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Downstream sedimentary and geomorphic impacts of the Three Gorges Dam on the Yangtze River

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ABSTRACT

Although large dams have been constructed and continue to be constructed on many rivers, the lack of long-term gauging data often makes it difficult to document either reservoir sedimentation or the dams' downstream impacts. More than 50 years of water and sediment data from 20 gauging stations within the Yangtze River's basin provide us a unique opportunity to delineate the impacts from the Three Gorges Dam (TGD), the world's largest dam. During the first decade after TGD completion in 2003, 1.8 Gt of sediments were trapped in the Three Gorges Reservoir (TGR). The TGR's sediment retention rate increased from ~65% during the first three years of operation to ~85% by 2008–2012, when the TGD was in normal operation; in the low-discharge drought years of 2006 and 2011, reservoir retention exceeded 90%. Sedimentation in the TGR has been discontinuous, the most prominent depocenters being at the broad section near the up-river entrance to the reservoir and just upstream of the dam, where sediment thickness locally exceeds 60 m. Median size of the sediments trapped in the TGR is 11 μm, whereas sediments discharged from the TGR are finer than 5 μm. As a result of sediment retention in the TGR, the river downstream has been eroded at a rate of 65 Mt/yr. Riverbed sediments have coarsened considerably in the first several hundred kilometers downstream of TGD. Sediment discharge into the Yangtze estuary, as measured at the Datong downstream gauging station, decreased by 130 Mt/yr relative to the normal water years of 2001–2002, nearly 90% of which can be attributed to the TGD. With planned construction of large upstream Cascade Reservoirs, the amount of sediment entering the TGR will decline dramatically, thus reducing sedimentation in the TGR and thereby extending its lifespan; by the end of the 21st century, the TGR should have retained more than 80% of its original storage capacity. Sediment outflow from the TGR will likely be less than 15 Mt/yr, compared to 50 Mt/yr at present. Even with downstream channel erosion, the long-term average sediment discharge into the Yangtze estuary in future decades most likely will decrease to ca. 110 Mt/yr, only 20% of its level in the 1960s, and further delta erosion is expected.

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1. Introduction

Historically rivers have discharged approximately 36,000 km^3 of freshwater and more than 20 Gt of solid and dissolved material annually into the global oceans (Milliman and Farnsworth, 2011). However, over the past century, rivers have become increasingly impacted and fragmented by dams and irrigation projects, which collectively have led to significant environmental and ecological consequences to both rivers and adjacent coastal areas (e.g., Vörösmarty et al., 2003; Nilsson et al., 2005; Syvitski and Milliman, 2007; Blum and Roberts, 2009; Milliman and Farnsworth, 2011). One of the most important impacts of river damming has been the trapping of sediment (Walling, 2006) as well as particulate organic matter (Zhou et al., 2013) in reservoirs. A tabulation of 35 large and small rivers that represent a collective basin area of 18.5 × 10^6 km^2, all of which to some extent have been dammed, shows an 80% (2.7 Gt/yr) decrease in the overall sediment discharge in the past 50 years (Milliman and Farnsworth, 2011). In recent years, dam construction has been active in developing countries, and especially in southeastern Asia. For example, the total sediment discharge of the Yellow, Yangtze, Pearl, Red and Mekong rivers decreased by more than 60% between 1985 and 2010 (Wang et al., 2011).

Although dams generally represent the most important cause of recent sediment decline, other factors can also be important. For example, 30% of the recent decline in sediment discharge from the Yellow River is attributable to decreased precipitation (Wang et al., 2007), as is 10% of the recent sediment decrease in the Pearl River (Wu et al., 2012). In contrast, half of the sediment decrease in the Mississippi River is due to land conservation and levee construction (Meade and Moody, 2010). It is therefore critical to identify and quantify the impacts from both dams and other influencing factors.

There are several ways to quantify reservoir sedimentation. Determining the thickness and character of reservoir deposits is particularly appropriate for the study of older reservoirs as well as those reservoirs that are small and morphologically regular in configuration (Dendy, 1974). For large reservoirs with fixed hydrological stations at their upper and lower ends, measuring the sediment inflow and outflow of the reservoir is possible (e.g., Brune, 1953; Yang et al., 2005b; Xu et al., 2006; S.B. Dai et al., 2008; Kummu et al., 2010). While this approach can yield even monthly sedimentation numbers, it must take into account the inputs from ungauged areas that surround the reservoir (Yang et al., 2007b). Another method is to estimate the sediment yield of the reservoir drainage basin and compare it with the measured sediment outflow from the reservoir (Dendy, 1974).

The retention rate, defined as the ratio of the reservoir sedimentation to the total sediment inflow, is a useful parameter to evaluate the efficiency of a reservoir to trap sediment. Delineating retention rates in relation to various influencing factors is critical to predicting the operation life of a reservoir, and thus helping the river management. Although many studies have examined the retention rate and its influencing factors, most of them have been conducted for small reservoirs (e.g., Brune, 1953; Dendy, 1974; Heinemann, 1981; Verstraeten and Poesen, 2000; Yang et al., 2005b). Another complicating factor is that retention rates vary from reservoir to reservoir, and vary temporally within a given reservoir.

The impacts of the Three Gorges Reservoir (TGR) on the Yangtze River have been the interest of many scientists and engineers not only because the Three Gorges Dam (TGD) is the world's largest hydropower project (Nilsson et al., 2005) but also because the Yangtze basin is home of more than 450 million people (Yang et al., 2005a), the world's largest river-basin population. Since the TGD's initial operation in 2003, several studies have examined the TGR's sedimentation and retention rates (e.g., CWRC, 2004–2011; Fu et al., 2006; Yang et al., 2007b; Chen et al., 2008; Hu et al., 2009). However, many of these studies had basic deficiencies: for example, the calculation of the sediment inflow computed by the CWRC (2003–2012) excluded the sediments derived from the ungauged areas within the TGR watershed (Fig. 1A). Although other studies did take into account the ungauged areas (Fu et al., 2006; Yang et al., 2007b; Chen et al., 2008; Hu et al., 2009), they assumed that the ratio of ungauged sediment inflow to gauged sediment inflow has remained unchanged, which was an untested assumption. Moreover, any approach based on this assumption will become biased after the construction of the Cascade Reservoirs upstream of the TGR (Fig. 1A), which will trap most of sediment load upstream of TGR. To solve these problems, it is necessary to estimate the ungauged sediment inflow that is independent from the gauged sediment inflow in calculation.

In this study, we first compute the annual and monthly sedimentation in the TGR based on sediment inflows and outflows. Then, we examine the temporal changes in sedimentation and retention rates and discuss the influencing factors. After we delineate the spatial distribution of the sedimentation and the grain size of deposited sediments, we then examine the impact of the TGR on downstream sediment transport and geomorphology. In this way, we develop a quantitative understanding of the sedimentary impacts of the TGR, allowing us to predict the future sediment retention in the TGR and the down-river sediment discharge and geomorphic responses.

2. Regional setting

The Yangtze River, which has a catchment area of 1,800,000 km^2, originates on the Qinghai–Tibet Plateau and flows 6300 km eastward to the East China Sea (Fig. 1A), the longest in Asia and the third longest in the world (Milliman and Farnsworth, 2011). Basin-wide precipitation