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Reservoir-induced changes to fluvial fluxes and their downstream impacts on sedimentary processes: The Changjiang (Yangtze) River, China

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A B S T R A C T

Reservoir interception has significantly affected the fluvial sediment budget as well as the sedimentary processes of the entire Changjiang catchment. To evaluate the impact of reservoirs, we analyze the combined effects of 1037 large and medium-sized reservoirs on the fluvial flux in general, and more specifically on the sedimentary processes in the middle and lower reaches. Results indicate that reservoir emplacement in the Changjiang catchment currently reduces the sediment load towards the East China Sea by 453 Mt y^{-1}. Estimates at Yichang station show that the sediment discharge would exceed 555 Mt y^{-1}, if there were no reservoirs involved. It is expected that in the near future, more dams will be constructed. The entire reach of the Changjiang River can be divided at Yichang station into two distinctly characterised reaches with regard to sedimentation, where the upper reach exhibits mostly siltation (over 589 Mt y^{-1} of sediment deposition), and the lower reach is affected by erosion (sediment loss, including sand extraction, exceeding 112 Mt y^{-1}). As a consequence, the sediment flux to the sea will further decrease to 100 Mt y^{-1}. Due to human interference, the upstream sediment load reduced and caused significant changes in the erosion/deposition pattern of the middle and lower reaches, which together altered the terrestrial sediment input to the sea. Before 2003, the upstream reaches were the dominant sediment source. After 2003, the sediment contribution of the middle and lower reaches became more important, and its sediment contribution will further increase to 78% of the total sediment load reaching the sea, after completion of the cascade reservoirs at the Jinsha Tributary. Hence, the middle and lower reaches are converting from a sediment sink to a major sediment source.

1. Introduction

Under natural conditions, temporal variations in fluvial water and sediment discharges are influenced mainly by changes in climate that indirectly can alter the land cover (Farnsworth and Milliman, 2003). During the last century, human activities such as freshwater extraction, sand mining of riverbeds, land use changes in river catchments and damming of rivers were intensified at an increasing rate, altering most global river systems (Syvitski, 2003, 2011; Wang et al., 2008a). Reservoir construction for e.g. flood control, storage of freshwater for irrigation, navigation, and generation of hydroelectric power, has the most significant anthropogenic impact on riverine fluxes on a global scale. By reducing the connectivity of rivers, watersheds become more fragmented, resulting in changes in the hydrological processes, downstream river channel morphology, and the depositional and erosional processes of estuary and subaqueous deltas (Milliman, 1997; Gao et al., 2011; Gupta et al., 2012).

Currently, there are more than 45,000 large and 800,000 medium to small reservoirs in the world (World Commission of Dams, 2005), which intercept ~25–30% of the global fluvial sediment (Vörösmarty et al., 2003). This reduction in sediment towards the

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oceans has its impact on river and coastal geomorphology as well as threatening fragile ecosystems (Walling, 2006; Li et al., 2007; Gao and Wang, 2008). The reduction in fluvial sediment load caused by reservoir emplacements has become a topic of global concern (Syvitski et al., 2005). Since 1950, China has built more than half of the world's large reservoirs, mainly for hydro-electrical purposes (Fuggle and Smith, 2000). Most of these are located in the Changjiang catchment (GMWR, 2009). The Changjiang River is 6370 km long and is globally ranked as the fifth river system in terms of water discharge, and ranks fourth when considering sediment load (Milliman and Farnsworth, 2011). There are over 50,000 reservoirs in the Changjiang catchment (Gao, 2006, 2007) and, therefore, the Changjiang River has become one of the highest impacted river systems in the world (Wang et al., 2011; Yang et al., 2011).

The Three Gorges Dam (TGD) became operational in 2003 and is currently the largest concrete gravity dam in the world. Due to its high capacity of sediment retention, the impacts of the TGD on the middle and lower reaches of the Changjiang River and its estuary became a focus for recent studies (e.g., Yang et al., 2002; Dai et al., 2008; Wang et al., 2013). However, few attempts have been made to quantify the overall impact of all reservoirs on the sediment flux. One might argue that a large reservoir such as the TGD has a significant influence on the total suspended sediment load. However, smaller reservoirs are often located closer to the sediment source areas, and as a consequence, they could collectively play a similar or even more important role as compared to large reservoirs (Shi et al., 2012). Hu et al. (2011) reported already a significant reduction in the annual sediment flux towards the sea before the emplacement of the TGD. Neglecting these small reservoirs may result in misinterpreting the quantity of sediment trapped by large dams, inducing bias in evaluating human's impacts on sediment discharge of the Changjiang River.

A proposed cascade reservoirs development plan for the upper stream of the Changjiang River has recently been approved, so water and sediment discharge will be subjected to even further adjustments in the coming decade (Q.S. Chen et al., 2008). To better predict the impact of future emplacement of dams, it is of importance to integrate all dams of the Changjiang catchment, and systematically analyze the relation between quantity of reservoir volume versus the sediment load reduction, in combination with the downstream effects, resulting in changes in freshwater and sediment discharge of the middle and lower reaches and to the estuary.

In this study, we aim to: (1) systematically analyze variation of reservoir storage capacity of the entire Changjiang catchment and its tributaries, and its effect on changes in downstream sediment load; (2) reconstruct the inter-annual variation of upstream sediment load without the influence of dam interception, and evaluate the contribution of dam interception to the reduction of sediment load; (3) investigate changes in sedimentary processes of the Changjiang River basin due to sediment reduction; and (4) predict future changes of water and sediment discharge of the Changjiang catchment, after the completion of the upstream cascade reservoirs emplacements, and explore the downstream impact of these reservoirs on the channel and the Changjiang estuary.

2. Regional setting

The Changjiang catchment covers an area of ~1.80×10^6 km^2. The upper reach of the river, from the hinterland to the Yichang gauging station (Fig. 1), is the main sediment source of the entire catchment (Shi, 2008). Its middle reach extends from Yichang to Hukou gauging station and the section between Hukou and Datong gauging station defines the lower reach of the river (Fig. 1). No large tributaries join the lower reach, and downstream of Datong gauging station, the river is influenced by tides. Therefore, Datong station is the last station of the Changjiang River, and its records are generally used to represent the riverine flux into the East China Sea. The geomorphology is characterized by mountains and hills in the upstream area and by extensive fluvial plains with numerous lakes in the downstream area. The middle reach of the Changjiang River is a meandering river system, which evolves to a more braided system in the lower section of the river (Yin et al., 2007).

The Changjiang River upstream of Datong gauging station includes seven major tributary basins: Jinsha, Min, Jialing, Wu, and Han rivers, together with two lakes: Dongting and Poyang Lakes (Fig. 1; Table 1). Dongting Lake is the second largest freshwater lake of China, and joins the main stream from the south, at Chenglingji gauging station (Du et al., 2001). The surface area of Dongting Lake decreased from 4350 km^2 in 1949–2623 km^2 in1995 due to siltation and land reclamation (BCRS, 2000). Poyang Lake is the largest freshwater lake of China, located at the junction of the south bank of the Changjiang River. Poyang Lake is a throughput type of lake; receiving runoff from five smaller tributaries: Gan, Fu, Xin, Rao and Xiu rivers and passing the freshwater through to the Changjiang River after regulation at Hukou. The contributed area to Poyang Lake is 16.2×10^4 km^2, accounting for 9% of the Changjiang River drainage area (Shankman et al., 2006).

Table 1
Characteristics of the seven major tributary basins upstream of Datong station.

River systems	Hydrological station	Length[a] (km)	Area[a] (10^4 km^2)	Discharge (km^3 y^{-1})			Sediment load (Mt y^{-1})		
				I	II	I–II	I	II	I–II
JinshaRiver	Pingshan	2316	34	143.0	146.48	−3.48	232	164	68
Min River	Gaochang	1062	16.09	84.93	77.97	6.95	45	31	14
JialingRiver	Beibei	1119	16	65.32	58.66	6.66	108	26	82
Wu River	Wulong	1018	8.7	48.56	44.08	4.47	24	8.0	16
Han River	Huangzhuang	1532	17.43	46.51	44.41	2.1	39	8.0	31
Dongting Lake	–	–	26.28	166.28	162.32	3.96	26	10	16
Poyang Lake	–	–	16.22	100.6	102.60	−2.0	17	6.0	11
Total	–	–	–	655.19	636.53	18.67	491	253	238

I and II denotes the period of 1956–2010 and 2001–2010, respectively. Sediment load at Dongting Lake system represents the total load of its four tributaries: Xiang, Zi, Yuan and Li rivers. Similar for the sediment load of Poyang Lake system, which represents the total sediment load of its tributaries: Gan, Fu, Xin, Rao, and Xiu Rivers.
[a] Represented data originating from Lin et al. (2010).

Recently, the water and sediment discharges of the Changjiang catchment have been significantly modified (Yan et al., 2011) due to the impact of climate variation, land cover changes, and human activities (Chen et al., 2001). A considerable number of reservoirs