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Hydrological responses to the combined influence of diverse human activities in the Pearl River delta, China

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A B S T R A C T

In this paper, temporal variations in the hydrological process of the Pearl River delta (PRD) are examined based on monthly datasets for water discharge, sediment load and suspended sediment concentration (SSC) since the 1950s using the methods of power spectrum analysis and Fourier transform. In addition, the underlying causes of the variations are examined to address the influence of diverse human activities on hydrological process. The results indicate that (1) for the monthly low pass filtering series with a timescale of more than 8 a, the water discharge from the Pearl River increased insignificantly with an average rate of 1.66 m^3/s per year, whereas the sediment load and SSC decreased significantly with an average rate of 18.54 kg/s and 0.002 kg/m^3 per year, respectively, between 1957 and 2009; (2) decadal change in the water discharge of the Pearl River can be identified with low periods in 1950s–1972, 1984–1992 and 2003–2009 and high periods in 1973–1983 and 1993–2002, which is in good agreement with precipitation changes. Decadal change in the sediment load generally differed among three tributaries. For the West River and the North River, before the 1970s, no significant change in the sediment load can be observed because of the balanced influences of dam construction and deforestation. In the 1980s, a significant increase occurred because deforestation exceeded dam construction. Since the 1990s, large reservoirs were constructed in the West River and North River basins. And total deposition rate of all the reservoirs in two river basins was estimated to be 168.8×10^6 m^3/a in the 1990s and reached to 881.1×10^6 m^3/a in the 2000s, respectively. The influences of dam construction and soil conservation have outweighed the impact of deforestation, which has resulted in a significant decrease in the sediment load. For the East River, since the dam construction in 1960, the influence of deforestation on the sediment load did not outweigh the influence of the dam construction, which gradually decreased the sediment load; (3) for the PRD, temporal change in the water discharge and sediment load in the West River and North River deltas correspond well with the change in the water discharge and sediment load upstream of the West River and the North River before the 1990s. Due to the uneven down-cutting of the riverbed in the upper PRD since the mid-1980s, which is primarily caused by intensified sand excavation from the river channel, the divided flow ratio and divided sediment ratio at Sanshui station in the North River delta increased by 7.8% and 7.7%, respectively, in the 1990s–2000s compared with the 1960s–1980s. Therefore, the water discharge and sediment load in the North River delta increased by 57.0% and 12.2%, respectively. These changes have resulted in morphological changes in the PRD and caused many environmental problems across the PRD, which should be paid special attention.

1. Introduction

As the primary link between the land and the ocean, rivers deliver terrigenous materials, such as fresh water, sediment and nutrients, into the sea, which not only significantly influence the geomorphology of the river channels, estuaries and deltas but also provide sufficient nutrients for estuarine and coastal ecosystems (Ludwig et al., 1996; Meybeck and Vörösmarty, 2005; Milliman and Farnsworth, 2011; Walling and Fang, 2003). However, worldwide, large river systems have been modified to meet society's socioeconomic requirements. Consequently, the natural hydrological processes have been altered by powerful human disturbances in river basins, such as dams, afforestation, deforestation and water abstraction. Such disturbances have substantially affected the water discharge and sediment load delivered into the sea (Carriquiry and Sanchez, 1999; Mikhailova, 2003; Panda et al., 2011; Siakeu et al., 2004; Syvitski et al., 2005; Vörösmarty et al., 2003; Walling, 2006). For example, in China, the Yangtze River has decreased its sediment flux to the sea by approximately one-third

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since the construction of Three Gorges Dam in 2003 (Yang et al., 2007). In the 2000s, the water discharge and sediment load delivered into the sea by the Yellow River decreased to 29.3% and 10.2%, respectively, of their levels in the 1950s due to climate change, reservoir construction, water and soil conservation measures and water abstraction since the late 1960s (e.g., Liu et al., 2011, 2012). Such variations in the Yangtze River and Yellow River have resulted in considerable geomorphologic change in the rivers' deltas and ecological and environmental problems in the river estuaries and coastal regions (Fan and Huang, 2008; Liu et al., 2012; Yang et al., 2003, 2005). Therefore, the study of the anthropogenic and climate-related variation in the water discharge and sediment load of large rivers into the sea is urgent. Such research is a goal of the International Geosphere Biosphere Program (IGBP) and its core project, Land–Ocean Interaction in the Coastal Zone (LOICZ) (Syvitski et al., 2005).

The Pearl River is China's second-ranked river in terms of water discharge and the nation's third-ranked river in terms of sediment load. The river is a major source of water and sediment for the Pearl River delta (PRD), which is China's most economically developed region, and the second-largest river system that flows into the South China Sea (SCS) (Zhang et al., 2008). The Pearl River basin has developed rapidly since the implementation of China's open-door and reform policies in the late 1970s. Consequently, the hydrological processes of the Pearl River basin have been substantially altered by intensifying human activity, and the Pearl River has become one of the world's most regulated rivers (Nilsson et al., 2005). In recent years, concern has been increasing regarding temporal variations in the Pearl River's water discharge and sediment load (e.g., Chen et al., 2012; Dai et al., 2008; Zhang and Lu, 2009; Zhang et al., 2008, 2009b, 2012a). However, studies have primarily focused on the annual data series, which may mask the actual change trend of the time series and the seasonal variation of the influences of human activity on the hydrological processes (Zhang and Lu, 2009). For example, a significantly decreasing trend in the monthly mean water discharge to the sea during the dry season from the Yangtze River basin since the 1970s was observed by Chen et al. (2001). This trend was not detected in the annual mean water discharge. In addition, studies have primarily concentrated on periods before 2005 and the regions above the PRD in the Pearl River basin. The PRD is one of the world's most complicated deltas. The delta is characterised by a compound river network, and water and sediment discharge from upstream of the Pearl River are redistributed before flowing into the river network and the SCS (Luo et al., 2007). Furthermore, as the fastest developing region in China, the PRD is subject to intense human activity, such as sand excavation, intense channel dredging and levee construction. This activity has caused many environmental problems, such as floods, salinity intrusion and storm surges (Luo et al., 2007). Furthermore, the decrease in sediment has occurred primarily in the bed load of the river channel. Change in the river channel caused by a decrease in the bed load below the effects of sand excavation is an irreversible process and will certainly affect the Pearl River Estuary (PRE) system. Although research on the variations in the hydrological process in the PRD is important, relatively little has been learned regarding this subject, particularly in recent years.

Therefore, in this paper, the temporal and spatial changes in the water discharge and sediment load in the PRD were investigated based on monthly datasets from the 1950s to 2009. The objectives of this paper are (1) to examine the periodic variations and the long-term trend change in the monthly water discharge and sediment load, (2) to identify the change phases of the water discharge and sediment load and examine their underlying causes and (3) to analyse the hydrological alternations in the PRD and reveal their causes and implications for the river delta and estuary.

2. Regional setting

2.1. Physical setting

The Pearl River originates in the Yunnan Plateau and flows eastward through hill country and mountains to the SCS. The Pearl River has a mainstream length of 2400 km and a catchments of 450,000 km^2 (Fig. 1a). As a compound river system, the Pearl River has three main tributaries: the West River, the North River and the East River. In addition, other smaller rivers drain into the PRD (Fig. 1b). The Pearl River's annual water discharge in 1950s-–2000s was 8952 m^3/s with a mean annual sediment load of 2273 kg/s. Among three main tributaries, the West River is the largest tributary and has the highest water discharge and sediment load, which represent 77% and 89% of the Pearl River's total water discharge and sediment load, respectively. The North River follows with the secondary highest water discharge and sediment load. And the lowest water discharge and sediment load can be found in the East River (Table 1). The West River and the North River converge at the Sixianjiao channel in the upper PRD and then flow into the PRD through Makou and Sanshui stations, respectively, forming a complicated river network in the deltaic region (Fig. 1b). After passing through the river network, the riverine materials are delivered into the PRE via eight river outlets and eventually transported to the SCS (Fig. 1c).

The Pearl River basin comprises a region of subtropical to tropical monsoon climate that straddles the Tropic of Cancer. The annual mean precipitation ranges from 1200 mm to 2200 mm and gradually decreases from the eastern to the western side of the river basin (Zhang et al., 2012b). Due to the influence of the summer monsoon, precipitation occurs primarily during the wet season from April to September which accounts for approximately 80% of the annual precipitation. The highest and lowest monthly precipitation occurs in June and December–January, respectively. The seasonal distributions of the water discharge and sediment load in the Pearl River strongly correlate with the precipitation patterns. The East River and North River flood seasons typically occur one month earlier than for the West River (Table 2).

2.2. Human activity in the river basin

2.2.1. Construction of reservoirs and dams

Since the 1950s, China has constructed over half of the world's large dams and reservoirs to meet the growing demand for water, power generation and flood control. In the Pearl River alone, there were over 8936 reservoirs in the Pearl River basin by the late 1990s, with a total storage capacity of 518×10^8 m^3, which represents 15.9% of the Pearl River's annual water discharge. These dams and reservoirs have been constructed for different primary purposes, for example, the main priority of the Xinfengjiang, Yantan and Longtan dams is power generation and that of the Feilaixia and Baise dams is flood control. These dams and reservoirs had achieved their construction goals and played a significant role in flood control and disaster mitigation for the Pearl River basin (He, 2003). In this paper, the reservoirs capacity index (RI), which is defined as the ratio of the total reservoir capacity and the average water discharge (total-reservoir-capacity/average-water-discharge), was calculated every ten years to reflect the influence of the degree of use of dams and reservoirs in the Pearl River basin since the 1950s. The data in Fig. 2 indicates that the RI of the West River and North River increased significantly since 1990, with the construction of many dams and reservoirs (Table 3), and the East River's RI remained relatively at a higher level after the construction of the Xinfengjiang reservoir in 1960. Although the sediment load and the SSC in the Pearl River are lower than in the Yellow River and the Yangtze River, the sediment trapped by the reservoirs in the basin is substantial, with a total annual deposition rate of 402–625 Mt/a (Dai et al., 2008), which is higher than the annual sediment load into the sea (72.4 Mt/a in 1950s–2000s). Furthermore, due to the retention influence of the reservoirs, most of the coarser sediment was deposited behind the reservoirs, which