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Decline in suspended sediment concentration delivered by the Changjiang (Yangtze) River into the East China Sea between 1956 and 2013

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ABSTRACT

The temporal evolution of suspended sediment concentration (SSC) in a river debouching into the ocean provides vital insights into erosion processes in the watershed and dictates the evolution of the inner continental shelf. While the delivery of sediment from rivers to the ocean has received special attention in the recent past, few studies focused on the variability and dynamics of river SSC, especially in the Changjiang (Yangtze) river, China, the longest river in Asia. Here, variations in SSC delivered by the Changjiang River to the East China Sea and possible causes of its variability were detected based on a long-term time series of daily SSC and monthly water discharge measured at the Datong gauging station. The SSC data are further compared to a hydrological analysis of yearly precipitation covering the entire catchment. The results indicate the presence of a decline in SSC in the period 1956–2013, which can be divided into three phases: (i) high SSC (0.69 kg/m^3) in the wet season and low SSC (0.2 kg/m^3) in the dry season from 1956 to 1970; (ii) relative high SSC (0.58 kg/m^3) in the wet season and low SSC (0.15 kg/m^3) in the dry season from 1971 to 2002; and (iii) low SSC (0.19 kg/m^3) in the wet season and very low SSC (0.09 kg/m^3) in the dry season after 2002. These three periods have a mean yearly SSC values of 0.62, 0.42, and 0.18 kg/m^3, respectively. Compared with 1956–1970, the slope of the rating curve between SSC and water discharge decreased, respectively, by 2% and 30% during the period 1971–2002 and 2002–2013. Soil erosion, dam construction, and banks reinforcement along the Changjiang River are the main causes of SSC variations. Fluctuations in water discharge are also controlling the SSC long-term variations. Specifically, from 1956 to 1970, the effect of soil erosion overrules that of dam impoundment, which is likely responsible for the high SSC; during the period 1970–2002, the influence of dam impoundment increases while that of soil erosion decreases, which together produce a small reduction in SSC. Since 2002, the impact of soil erosion further decreases and large-scale sediment trapping behind the Three Gorges Dam is responsible for the occurrence of extremely low SSC. The results presented herein for the Changjiang River can inform a better management strategy of sediment resources and water quality for both the river and the coast. Our conclusions can be well applied to other rivers discharging in the ocean subject to similar human activities.

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1. Introduction

Sediment transport from rivers to the ocean has been seen as a vital pathway of material transfer on the Earth surface, playing a key role in global biogeochemical cycles (Dagg et al., 2004; Walling, 2006; Kettner et al., 2007; Liu et al., 2007; Huang, 2010). However, the river sediment supply to the ocean has been strongly regulated by human structures in recent decades, leading to a drastic decrease in flux as a result of significant alterations of the estuarine and river environment (Milliman and Boyle, 1975; Syvitski et al., 2005; Milliman and Farnsworth, 2011; Allison et al., 2012). As a result, in recent years attention has increased on the reduction of fluvial transport of suspended sediment into the ocean (Horowitz, 2003; Syvitski et al., 2005).

Some studies indicate that dams have a serious impact on the decrease of suspended sediment discharge (SSD) in rivers (Vörösmarty et al., 2003; Walling and Fang, 2003; Dai et al., 2011c; Milliman and Farnsworth, 2011). A typical example is the reduction of SSD of the Nile River, Egypt. A 98% decrease in SSD into the Nile delta was measured after the construction of the Aswan High Dam in 1964 (Frihy et al., 1998). Similarly, the Colorado River has lost almost 100% of its sediment load since 1941, and the SSD of the Danube River in Europe has

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decreased by 35% in the last century (Milliman and Farnsworth, 2011). The Changjiang (Yangtze) River, China, was discharging into the estuary a mean yearly SSD of about 433×10^6 t/y between 1950 and 2000. Since 2003 it has experienced nearly 70% reduction in SSD from the construction of the Three Gorges Dam (TGD; Dai et al., 2014).

Reduction in SSD to the ocean can be attributed to several anthropogenic activities, such as soil and water conservation, revetment of river banks, and sediment erosion control programs (Walling and Fang, 2003). A recent study has pointed out that river engineering has caused a decline in SSD in the Mississippi River system in the period 1940–2007 (Meade and Moody, 2010). In the Yellow River, China, soil conservation practices are responsible for 40% of the total SSD decrease in recent years (Wang et al., 2007). Kronvang et al. (1997) showed that in an arable catchment, most of the annual sediment transport usually takes place during few events, and thus the short-term dynamics of storm events are important in sediment delivery. Recently, Dadson et al. (2003) indicated that the storm-driven runoff variability is responsible for large fluctuations in SSD in a mountainous river in Taiwan. A more recent study revealed that the frequent floods in the Wadi Sebdou catchment, Algeria, accounted for 64% of the total sediment flux (Megnounif et al., 2013). Since the amount of sediment discharged from rivers to the sea directly impacts the morphology of estuaries and deltas, considerable efforts have been focused on understanding the dynamics of SSD.

However, SSD is a product of suspended sediment concentration (SSC) and water discharge (Phillips et al., 1999). Changes of river SSC should be one of the important factors determining the amount of SSD reaching the ocean. Variations in riverine SSC can induce alterations of local species composition (Quinn et al., 1992), fish mortality (Greig et al., 2005; Heywood and Walling, 2007), restriction of periphyton growth (Yamada and Nakamura, 2002), and an increase in the delivery of phosphorus (Ballantine et al., 2009; Quinton et al., 2001). While the delivery of suspended sediments from rivers to the ocean has received particular attention in recent years, the variability and dynamics of suspended sediment concentration (SSC) require a more in-depth analysis.

Many studies indicate that SSC is a key variable in a river because it is directly related to contaminant transport, water quality, reservoir sedimentation, silting, soil erosion, and loss and has clear ecological and recreational impacts (Walling, 1977; Ferguson, 1986; Horowitz et al., 2001; Rovira and Batalla, 2006). Some studies have revealed that catchment topography, geology, and climate could determine the quantity and quality of suspended sediment in rivers (Walling, 1977; Wass and Leeks, 1999). Other studies have linked SSC to runoff, land use, construction activities, hillslope, and channel erosion (Walling et al., 1999; Rondeau et al., 2000; Siakeu et al., 2004). So far, research on variations in riverine SSC is mainly based on the discharge-SSC relationship, which is used to gain a comprehensive understanding of river processes (Sickle and Beschta, 1983; Walling, 1997; Steegen et al., 2000; Terfous et al., 2001; Horowitz, 2003; Xu and Milliman, 2009; Eder et al., 2010; Megnounif et al., 2013).

However, traditional relationships between SSC and discharge are empirical and usually variable in time, thus causing a large scatter of SSC data for a given discharge and failing to explain short- and long-term hysteresis effects (Eder et al., 2010). The relationship between SSC and water discharge is complex because of the many factors controlling it, such as snowmelt, volcanic activities, climate variability, catchment geology, and anthropogenic activities (Mouri et al., 2014). For example, a recent study found that floods can substantially alter the relation between discharge and SSC in the Mississippi River (Horowitz, 2003). By far, most studies on SSC behavior were based on annual or monthly mean data and discontinuous water sampling, thus failing to address the variability and dynamics of SSC in streams. We advocate that daily SSC data are necessary to understand how and to what degree riverine hydrological processes are affected by natural and human drivers, especially in the Changjiang River, China. The Changjiang River is the longest river in China with a catchment area of 1.8×10^6 km^2. The river can be divided into two parts: the upper stream above the city of Yichang, and the mid-lower stream from Yichang to the ocean (Fig. 1). The geomorphology of the Changjiang River basin is characterized by mountains and hills in the upper-stream area and extensive fluvial plains with numerous lakes in the mid-lower reaches (Chen et al., 2007). The annual water discharge and SSD at the beginning of the estuary was high between 1950 and 2000, with an average value of 905.1×10^{12} m^3/y and 433×10^6 t/y, respectively (BCRS, 2001). However, since the TGD (the largest dam in the world) was constructed in the upper stream in 2003, the SSD into the Changjiang estuary has decreased nearly 70% (Dai et al., 2014; Yang et al., 2015). Such a large decline in a relatively short period has received much attention from the scientific community (Xu and Milliman, 2009; Chen et al., 2010; Dai et al., 2014; Yang et al., 2015). A number of studies focused on the yearly changes in SSD from 1951 to 2000s (Yang et al., 2002; Gao and Wang, 2008), on the fate of suspended sediments delivered to the East China Sea (Liu et al., 2007), on the many impacts of such a decline in SSD (Yang et al., 2015), on the relation between SSD and water discharge (Xu and Milliman, 2009), and on the effects of extreme droughts on SSD (Dai et al., 2011a).

Clearly, previous research on the Changjiang River mainly focused on SSD variations and related consequences on the basis of monthly or yearly hydrological data. The SSD from the Changjiang River to the sea is estimated through water discharge and SSC; however, the impact of dam impoundment on water discharge is much less than SSD (Xu and Milliman, 2009). Compared to SSD, the riverine SSC is more sensitive to the influence of natural forces and human activities. Dams along the Changjiang River, especially the TGD, have decreased the SSD reaching the sea, but have had an insignificant impact on water

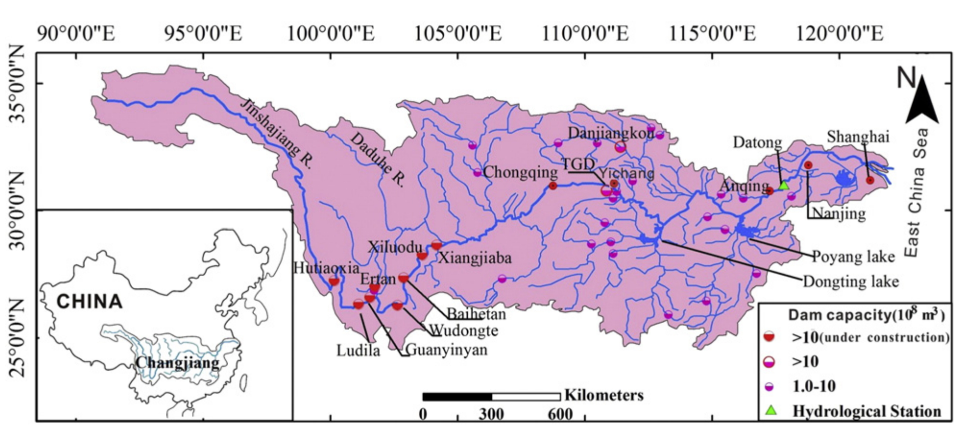

Fig. 1. Changjiang catchment and location of the hydrological gauging station (green triangle) and river dams (circles).

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