data sources

Seventy-four images covering the entire basin were downloaded from the Landsat imagery database for reservoir identification and analysis (Ran & Lu, 2012). To minimize interference by clouds, only images with a cloud cover less than 5% were selected. The overpass dates of the images extend from May 2006 to October 2009, and almost all the images (93%) were taken during the wet season to avoid errors associated with using images relating to different seasons. For example, a reservoir's water surface area is likely to vary considerably between the dry season and flood season, especially in semi-arid areas, such as the Yellow River basin, where the seasonal variation of precipitation is marked. For this reason, the downloaded satellite images aimed to capture a reservoir's greatest surface area at its highest water level. Due to the lack of suitable satellite coverage of the entire river basin taken in a single year, the estimates of reservoir storage capacity, residence time and sediment trapping efficiency are based on the assumption that no new reservoirs were completed during the study period (2006–2009).

Sediment load and water discharge data were obtained from the *Yellow River Hydrological Yearbooks* produced by the Yellow River Conservancy Commission (YRCC), which regularly publishes hydrological records from a network of hydrological stations for internal use.

Reservoir delineation

The infrared, visible red and near-infrared bands provided by the Landsat images were used to distinguish between land and water and to map the extent of open water surfaces (Annor *et al*., 2009). In the near-infrared and mid-infrared wavelengths, water, when not turbulent, increasingly absorbs energy making it appear darker on the satellite images, while vegetation appears as bright spots or stripes. This discrimination is, however, dependent upon water depth and wavelength. For the visible spectrum, water bodies generally have a high reflectance. However, this also depends on the turbidity, since clearer water tends to have a lower reflectance than turbid water. A combination of bands 7, 4 and 3 was used to separate water bodies from surrounding surface features. Before discriminating water bodies from other surface feature categories, the satellite images were first pre-processed, including radiance and atmospheric corrections. All the information extraction steps were conducted on the ENVI 4.5. Further details of the reservoir delineation procedure can be found in Ran & Lu (2012). In total, 2816 reservoirs, with a total water surface area of about 2380.65 km^2, were identified from the remote sensing images, which accounts for 89.5% of the official reservoir inventory (Ran & Lu, 2012).

RESULTS AND DISCUSSION

Residence time changes and their impacts

As a completed reservoir is put into operation, the water inflow will be intercepted and the released flow will be reduced to varying extents, depending on the reservoir's operation scheme. While various human needs can be met by water interception and storage, reservoir operation also causes a substantial distortion of the freshwater runoff from the continents to the ocean, increasing the time taken by water to be transferred along river channels to the oceans (Wisser *et al.*, 2010). Vörösmarty *et al.* (1997) introduced the concept of river water ageing to illustrate the impact of the construction of artificial impoundments on river flow regimes and the water cycle. The average length of time water remains within a reservoir is one of the key parameters determining a number of direct and indirect changes in its physical, biogeochemical, geomorphological and hydrological behaviour, including hydrograph distortion, nutrient exchange, microbial growth and sediment trapping (Wisser *et al.*, 2010).

Further study of these secondary effects requires a clear understanding of water transport and mixing, as they are closely interrelated. The extent to which reservoirs affect flow distribution and transfer varies from place to place, due to differences in the natural conditions and social requirements. The timescale, which is generally referred to as the residence time, therefore provides a first-order description of multiple and complex processes occurring within the waters of the reservoir considered. For all the reservoirs located in a given basin, the average residence time ($\Delta\tau_{reg,j}$) is defined as follows (Vörösmarty *et al.*, 2003):

$$\Delta\tau_{reg,j} = \frac{\sum_{i=1}^{n_j} V_i}{Q_j} \qquad (1)$$

where, V_i is the estimated volume of reservoir i storage (km^3) and Q_j is the annual discharge at the mouth of each regulated sub-basin j (km^3 year^{-1}).

To obtain an in-depth understanding of the impacts of reservoir operation on flow regulation within the Yellow River basin, the basin was further divided into 12 sub-basins. The mainstem was divided into four reaches: the reach upstream of Lanzhou (UL), the reach between Lanzhou and Toudaoguai (LT), the reach between Toudaoguai and Huayuankou (TH), and the reach below Huayuankou (DH). Eight major tributaries located in the high sediment yielding loess region were extracted for individual consideration. In addition, four mainstem gauging stations: Toudaoguai, Sanmenxia, Huayuankou and Lijin, were used to define the cumulative response of the basin from upstream to its outlet at Lijin (see Fig. 1).

In order to provide an objective assessment of the residence time associated with the reservoirs, we used the estimates of natural water discharge provided by Li & Yang (2004), which were assumed to be affected by climate change alone. The results revealed the extent to which the reservoirs can affect the water cycle in theory. The spatial variation of residence time for the 12 sub-basins is presented in Fig. 2.

Individually, most of the major tributaries have low residence times (<0.4 year), indicating that the reservoirs associated with each tributary have the capability to store the water input for around five months without releasing it. In the case of the Beiluohe, Weihe, Jinghe, Kuyehe and Qinhe rivers, the water exchange rate was relatively fast, implying that the reservoirs exert a more limited effect on the water cycle relative to other sub-basins. In contrast, with a residence time of 0.78 year, the Wudinghe River shows an exceptionally strong impact on water discharge exchange. With its concentrated rainfall regime, erodible soils and degraded vegetation resulting from human activities, the Wudinghe River experiences very severe erosion and has been identified as a national key area for soil erosion control since 1982 (Xu, 2004). Since then, a number of reservoirs have been constructed, resulting in the high residence time and thus greatly reducing the exchange rate, since the primary the role of these reservoirs is to intercept sediment.

The residence time indicates the degree to which a river's flow regime has been altered by reservoirs (Wisser *et al.*, 2010). The impacts of these impoundments vary depending on the

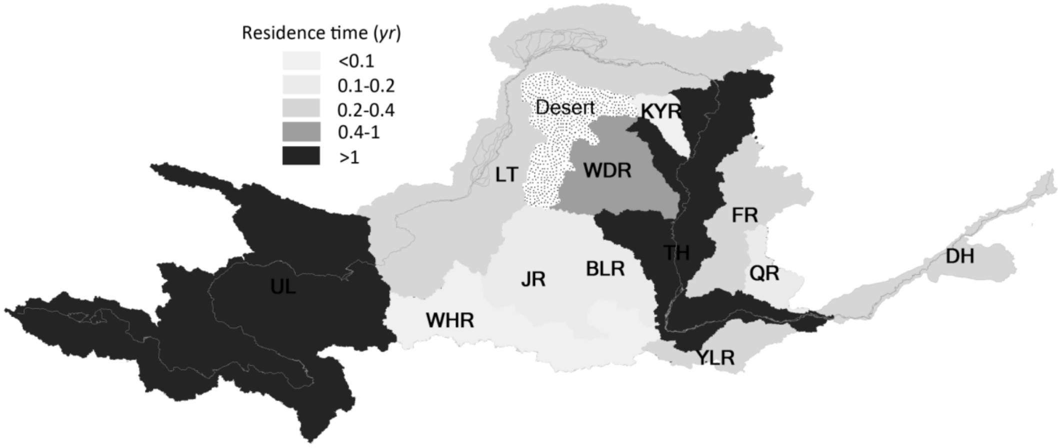

Fig. 2 Spatial variation of residence time within the river basin.

number and size of the reservoirs, their location in the river basin, as well as their storage capacity. To assess the magnitude of flow regulation resulting from reservoir operation in recent years, we have also determined the residence time for the period 2006–2009 (Fig. 3). The differences between these values and the initial values under natural conditions provide an indication of the degree of flow regulation. During the period 2006–2009, the residence time in all the tributaries has increased significantly due to large-scale reservoir construction. In particular, in the Wudinghe, Weihe, Jinghe and Yiluohe rivers, the residence time has doubled; while in the Qinhe, Kuyehe and Fenhe rivers, the residence time was >3 times the initial value. Substantially reduced water exchange rates lead to alterations in the flow regime, reflecting the strong regulation impacts of reservoirs on water flow.

For the whole Yellow River basin, upstream of Lijin, the residence time has tripled to 3.97 years. The long residence time is consistent with the reports of strong flow regulation in the basin (Vörösmarty *et al*., 2000; Nilsson *et al*., 2005). Vörösmarty *et al*. (2000) indicated that the Nile and Colorado rivers represent the world rivers most impacted by anthropogenic disturbances in terms of residence time (>1 year) and flow regulation. However, their work is likely to have underestimated the residence times because only large reservoirs were considered. It therefore seems reasonable to conclude that the Yellow River is at least amongst the top three of the list of impacted rivers, if not the first.

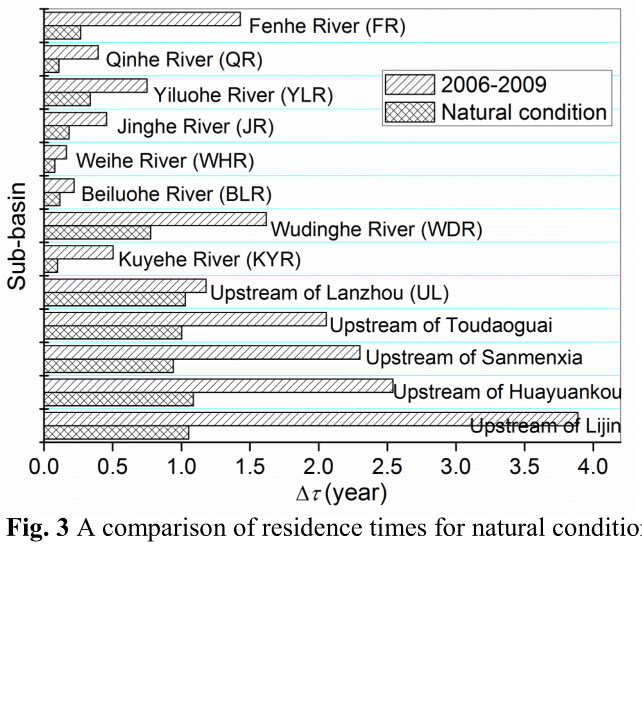

Fig. 3 A comparison of residence times for natural condition and the period 2006–2009.

Estimation of sediment trapping efficiency

The land–ocean transfer of sediment by rivers represents a fundamental pathway within the global geochemical cycle. Numerous attempts have been made to estimate the sediment flux to the oceans over varying spatial and temporal scales, although accurate estimates still remain elusive and many uncertainties exist (Syvitski *et al*., 2005). The construction of dams has considerably changed the flow regimes of many world rivers and has also resulted in changing sediment fluxes to different degrees, depending on the characteristics of the sediment inflow and the mode of operation of the reservoirs involved.

For a single reservoir, the theoretical amount of trapped sediment can be calculated through the empirical sediment retention function originally developed by Brune (1953). The same approach can also be employed for predicting the total amount of sediment trapped by a group of reservoirs in a basin (Vörösmarty *et al*., 2003). Here, the refined approach proposed by Vörösmarty *et al*. (2003) was used. This divides a basin into several sub-basins with each sub-basin being gauged at its outlet. Initially, the residence time change for each sub-basin ($\Delta\tau_{reg,j}$) is determined using an aggregate-impounded storage volume and discharge (equation (2)). Then, the aggregate trapping efficiency for each sub-basin ($TE_{reg,j}$) is estimated and finally, the whole basin sediment trapping efficiency (TE_{bas}) is adjusted by a discharge weighting associated with unimpounded inter-fluvial areas. The formulae employed are as follows:

$$TE_{reg,j} = 1 - \frac{0.05}{\sqrt{\Delta\tau_{reg,j}}} \qquad (2)$$

$$TE_{bas} = \frac{\sum_{j=1}^{m} TE_{reg,j} Q_j}{Q_m} \qquad (3)$$

where, Q_m is annual discharge at the basin mouth (km^3 year^{-1}), n_j is the number of reservoirs in each regulated sub-basin *j*, and *m* is the number of regulated sub-basins.

The estimates of sediment trapping efficiency are presented in Table 1. In the tributary basins, at least 82% of the sediment will be trapped by the reservoirs. In the case of the Wudinghe River, 94.3% of its sediment load will be trapped, because of the large storage capacity of its reservoirs in comparison with the annual water discharge. For the mainstem cumulative basins, the trapping efficiency does not show significant spatial variation, and is stable at ~95%. Overall, about 95.2% of the sediment entering the channels in the Yellow River basin will be trapped by the reservoirs. Reservoir impoundment has been an important reason for the reduced sediment flux entering the ocean (Wang *et al*., 2007). With more reservoirs to be completed, it is expected the sediment load reaching the ocean will further decrease.

CONCLUSIONS

Relative to conventional methods, the use of remote sensing data has been shown to provide a rapid and effective approach for assembling information on the distribution of reservoirs within a river basin, especially for large-scale study areas. Landsat images covering the Yellow River basin have been used to assess the flow residence time and the sediment trapping efficiency of the reservoirs.

In combination with water discharge data measured at the outlet of each sub-basin, residence time analyses showed strong flow regulation resulting from reservoir operation. The extent to which reservoirs affect water exchange varies greatly between the sub-basins. Comparison of residence times relating to natural water discharge and recently measured data reveals strong flow regulation over the past decades. As regards the whole river basin, water cycling in the basin has been greatly regulated and its residence time has increased to 3.97 years during 2006–2009, ranking the Yellow River in the top three of the world's large river systems in terms of the degree

Table 1 A summary of the sediment trapping efficiency of the sub-basins.

Sub-basin	Controlling station	Storage (km^3)	Natural annual discharge (km^3 $year^{-1}$)	*TE* (%)
Mainstem stretch:				
Lanzhou-Toudaoguai (LT)	Toudaoguai	0.605	1.527	92.1
Toudaoguai-Huayuankou (TH)	Huayuankou	25.151	5.258	97.7
Downstream Huayuankou (DH)	Lijin	0.881	2.649	91.2
Tributaries:				
Kuyehe River (KYR)	Wenjiachuan	0.073	0.753*	83.9
Wudinghe River (WDR)	Baijiachuan	1.196	1.541*	94.3
Beiluohe River (BLR)	Zhuangtou	0.103	0.89	85.3
Weihe River (WHR)	Huaxian	0.595	6.976	82.9
Jinghe River (JR)	Zhangjiashan	0.447	1.953	89.6
Yiluohe River (YLR)	Heishiguan	1.058	3.153	91.4
Qinhe River (QR)	Wuzhi	0.129	1.186	84.9
Fenhe River (FR)	Hejin	0.56	2.103	90.3
Mainstem cumulative basin:				
Upstream of Lanzhou (UL)	Lanzhou	35.912	34.244	95.1
Upstream of Toudaoguai	Toudaoguai	36.517	35.771	95.1
Upstream of Sanmenxia	Sanmenxia	53.825	54.13	95
Upstream of Huayuankou	Huayuankou	65.108	59.584	95.2
Upstream of Lijin (whole basin)	Lijin	66.71	62.233	95.2

* The natural annual discharge of the Kuyehe and Wudinghe rivers were averaged based on measured data during 1956–1969 provided by the YRCC (1950–2009); this period is usually assumed to lack strong human impact and flow varied under "natural" conditions (Ran & Lu, 2012).

of regulation. In the future, it is estimated that decreasing water discharge and increasing storage capacity due to continued reservoir construction are likely to further increase residence times. Most of the sediment entering the channels will be trapped, although the trapping efficiency is spatially variable. For the whole river basin, about 95.2% of the sediment entering the river system will be intercepted. Reservoir impoundment represents an important cause of the recently observed reduction of the sediment load reaching the Bohai Sea.

Acknowledgements This work was financially supported by a grant from the National University of Singapore (R-109-000-086-646). We are grateful to Professor Des Walling for his constructive comments.

REFERENCES

Annor, F. O., van de Giesen, N., Liebe, J., van de Zaag, P., Tilmant, A. & Odai, S. N. (2009) Delineation of small reservoirs using radar imagery in a semi-arid environment: a case study in the upper east region of Ghana. *Physics and Chemistry of the Earth* 34, 309–315.

Brune, G. M. (1953) Trap efficiency of reservoirs. *Transactions of the American Geophysical Union* 34, 407–418.

Li, C. H. & Yang, Z. F. (2004) Division assessment of natural runoff in the Yellow River basin. *Journal of Beijing Normal University (Natural Science)* 40(4), 548-553 (in Chinese).

Liebe, J., van de Giesen, N. & Andreini, M. (2003) Region-wide estimation of small reservoir storage capacities and evaporation losses in a semi-arid environment. A case study in the upper east region of Ghana. *EGS-AGU-EUG Joint Assembly* 6-11 April, Nice, France, vol.5, 6946.

Magome, J., Takeuchi, K. & Ishidaira, H. (2002) Estimating water storage in reservoirs by satellite observations and digital elevation model: A case study of the Yagisawa Reservoir. *J. Hydroscience and Hydraulic Engineering* 20(1), 49–57.

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.

Onikienko, T. S. (1995) Corrected correlations between the capacity and levels of the Ust'-Khantaika hydroelectric power plant. *Power Technology and Engineering* 29, 157–163.

Peng, D., Guo, S., Liu, P. & Liu, T. (2006) Reservoir storage curve estimation based on remote sensing data. *Journal of Hydrologic Engineering* 11, 165–172.

Propastin, A. P. (2008) Simple model for monitoring Balkhash Lake water levels and Ili River discharges: Application of remote sensing. *Lakes & Reservoirs: Research and Management* 13(1), 77–81.

Ran, L. & Lu, X. X. (2012) Delineation of reservoirs using remote sensing and their storage estimate: an example of the Yellow River Basin, China. *Hydrological Processes* 26, 1215-1229.

Syvitski, J. P. M., Vörösmarty, C. J., Kettner, A. J. & Green, P. (2005) Impacts of humans on the flux of terrestrial sediment to the global coastal ocean. *Science* 308, 376–380.

Vörösmarty, C. J., Meybeck, M., Fekete, B., Sharma, K., Green, P. & Syvitski, J. P. M. (2003) Anthropogenic sediment retention: major global impact from registered river impoundments. *Global and Planetary Change* 39, 169–190.

Vörösmarty, C. J., Sharma, K., Fekete, B., Copeland, A. H., Holden, J., Marble, J. & Lough, A. (1997) The storage and aging of continental runoff in large reservoir systems of the world. *Ambio* 26, 210–219.

Wang, H., Yang, Z., Saito, Y., Liu, J.P., Sun, X. & Wang, Y. (2007) Stepwise decreases of the Huanghe (Yellow River) sediment load (1950–2005): impacts of climate change and human activities. *Global and Planetary Change* 57, 331–354.

Wang, Y., Xia, H., Fu, J. & Sheng, G. (2004) Water quality change in reservoirs of Shenzhen, China: detection using LANDSAT/TM data. S*cience of the Total Environment* 328, 195–206.

WaterPub (2007) *Introduction to the Yellow River*. China WaterPower Press, Beijing (http://www.waterpub.com.cn/jhdb/DetailRiver.asp?ID=2).

Wisser, D., Fekete, B. M., Vörösmarty, C. J. & Schumann, A. H. (2010) Reconstructing 20th century global hydrography: a contribution to the Global Terrestrial Network-Hydrology (GTN-H). *Hydrological and Earth System Sciences* 14, 1–24.

World Commission on Dams (2000) *Dams and Development: A new framework for decision-making*. Earthscan, London, UK.

Wu, B., Wang, G., Xia, J., Fu, X. & Zhang, Y. (2008) Response of bankfull discharge to discharge and sediment load in the Lower Yellow River. *Geomorphology* 100, 366–376.

Xin, Z. B., Yu, X. X. & Lu, X. X. (2011) Factors controlling sediment yield in China's Loess Plateau. *Earth Surface Processes and Landforms* 36, 816–826.

Xu, J. X. (2004) Response of erosion and sediment producing processes to soil and water conservation measures in the Wudinghe River Basin. *Acta Geographica Sinica* 59, 972–981 (in Chinese).

Xu, J. X. & Yan, Y. X. (2005) Scale effects on specific sediment yield in the Yellow River basin and geomorphological explanations. *Journal of Hydrology* 37, 219-232.

YRCC (1950-2009) *Yellow River Sediment Bulletin*. The Ministry of Water Resources of China (http://www.mwr.gov.cn/).

Zhang, Z., Chen, Y., Tian, H., Ding, H., Wang, W. & Pan, S. (2008) Calculation of reservoir-retained sediment and characteristics of sediment distribution of the Yellow River basin. *Soil and Water Conservation in China* 4, 20–23 (in Chinese).

Zhao, W. L. (1996) *Water Resources Science and Technology Series of the Yellow River: Sediment*. Yellow River Water Resources Press, Zhengzhou (in Chinese).

.