The characteristics of sediments in the middle and lower Yangtze River influenced by dam operation

Anan Guo1,2, Li He*1
1Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China
2College of Resources and Environment, University of Chinese Academy of Sciences, Beijing, 100049, China
*heli@igsnrr.ac.cn

Abstract. Since the Three Gorges Dam (TGD) was operated, the sediment characteristics in the downstream river have changed significantly. The characteristics of sediments can be partly reflected by the critical diameter to distinguish wash load and bed material load (WAB) and the ratio of wash load to suspended sediment (WTS). However, the WAB and WTS of the Yangtze River (YR) have not been fully investigated. In this study, data of sized suspended sediment and bed material at four stations in the middle and lower YR were collected to calculate the WAB and WTS, using the most-curvature method. The variations were then analyzed. The results suggest that the WAB and WTS of Yichang station varied greatly before the impoundment, while that of other stations were in small fluctuations. After the impoundment, the WAB of Yichang station increased dramatically to 1.856 mm, and the growth rate of the WAB at Jianli and Hankou stations were 1.0% and 4.1%, respectively (compared with WAB in 2002), while that of Datong station was -8.4%. Comparing with the rising WAB, the WTS of Yichang station continued to rise until it was close to 100%. However, the WTS of other stations decreased overall (30%-40% in Jianli and Hankou, and 8% in Datong).

1. Introduction

Changed sediment characteristics caused by dam construction is one of the most important problems in the field of sediment dynamics[1]. Researchers have investigated the amount of the sediment out of reservoirs and the sediment composition divided by particle size in the downstream river after the dam operation[2-3]. Another way of showing sediment composition is classifying sediments into two parts, wash load (WL) and bed material load (BML)[4-5], which is also significant to represent sediment characteristics. Accordingly, many studies appeared on the topic of the critical diameter for distinguishing the WL and BML (WAB) and the ratio of two kinds of loads (e.g. WTS, which means the ratio of WL to suspended sediment). However, the studies of the variations of WAB and WTS caused by the dam operation are still lacked and the influence of the distance to the dam was not fully considered.

WAB reflects the characteristics of sediments depending on the sources[6]. The separation of sediments to wash and bed material loads has been conducted in previous research[7-9]. In 1986, Yu [10] concluded that 0.05mm could be used as the critical size to distinguish BML and WL in the middle and lower reaches of the Yangtze River (YR). Fang [11] used the most-curvature method to distinguish WL and BML and found that the majority of the cross-sectional average WAB was greater than 0.06mm, which is close to the usual diameter limit of 63 microns (boundary between sand and silt) between WL
and BML[12-13], and the proportion of WAB around 0.1mm was the highest. Despite the long-term rough mean value of WAB were obtained, which are aimed to simplify the analysis of sediment transport, the demand of reflecting precise changes of sediments cannot be met.

The ratio of two kinds of loads represents the composition of sediments. Chen et al.[8] believed that WTS accounted for more than 85% in the middle and lower reaches of general rivers. In a forest watershed in Iran, the ratio of the suspended bed material load to WL at all seasons was calculated[14]. There are other similar ways to describe the composition. A study demonstrated a simple linear relationship between WL and BML in the Yellow River, indicating a direct proportionality between them[15]. In the Tweed and the Humber watersheds, more than 95% of suspended sediment were smaller than 63 microns (usually be regarded as wash load) during 1994-1998[16]. However, the ways to describe the composition of sediment mentioned earlier share the same idea, but are not unified. Therefore, it is inconvenient to compare them among different articles. Moreover, the spatial and temporal variations of the ratio have rarely been examined.

In this study, we used the data of sized suspended sediment and bed material at four stations in the middle and lower YR to explore the changes of the sediment characteristics before and after the dam operation. We used the most-curvature method in order to calculate WAB and WTS and analyze their variations, thus contribute to promoting the research on sediment transport in the downstream of the dam.

2. Study Reach and Methodology

2.1. The Study Reach

The studied river reach ranges from Yichang to Datong hydrological stations (Figure 1). The middle YR ranges from Yichang station to Hukou. Downstream river reach of Hukou is the lower YR. Distance of the four stations from the Three Gorges Dam (TGD) are 40km, 340 km, 699km, and 1183km, respectively. The Han River is a branch of the YR. Dongting Lake and Poyang Lake are connected with the YR (Figure 1). Daily discharge and sediment concentration measured at Yichang, Jianli, Hankou, and Datong hydrological stations were collected. Data were measured and published in the yearbooks by the Changjiang Water Resources Commission.

In order to analyze the variations of WAB and WTS, data of sized suspended sediment and bed material were also collected. According to the operation of TGD, data measured in 1979-1985 and 2001-2002 were collected to represent the pre-operation stage, while data measured in 2003-2009 were collected to represent the operation stage.
2.2. Methodology

In this paper, WAB was determined using the most-curvature method\[17\]. The greater the curvature is, the faster the particle size changes in the critical zone of BML and WL, and the greatest-changed point is considered as the boundary of BML and WL.

The bed material grading curve can be described as a hyperbolic tangent function equation\[18\]. The maximum curvature point can be obtained by solving the extreme value of curvature. Eq. (1-3) could be adopted:

\[
\varphi = \frac{d_{75}}{d_{25}}
\]

(1)

\[
\varphi = 0.55 \cdot \log^{-1} \psi
\]

(2)

\[
\varphi = \frac{12x_r - 8}{3x_r^2 - 4x_r^2}
\]

(3)

in which, \(d_{25}\) and \(d_{75}\) represent the grain size with p=25% and 75%, respectively; \(\psi\) is a nonuniformity parameter; \(\varphi\) could be used to evaluate the uniformity of sediment gradation; and \(x_r\) is the root of the Eq. (3) in the range of 0 to 1. A large \(\varphi\) represents more uniformity and vice versa.

Eq. (4) is used to calculate the critical size:

\[
d_k = d_{50} \cdot 10^{-\frac{1}{2\varphi} \cdot \ln \frac{1+\sqrt{1-x_r}}{1-\sqrt{1-x_r}}}
\]

(4)

in which, \(d_k\) is WAB, and \(d_{50}\) is the median diameter of bed materials.

After WAB is determined by the most-curvature method, the corresponding mass percentage less than a certain particle size can be determined according to the suspended sediment grading curve. This percentage is defined as WTS.

3. Results

3.1. Variation of WAB

In order to compare the effects of dam operation on the WAB, data measured in 2002 (the year before impoundment) were also illustrated in Figure 2a. During the pre-operation stage (1979-1985, 2001-2002), the mean WAB of the four stations ranged from 0.04 to 0.1 mm. WAB tended to increase slightly at each station in 2002, up to a range of 0.08-0.1 mm. During the operation stage (2003-2009), the WAB of Yichang station increased dramatically to 1.856 mm. Compared with the WAB in 2002, the WAB of Jianli and Hankou stations grew slightly and the growth rate was 1.0% and 4.1%, respectively. The WAB of Datong station showed a slight decline, with decrements of 8.4% and 5.3%, respectively, compared with the WAB of 2002 and that of pre-operation stage (Figure 2a).

During the study years before and after the operation, the WAB of Yichang station had the greatest rise. The change of WAB at the rest three stations were limited. The WAB of Jianli and Hankou stations rose slightly, up to 0.106 mm and 0.104 mm respectively in 2009, and the WAB of Datong station dropped a little after the impoundment (0.08 mm in 2009). Since 2006 is a once-in-a-century dry year with less flow discharge and sediment load, the WAB of Datong in 2006 reached the lowest point (0.027 mm) (Figure 2b).
3.2. Variation of WTS

WTS changes according to the distance from the dam. Before the operation of the TGD, the mean WTS increased along the river reach of Yichang-Datong. After the TGD was built, the WTS of Yichang station was the greatest, then followed by Datong, Hankou and Jianli stations (Table 1).

From 2003 to 2009, the mean WTS at Jianli, Hankou and Datong stations were decreased by 34.78%, 17.36% and 5.73%, respectively, by comparing with that before the dam operation. It can be concluded that the farther to the dam, the less the attenuation of the WTS is. However, it is not applied to the nearest station to the dam. The mean WTS of Yichang station before and after impoundment were 0.59 and 0.97 respectively, with a growth rate of 63% (Table 1).

The WTS of Yichang station before impoundment varied greatly (about 40% during 1980-1984, 80% in 1979 and 1985) and the variance of WTS is 0.0613. It gradually rose to 85% before impoundment (in 2002), and then kept a stable growth until it was close to 100% (Figure 3a).

The WTS variations of other stations were completely different from that of Yichang station (Figure 3b, 3c, and 3d). Before the impoundment, the WTS of Jianli, Hankou and Datong stations were all in slight fluctuations (variances are 0.0008, 0.0020 and 0.0010, respectively, much lower than that of Yichang). During the operation stage, the overall trends of WTS showed declines with fluctuates (decreased by 30%-40% in Jianli and Hankou, and 8% in Datong). The WTS of Jianli and Datong stations both reached the lowest point in 2006 for a dry year (39.15% and 71.9%, respectively).

Table 1. The mean WTS and its variations of the stations in the downstream of the TGD during 1979-1985, 2001-2009.

|                  | Yichang | Jianli | Hankou | Datong |
|------------------|---------|--------|--------|--------|
| The mean WTS before the operation | 0.59    | 0.85   | 0.87   | 0.90   |
| The mean WTS after the operation  | 0.97    | 0.56   | 0.72   | 0.84   |
| Rate of change of WTS (%)          | 63.00   | -34.78 | -17.36 | -5.73  |
4. Discussion

This study suggests that, during the operation stage, the WAB and WTS in the downstream of the TGD were changed differently, according to the distance from the TGD (Figure 2, Figure 3).

Differences of WAB and WTS between Yichang and other downstream stations indicate that the influence of the TGD on the river reach near the dam is much apparent, while the change of channel geometry and size distribution of suspended sediment and bed material along the river reach may offset the influence.

After the impoundment of the TGD, the sediments in the lower reaches were thereby mainly consisted of fine particles and had a decreased number[2]. Accordingly, the sediment concentration decreased and sediment transport capacity increased after the impoundment in the lower reaches. It can be inferred that these phenomena caused the increase of the WAB in the downstream of the TGD. The WAB of Yichang station, which is the closest station to the TGD and was subjected strongest flow, increased significantly after the impoundment for the sharply decreased sediment concentration and the increased sediment transport capacity of the WL. The flow intensity of Jianli and Hankou stations was weaker than that of Yichang station, but it still increased compared with that before the impoundment, and the sediment transport concentration decreased. As a result, the WAB of Jianli and Hankou stations increased slowly. The WAB of Datong station decreased slightly after the impoundment for more fine sediments were supplied than other stations [19] and the influence of dam construction is slight. These explanations for the variations of WAB are applications of previous studies and make sense. Zhong[9] proposed that the transformation between WL and BML is related to flow intensity and sediment transport capacity.

The results of WAB are consistent with an earlier finding that ‘the proportion of WAB around 0.1mm was the highest’[11]. However, the value of WAB in both pre-operation stage and operation stage differs from that in Yu’s research, who estimated that 0.05mm was the mean WAB in the YR[10]. Yu used the empirical method to divide particle sizes and the observation time was too early. Therefore, the WAB in our research are supposed to be credible.

According to the calculation method, WTS is determined by WAB and the composition of suspended sediment. On the certain curve of suspended sediment gradation, the greater the WAB is, the greater the
WTS is. On the condition that the WAB is fixed, WTS increases when the WL is relatively increased than the suspended sediment.

There are two reasons for the increase of WTS at Yichang station after impoundment. One is that the WAB increased (Figure 2b). Another is that the WL was relatively increased than the suspended sediment. The large sediment particles in the suspended sediment were intercepted by the TGD after the construction of the dam, while the WL weren’t. Due to the geographical location, the flow intensity of Yichang Station increased after impoundment, so the WL transport capacity and the WAB increased, which means that the definition range of WL became larger. Therefore, the increased WTS at Yichang station was caused by the co-contribution of the WAB and the suspended sediment composition. As time went on after the dam was built, the interception of sediment and the increase of WAB were not stopped, hence the WTS of Yichang station continued to rise until the suspended sediment was almost entirely consisted of the WL (Figure 3a).

The variation of WTS was consistent with the variation of corresponding WAB in Yichang and Datong stations (Figure 2b, Figure 3a, 3d). However, in Jianli and Hankou stations, the variation of WTS was inconsistent with the variation of WAB, which may suggest that the coarsening of the suspended sediment became the main factor determining the decrease of WTS, exceeding the influence of WAB’s increase (Figure 2b, Figure 3b, 3c). The change in particle size was not obvious in Datong station due to the slight influence of the TGD, and the WAB decreased slightly, therefore the WTS of Datong station showed a relatively gentle downward trend (except 2006). For 2006 was a dry year, and the suspended sediment was significantly refined[20]. The increase of fine sediment concentration means that the transport capacity of the WL is too little to carry the excess fine sediment, and part of the fine sediment deposit. As a result, the WAB decreased, and the WTS decreased accordingly in 2006 at Datong station (Figure 3d).

The results of WTS are different from Chen et al.'s' opinion that WTS accounted for more than 85% in the middle and lower reaches of general rivers[8]. At stations far away from the dam (e.g. Datong station), the WTS usually accounts for more than 85%. However, influenced by the change of composition of sediments and water intensity caused by major watershed projects and extreme weather, the WTS may accounts for less than 85% as well.

There also exist some limitations of our work. Firstly, the time series is too short, and this problem caused some errors like the WTS at Yichang station before the operation was unstable. However, this is an unavoidable limitation because there is no needed data for other years at the four stations in the hydrological yearbooks. Secondly, in addition to the most-curvature method, there are also some other methods to calculate WAB, which may give different results. Nevertheless, the most-curvature method has the advantages of simple calculation and relatively accurate results. Therefore, we didn’t choose other method as a comparison.

In conclusion, our research suggests that the WAB and WTS of Yichang station increased apparently after the TGD operation. The WAB of Jianli and Hankou stations increased slightly, and there was a downtrend of the WAB at Datong station. The WTS of Jianli, Hankou and Datong stations all decreased. This leads us to speculate that the WAB and WTS in the downstream of some major projects have the same variations in other watersheds. Moreover, we expect this study can provide reference for the following research on the WAB and WTS, thus further exploring the characteristics of sediment transport in the downstream of the dam.

5. Conclusions
The characteristics of sediment have changed significantly with the operation of the TGD. Based on the data of bed material and suspended sediment at four hydrological stations (Yichang, Jianli, Hankou, Datong) in the middle and lower reaches of the YR before and after impoundment, the variations of WAB and WTS are analyzed in this study. The conclusions can be summarized as follows:

(1) From 1979 to 1985, WAB in Yichang station ranged from 0.01 to 0.09mm, while in other stations (Jianli, Hankou and Datong) were all around 0.09mm. During the operation stage, WAB of Yichang station increased dramatically to nearly 1.85mm, and WAB of Jianli and Hankou stations increased
slowly (1.0% and 4.1% respectively, compared with the WAB of 2002). There was a slight decrease of WAB in Datong station (decreased by 8.4% and 5.3%, respectively, compared with the WAB of 2002 and that of pre-operation stage).

(2) At Yichang station, the WTS trend was basically consistent with the WAB trend. After impoundment, the WTS of Yichang station continued to rise until it was close to 100% and then plateaued, and the WTS of Jianli and Hankou stations showed a trend of decrease in fluctuations, the drop rate of which could reach 30%-40%, while at Datong station, the WTS fell slowly, with a drop rate of only 8%.

(3) With the increase of WAB and the refinement of the suspended sediment, the WTS of Yichang Station increased. In Jianli and Hankou stations, the coarsening suspended sediment became the main factor determining the change of WTS, part of which offset the increase of WAB, so the WTS decreased. The WTS of Datong station showed a relatively gentle downward trend for the change in particle size was not obvious in Datong station due to the slight influence of the TGD and the WAB decreased slightly.

Acknowledgments:
This research was financially supported by the National Natural Science Foundation of China (Nos. 51979264).

References
[1] Wang, Y. K., Rhoads, B. L., Wang, D., et al. (2018) Impacts of large dams on the complexity of suspended sediment dynamics in the Yangtze River[J]. Journal of Hydrology, 558 184-195.
[2] Xu, K., Milliman, J. D., Yang, Z., et al. (2006) Yangtze sediment decline partly from Three Gorges Dam[J]. Eos, Transactions American Geophysical Union, 87(19): 185-190.
[3] Yang, Y. P., Zhang, M. J., Li, Y. T., et al. (2016) Suspended sediment recovery and bedsand compensation mechanism affected by the Three Gorges Project[J]. Acta Geographica Sinica, 71(7): 1241-1254.
[4] Belperio, A. P. (1979) The combined use of wash load and bed material load rating curves for the calculation of total load: An example from the Burdekin River, Australia.[J]. CATENA, 6(3-4): 317-329.
[5] H. A. Einstein, A. G. A., Joe W. Johnson. (1940) A distinction between bed-load and suspended load in natural streams[J]. Eos, Transactions American Geophysical Union, 21(2): 628-633.
[6] Poplawski, W. A., Piorewicz, J., Gourlay, M. R. (1989) Sediment transport in an inland river in North Queensland[J]. Hydrobiologia, 176(1): 77-92.
[7] H. A. Einstein, N. C. (1953) Can the rate of wash load be predicted from the bed-load function?[J]. Eos, Transactions American Geophysical Union, 34(6): 876-882.
[8] Chen, H., Zhu, L. J., Wang, J. Z., et al. (2016) Review on division criteria between bed material load and wash load[J]. Journal of Sediment Research, (04): 74-80.(in Chinese)
[9] Zhong, D. Y., Wang, S. Q., Wang, G. Q. (1998) Research on wash load transport capacity of rivers[J]. Journal of Sediment Research, (03): 3-5.(in Chinese)
[10] Yu, W. C. (1986) An empirical formula of the sediment-laden capacity of flow at the lower Yangtze River[J]. Journal of Yangtze River Scientific Research Institute, (01): 45-53.(in Chinese)
[11] Fang, B. (2004) The formula of the sediment-laden capacity of flow in Datong - Zhenjiang reach of Yangtze River[J]. Yangtze River, (12): 42-44.(in Chinese)
[12] Asselman, N. E. M. (2000) Fitting and interpretation of sediment rating curves[J]. Journal of Hydrology, 234(3-4): 228-248.
[13] Woo H S, J. P. Y., Richardson E V. (1986) Washload and fine sediment load[J]. Journal of Hydraulic Engineering, (6): 541-545.
[14] Sadeghi, S. H., Zakeri, M. A. (2015) Partitioning and analyzing temporal variability of wash and bed material loads in a forest watershed in Iran[J]. Journal Of Earth System Science, 124(7): 1503-1515.
[15] Yang, C. T., Simoes, F. J. M. (2005) Wash load and bed-material load transport in the Yellow River[J]. Journal Of Hydraulic Engineering, 131(5): 413-418.

[16] Walling, D. E., Owens, P. N., Waterfall, B. D., et al. (2000) The particle size characteristics of fluvial suspended sediment in the Humber and Tweed catchments, UK[J]. Science Of the Total Environment, 251 205-222.

[17] Chen, W. B., Xie, J. H., Zhang, R. J. (2007) Fluvial Dynamics. Wuhan University Press: Wuhan, (in Chinese)

[18] Xiong, Z. P. (1985) The equation of sediment gradation curve function and the determination of the critical size between bed material load and wash load[J]. Journal of Sediment Research, (02): 88-94.(in Chinese)

[19] Zhang, W., Yang, Y. P., Zhang, M. J., et al. (2017) Suspended sediment recovery and bedsand compensation mechanism affected by the Three Gorges Project[J]. Journal of Geographical Sciences, 27(04): 463-480.(in Chinese)

[20] Yan, H., Dai, Z. J., Li, J. F., et al. (2008) Variation of bed-load and suspended sediment along middle and lower reaches of the Yangtze River during the period of the extreme low discharge in 2006[J]. Resources and Environment in the Yangtze Basin, 17(S1): 82-87.(in Chinese)