Effects of cross-sectional geometry on sediment transport ratio: Case study in the Lower Yellow River

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Abstract: Sediment transport ratio fitted by measured data indicates a closely relation with average discharge and suspended sediment concentration. However, theoretical speaking, the cross-sectional geometry may also influence the sediment transport. In present study, numerical simulation is adopted to analyze the influence of cross-sectional geometry on sediment transport ratio. Two flood events occurred in 1977 were simulated by one-dimensional model for unsteady hyper-concentrated sediment-laden flow. Analysis indicates that, the cross-sectional formation during flood events may also contribute to sediment transport ratio. Besides, over-flooding hyper-concentrated flood followed by normal one may lead to larger sediment transport ratio.
Keywords: cross-sectional geometry; sediment transport ratio; numerical simulation; Lower Yellow River

1 Introduction

The aggradation state of the Lower Yellow River (LYR) is widely known. The total amount of siltation in the LYR is approximately 5.5 $\times 10^9$ m^3 in 1950–1999 [1,2]. Then, the main channel in the LYR has shrunk significantly because of the siltation in the main channel [1].

On behalf of channel regulation, flood event should transport as much sediment as possible, which leading to less deposition. So, one important indicator of fluvial regulation is sediment transport ratio. The sediment transport ratio fitted by measured data is highly related with average discharge and suspended-sediment concentration (SSC) during flood event. Theoretically speaking, deposition performances of given hydrograph transporting through different cross-sections are different. Cross sections with narrow-deep main channel may take more advantage on sediment transporting, as the average velocity in narrow-deep cross-section (larger B/H) should be larger, the same as sediment carrying capacity [3]. It means that, cross-sectional geometry may also contribute to sediment transport ratio and related deposition. However, channel geometry has not been included in the fitted equation of sediment transport ratio. Thus, the present study focuses on investigating the effects of channel geometry on sediment transport. The analysis may also give evidence to a long-standing controversy, 'Is it possible to achieve a non-siltation or event scouring-channel by regulating the lower reach to optimize the utilization of hyper-concentrated flood ?' And Sun et al. [4] discussed the way of narrowing the lower channel.

Pre- and post-flood geometry data are measured before and after flood season, which may consist of several flood events. Thus, detailed geometry of cross-sections before and after flood events are difficult to obtain. Numerical simulation takes its advantage here. Numerical model for unsteady hyper-concentrated sediment-laden flood by He et al. [5] is adopted to investigate the effects of channel geometry on sediment transport ratio. The propagation of hyper-concentrated flood events of 1977 are analyzed as its high concentration. The selected model is adopted to simulate the fluvial processes of two flood events in the same channel, and simulated deposition and cross-sectional deformation are collected to analyze the influence of cross-sectional geometry on sediment transport ratio.

2 Environmental Setting

As the secondary largest river in China, the drainage area of Yellow River measures approximately 795000 km^2, and the stream length is approximately 5464 km. The annual average runoff depth is approximately 77 mm, and the annual average natural runoff is approximately 58×10^9 m^3 [6, 7]. The annual average suspended-sediment load is 1.6 $\times 10^9$ t (at Sanmenxia Hydrology Station), and the average concentration measured at this station reaches 36.8 kg/m^3 in 1919–1960 [8].

The LYR runs from Taohuayu to Lijin (LJ) and is approximately 786 km long, as shown in Figure 1 [7]. The LYR could be divided into three reaches with distinctly different geomorphologies [9], braided (Taohuayu–Gaocun), transition (Gaocun–Taochengpu), and meandering (Taochengpu–LJ) reaches. The sinusitis of these three reaches vary between 1.15 and 1.33, while the channel slope shows a decreasing trend along the river reach. The widths of main channel show a decreasing trend from upstream to downstream.

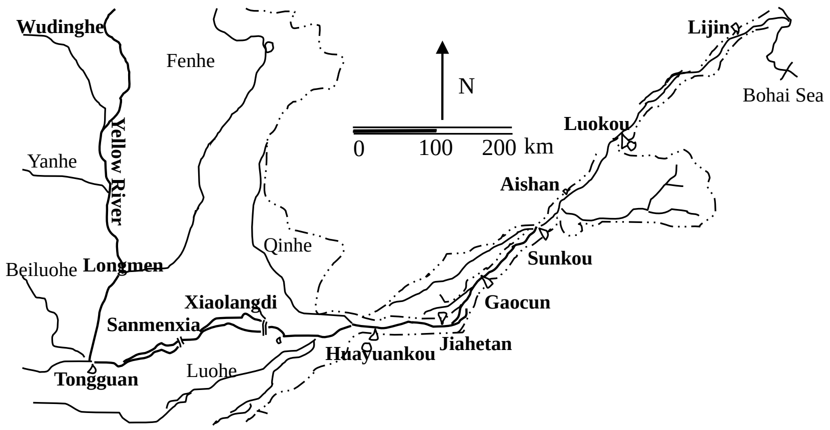


Figure 1. Sketch map of the Lower Yellow River.

3 Methods and Data

3.1 Methods

In order to analyze the effects of cross-sectional geometry on sediment transport, one important thing is identifying the different transporting performance of certain hydrographs contributed by channel geometry. Analyzing steps are as follows:

(1) Selecting typical hydrograph. The hydrograph of floods occurred in 1977 is selected, which has the largest SSC at Huayuankou station.

(2) Scenarios design. There are two scenarios, measured and designed. The measured scenario is composed of measured hydrographs and measured geometry data. The flood season of 1977 in the LYR is composed of two flood events, Event 1 and Event 2. The designed scenario is designed by exchanging the order of these two measured flood events. It means that, flood events in designed scenario are Event 2 and then Event 1 followed, while these two flood events in designed scenario are named as Event 21 and Event 11 for distinguishing. Flood events of Event 21 and Event 11 are exactly the same as that of Event 2 and Event 1 in measured scenario, respectively, both the hydrographs of discharge and SSC. So, the first flood events of these two scenarios (measured and designed) have exactly the same channel geometry.

(3) Numerical simulation. The one-dimensional model for hyper-concentrated flood in the LYR is adopted to simulate the propagation of flood events [5]. Detailed description of the model can refer to He et al. [5]. The initial bed formations are the same in these two scenarios, which are measured geometry data before flood events by Yellow River Conservancy Commission (YRCC). The upstream condition of the simulation is the processes of discharge and sediment concentration at XLD. The downstream conditions of the simulation is rating curves of LJ. Diameter of suspended sediment carried by flow and bed materials are also considered in the numerical model.

3.2 Data

Discharge and SSC at fixed hydrology sections are being measured according to Chinese national standard criterion. Data of discharge, concentration, and sediment load with different time intervals (daily, monthly, and annually) are published as “Hydrological Records” by YRCC. There are eight main hydrology stations in the lower channel, Xiaolangdi (XLD), Jiahetan (JHT), Gaocun (GC), Sunkou (SK), Aishan(AS), Luokou(LK), and LJ. Dataset of flow discharge and sediment concentration at these eight hydrology stations are collected and used in present analyses.

There are 88 cross sections with geometry data, and the average distance between two adjacent cross sections is approximately 8.4 km. The cross-sectional geometry of pre-flood is measured during 14^{th}–24^{th} June, 1977. It means that, the geometry data are measured before the first flood event.

4 Results

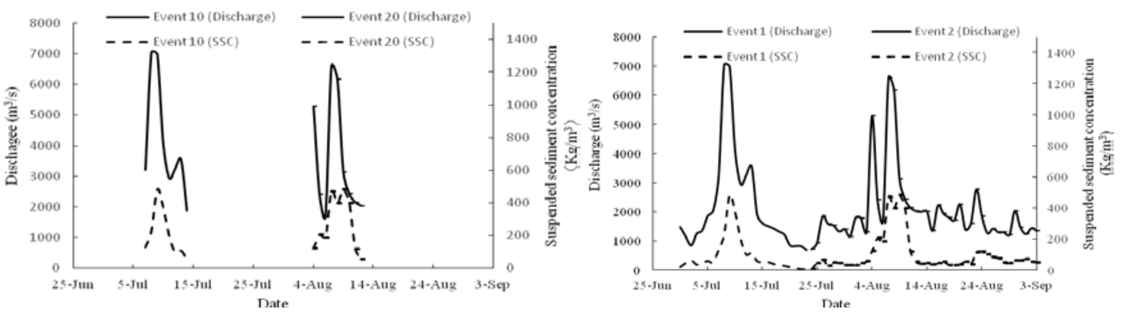
4.1 Experiential equation

The sediment transport ratio (η) fitted by measured data is highly related with average discharge and SSC during flood event [10]. It is expressed as

$$\eta = 48.56 \ln\left(\frac{\overline{S}}{\overline{Q}^{0.65}}\right) + 53.05 \tag{1}$$

in which $\overline{Q}$ and $\overline{S}$ are the average discharge and SSC of the flood event, respectively. Simulated η-value can also be estimated by Eq. (1) with calculated hydrographs.

Flood events occurred in 1977 is adopted as an example to illustrate the importance of channel geometry. There are two hyper-concentrated flood events in the LYR, 1977, as shown in Figure 2a. The first flood event occurred during 7th to 14th, July, and the second flood event occurred during 4th to 12th, Aug. Comparing to the first flood events, the average discharge of the second flood event is smaller, while the peak discharge of the second flood event is larger (Table 1). Besides, the concentration of the second flood event is larger than that of the first flood event, and suspended sediment contained by the second flood event is coarser. According to influencing factors of sediment transport ratio, the performance of sediment transporting of the second flood event is better than that of the first flood event, and the η-value of the second flood event should be relatively larger (Table 1). Measured data also shows that, the η-value of the second flood event is 49.9, which is larger than that of the first flood event (47.1).



(a) (b)

Figure 2. Hydrographs of discharge and suspended sediment of flood occurred in 1977.

Table 1. Sediment transport ratio (η-value) of flood events.

	Date	Average discharge (m^3/s)	Average SSC (kg/m^3)	η		Deposition ($\times 10^8$ m^3)	
				Eq. (1)	Simulated	Sediment-balanced method	Simulated
Measured	7.07–7.14 (1977)	4368	205.5	47.1	–	2.9	–
	8.04–8.12 (1977)	3861	216.9	49.9	–	3.2	–
Measured series	Event 1	2212	170.9	59.6	52.5	4.6	4.1
	Event 2	2010	151.6	56.8	42.4	6.3	4.7
Designed series	Event 21	2010	151.6	56.8	53.9	–	6.0
	Event 11	2212	170.9	59.6	78.9	–	6.2

4.2 Flood characteristics

Sediment loads by these two flood events (flood during 7th and 14th, July, and flood during 4th and 12th, August) are 6.2×10^8 t and 6.5×10^8 t, respectively. Hyper-concentrated flood events can be grouped into three groups according to erosion and deposition [10]. The first group is over-flooding hyper-concentrated flood events, and the sediment load is larger than 10×10^8 t. The second group is normal hyper-concentrated flood events with sediment load ranges between 4×10^8 t and 10×10^8 t. The third group is small hyper-concentrated flood events with sediment load less than 4×10^8 t. Both of these two flood events can be grouped to normal hyper-concentrated flood events.

However, these two flood events are separate as low water periods are not considered (Fig. 2a). These kind of hydrographs are difficult to be simulated with numerical model. So, the first flood event is extended from 30th June to 23th July (Event 1), and the second flood event is extended from 24th July to 3rd September (Event 2), as shown in Figure 2b. According to the sediment load of these two extended-events, the first extended-event can be grouped as normal hyper-concentrated flood event (with sediment load of 7.8×10^8 t), and the second extended-event can be grouped as over-flooding hyper-concentrated flood event (with sediment load of 11.1×10^8 t). The measured transport ratios [estimated with measured data by Eq. (1)] of these extended flood events have also been summarized in Table 1. It shows that, the η-value of Event 2 (over-flooding hyper-concentrated flood event) is smaller than that of Event 1 (normal hyper-concentrated flood event). The ratios of extended flood events increased approximately 14–27%.

4.3 Simulated sediment transport ratio

After numerical simulation, the simulated sediment transport ratios (η-value) have also been summarized in Table 1. For measured scenario, both of the simulated and measured η-values of Event 2 (over-flooding hyper-concentrated flood event) are smaller than that of Event 1 (normal hyper-concentrated flood event). For designed scenario, both of the simulated and measured η-values of Event 21 (over-flooding hyper-concentrated flood event) are also smaller than that of Event 11 (normal hyper-concentrated flood event).

For measured scenario, the simulated η-values of these two hyper-concentrated events are underestimated with a ratio around 12–25%.

Comparing Event 1 and Event 21 (with exactly the same bed geometry and different flood characteristics), the simulated and measured sediment transport ratios are almost the same (with a difference less than 5%). Comparing Event 2 and Event 21 (with different bed geometry and exactly the same flood characteristics), the simulated sediment transport ratios increased approximately 20%. Comparing Event 1 and Event 11 (with different bed geometry and exactly the same flood characteristics), the simulated sediment transport ratios increased approximately 50%. It means that, for these two events and channel geometry, the contribution of bed geometry on sediment transport ratio is approximately 20–50%.

Comparing Event 2 and Event 11 (with different bed geometry and different flood characteristics), the simulated sediment transport ratios increased approximately 86%, while the measured ratios are almost the same (with a difference less than 5%). It means that, after the over-flooding hyper-concentrated flood event (Event 21), the sediment transport ratio of normal hyper-concentrated flood event (Event 11) increases dramatically (with a ratio of 86%). So, for these two events and channel geometry, the channel geometry contribute more to event-scale sediment transport ratio than flood characteristics.

For the empirically fitted relation [Eq. (1)], only discharge and concentration are considered, while channel geometry is not included. The reason may be that, it’s difficult to measure detailed channel geometry after each flood events. More importantly, channel geometry can also be expressed as a result of flow conditions, as $W = aQ^b$ and $H = cQ^f$, where *W* and *H* are the width and depth, respectively, *Q* is discharge, *a* and *c* are the coefficients, and *b* and *f* are the exponents. Besides, less variables make it much more easier to be fitted and a wider application.

5 Conclusion

This paper analyzed the effects of channel geometry on sediment transport ratio. Analyses show that,

(1) The channel geometry also contribution to sediment transport ratio. A narrow-deep cross-sectional helps transporting sediment into the sea.

(2) Different order of flood events has limited impacts on deposition in view of the total deposition. However, over-flooding hyper-concentrated flood followed by normal one may lead to larger sediment transport ratio.

Acknowledgements

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6 References

[1] Xia, J.Q., Wu, B.S., Wang, G.Q. & Wang, Y.P. 2010. Estimation of bankfull discharge in the Lower Yellow River using different approaches. Geomorphology, 117(s1-2): 66–77.

[2] Zheng, S., Wu, B.S., Thorne, C.R. & Tan, G.M. 2014. Case study of variation of sedimentation in the Yellow and Wei Rivers. Journal of Hydraulic Engineering, 141(3): 05014009.

[3] Shu, A.P. & Fei, X.J. 2008. Sediment transport capacity of hyperconcentrated flow. Science in China Series-G Physics Mechanics and Astronomy, 51(8): 961–975.

[4] Sun, Z.Y., Wang, W.Z., Li, Y., Zhang, M.W., Shang, H.X. & Zhang, F.X. 2016. Can the narrowing of the Lower Yellow River by regulation result in non-siltation and even channel scouring ? J. Geogr. Sci., 26(9): 1337–1348.

[5] He, L., Duan, J.G., Wang, G.Q. & Fu, X.D. 2012. Numerical simulation of unsteady hyper-concentrated sediment-laden flow in the Yellow River. Journal of Hydraulic Engineering, 138(11): 1–12.

[6] He, L., Wang, G.Q. & Fu, X.D. 2010. Disaggregation model of daily rainfall and its application in the Xiaolihe watershed, Yellow River. Journal of Environmental Informatics, 16(1): 11–18.

[7] He, L., Wang, G.Q. & Zhang, C. 2012. Application of Loosely Coupled Watershed Model and Channel Model in Yellow River, China. Journal of Environmental Informatics, 19(1): 30–37.

[8] Wu, B.S., Wang, G.Q., Xia, J.Q., Fu, X.D. & Zhang, Y.F. 2008. Response of bankfull discharge to discharge and sediment load in the Lower Yellow River. Geomorphology, 100: 366–376.

[9] Wu, B.S., Wang, G.Q., Ma, J.M. & Zhang, R. 2005. Case study: River training and its effects on fluvial processes in the Lower Yellow River, China. Journal of Hydraulic Engineering, 131(2): 85–96.

[10] Report of the National "Twelfth Five Year" Plan for Science & Technology Support 2016 Tsinghua University, Beijing.