Global and Planetary Change 162 (2018) 8–17

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Human impacts on sediment in the Yangtze River: A review and new perspectives

H.F. Yang[a,b], S.L. Yang[a,*], K.H. Xu[b,c], J.D. Milliman[d], H. Wang[e], Z. Yang[e], Z. Chen[a], C.Y. Zhang[f]

[a] State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai 200062, China
[b] Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA 70803, USA
[c] Coastal Studies Institute, Louisiana State University, Baton Rouge, LA 70803, USA
[d] School of Marine Science, Virginia Institute of Marine Science, College of William & Mary, Gloucester Point, VA 23062, USA
[e] College of Marine Geosciences, Ocean University of China, 238 Songling Rd., Qingdao 266100, China
[f] Survey Bureau of Hydrology and Water Resources of the Changjiang Estuary, Changjiang Water Resources Commission, Shanghai 200136, China

ARTICLE INFO

Editor: Dr. T.M. Cronin

Keywords:
Sediment
Grain size
Yangtze River (Changjiang)
Three Gorges Dam
Human impacts

ABSTRACT

Changes in riverine suspended and riverbed sediments have environmental, ecological and social implications. Here, we provide a holistic review of water and sediment transport and examine the human impacts on the flux, concentration and size of sediment in the Yangtze River in recent decades. We find that most of the fluvial sediment has been trapped in reservoirs, except for the finest portion. Furthermore, soil-conservation since the 1990s has reduced sediment yield. From 1956-1968 (pre-dam period) to 2013–2015 (post-dams and soil-conservation), the sediment discharge from the sub-basins decreased by 91%; in the main river, the sediment flux decreased by 99% at Xiangjiaba (upper reach), 97% at Yichang (transition between upper and middle reaches), 83% at Hankou (middle reach), and 77% at Datong (tidal limit). Because the water discharge was minimally impacted, the suspended sediment concentration decreased to the same extent as the sediment flux. Active erosion of the riverbed and coarsening of surficial sediments were observed in the middle and lower reaches. Fining of suspended sediments was identified along the river, which was counteracted by downstream erosion. Along the 700-km-long Three Gorges Reservoir, which retained 80% of the sediment from upstream, the riverbed gravel or rock was buried by mud because of sedimentation after impoundment. Along with these temporal variations, the striking spatial patterns of riverine suspended and riverbed sediments that were previously exhibited in this large basin were destroyed or reversed. Therefore, we conclude that the human impacts on sediment in the Yangtze River are strong and systematic.

1. Introduction

Sediment is an important element in rivers and their connecting waters. The sediment flux determines the deposition rate in a delta, thereby affecting its fate in the face of sea level rise (Giosan et al., 2014). The suspended sediment concentration (SSC) plays a key role in determining sunlight penetration and water quality (Stefan et al., 1983; Bilotta and Brazier, 2008). The grain size of sediments in hydro-environments also has major implications for ecology, geomorphology and engineering (Etter and Grassle, 1992; Xu et al., 2012).

Rivers are increasingly affected by human activities such as dam construction, soil conservation, water diversion and sand mining (Syvitski et al., 2005; Tessler et al., 2015). In many rivers, including the Mississippi, Yellow, Indus, Orange, Yenisei, Chao Phraya, Volta, Song Hong and Krishna Rivers, sediment fluxes have declined by 60–90% over recent decades (Walling, 2006; Milliman and Farnsworth, 2011). In extreme examples, such as the Nile, Ebro, Colorado and Yisil Irmak Rivers, sediment fluxes have decreased to almost nothing (Vörömarty et al., 2003; Milliman and Farnsworth, 2011). In response to this sediment starvation, the effect of subsidence becomes increasingly evident and many deltas have experienced increased erosion (e.g., Wiegel, 1996; Chu et al., 2006; Blum and Roberts, 2009; Giosan et al., 2014). Despite the many studies of anthropogenic changes in the flux of fluvial sediments, less is known about the human impacts on the SSC and the grain size of suspended and riverbed sediments. There is a need to understand human-induced systematic changes in riverine sediment properties (e.g., flux, concentration, grain size and deposition/erosion).

The Yangtze River (Fig. 1) is an ideal site for studying human impacts on fluvial sediment because of the river's rapid socio-economic development over the past four decades and the availability of

* Corresponding author.
E-mail address: slyang@sklec.ecnu.edu.cn (S.L. Yang).

https://doi.org/10.1016/j.gloplacha.2018.01.001
Received 17 October 2017; Received in revised form 27 December 2017; Accepted 2 January 2018
Available online 05 January 2018
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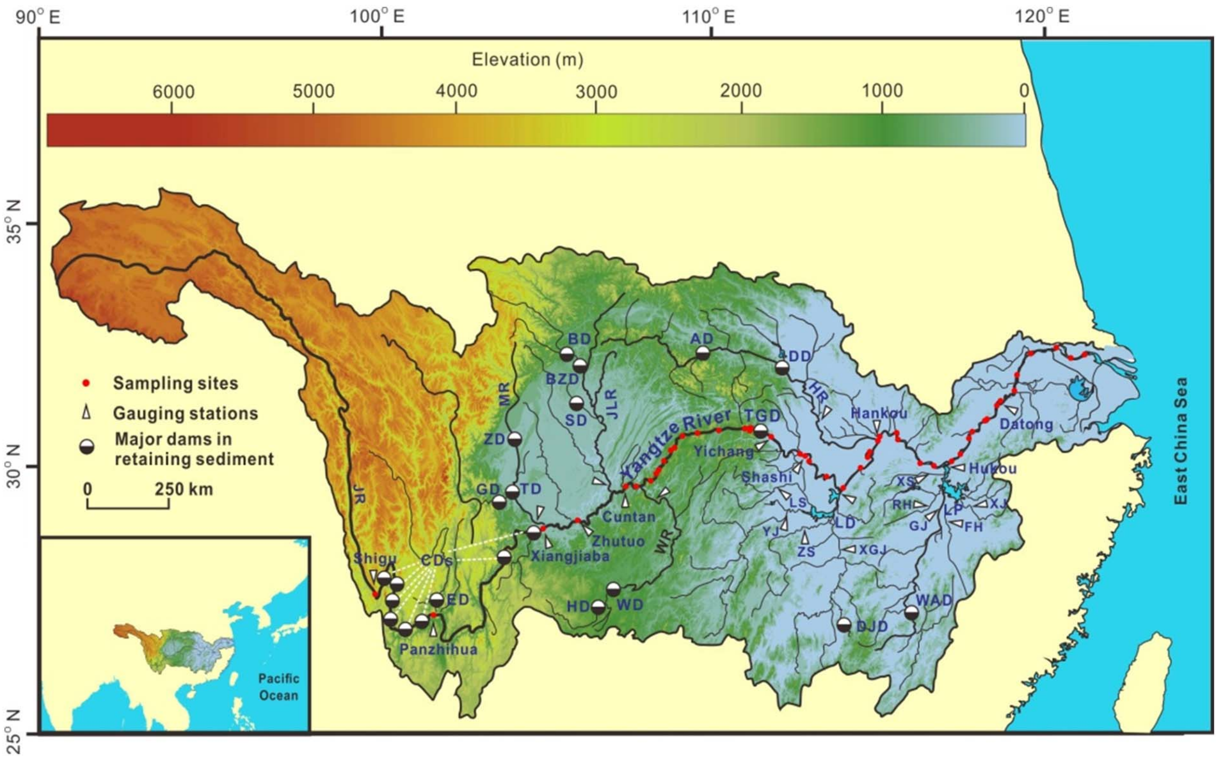

Fig. 1. Sketch map of the study area showing the sediment sampling sites (red dots), gauging stations (white triangles) and super reservoirs (circles). JR: Jinshajiang River; MR: Minjiang River; JLR: Jialingjiang River; HR: Hanjiang River; WR: Wujiang River; LD: Lake Dongting; LP: Lake Poyang; DD: Danjiangkou Dam; TGD: Three Gorges Dam; AD: Ankang Dam; GD: Gongzui Dam; TD: Tongjiezi Dam; ZD: Zipingpu Dam; BD: Bikou Dam; SD: Shengzhong Dam; BZD: Baozhusi Dam; WD: Wujiangdu Dam; HD: Hongjiadu Dam; ED: Ertan Dam; DJD: Dongjiang Dam; WAD: Wanan Dam; CDs: Cascade Dams; LS: Lishui; YJ: Yuanjiang; ZS: Zishui; XGJ: Xiangjiang; XS: Xiushui; RH: Raohe; GJ: Ganjiang; FH: Fuhe; XJ: Xinjiang. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

extensive data. Over the past 15 years, many studies have investigated the anthropogenic changes in Yangtze sediment discharge (e.g., Yang et al., 2002; Yang et al., 2006; Zhang et al., 2006; Chen et al., 2008; Dai and Liu, 2013; Dai and Lu, 2014). However, previous research has not incorporated the changes after 2012, when cascade reservoirs began to operate in the Jinshajiang River, the main sediment source of the Yangtze. As in other rivers, little is known of the human impacts on the SSC and grain size in the Yangtze River. Although the temporal changes in the SSC at Datong (tidal limit of the Yangtze) between 1956 and 2013 have recently been reported (Dai et al., 2016), the changes in the SSC remain unknown both for most of the main river and for the tributaries of the Yangtze. The human impacts on the sediment grain size are also undetermined for most of the Yangtze River, despite the sediment coarsening that has been identified immediately downstream of the Three Gorges Dam (TGD) (Luo et al., 2012). In this study, we provide a holistic review of water and sediment transport in the Yangtze basin and examine the systematic human impacts on sediment (flux, concentration, grain size, channel deposition/erosion) of the Yangtze River at the basin scale between 1956 and 2015 with newly updated data. In addition, the last sediment source, the Jinshajiang River which contributes an average of ~234 Mt/yr sediments to the main river between 1956 and 2012, now has been retained by large dams and the sediment flux has decreased by > 99% since 2013 (MWRC, 2013). Therefore, our results can represent the maximum impact on sediment resulting from human activities in the Yangtze River in some respects.

2. Study area

The Yangtze River originates on the Qinghai-Tibet Plateau 5100 m above sea level, and flows eastward to the East China Sea (Fig. 1). Among global large rivers, the Yangtze ranks first in population (450 million people), 12th in basin size (1800,000 km^2), 3rd in length (6300 km), 5th in water discharge (900 km^3/yr), and 4th in sediment flux (470 Mt/yr before dams) (Milliman and Farnsworth, 2011; Yang et al., 2015). The Yangtze basin is characterized by a subtropical, warm and wet climate. The basin-wide precipitation average is ca. 1050 mm/yr. Approximately half of the precipitation is lost to evaporation (Jiang et al., 2007). The Yangtze Basin consists of seven major sub-basins with variable climatic and hydrological conditions (Table S1): the Jinshajiang, Minjiang, Jialingjiang, Hanjiang and Wujiang Rivers and Lakes Dongting and Poyang (Fig. 1). Precipitation is lower in the northern and western regions compared to the southern and eastern regions, ranging from 730 mm/yr in the Jinshajiang basin to 1560 mm/yr in the Lake Poyang basin (Table S1). The upper reaches of the Yangtze are generally considered to extend to Yichang, i.e., the outlet of the Three Gorges Dam; the middle reaches extend from Yichang to Hukou, where Lake Poyang flows into the main river, and the lower reaches extend from Hukou to the river mouth (Zhao et al., 2000). The upper reaches drain mountainous areas, whereas the middle and lower reaches flow through low-lying plains with wider channels (Fig. 1) (Chen et al., 2007).

3. Materials and methods

Riverbed sediments were sampled with a grab sampler along the main Yangtze River (Fig. 1) from 2000 to 2015 (Table S2) to investigate the downstream trends of grain size and to compare pre- and post-TGD riverbed grain sizes. The water discharge, suspended sediment flux and median size (D_{50}) data were obtained from the Yangtze Water Resources Committee (YWRC) of the Ministry of Water Resource of China (MWRC) (http://www.mwr.gov.cn/sj/#tjgb). The multi-year average of D_{50} ($\overline{D}_{50}$) was calculated using the following equation:

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