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Phosphorus export during storm events from a human perturbed watershed, southeast China: Implications for coastal ecology

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ABSTRACT

Understanding how major storms impact riverine nutrient export to estuaries and the coastal region is crucial in the context of increasing anthropogenic climate and environmental perturbation. In this study, the effects of major storms on river phosphorus (P) were investigated in an agricultural river (SE China), through continuous sampling of dissolved and particulate P during the three largest storm events (A–C) in 2013. There was a major increase in the total P load (3.4–16 fold compared with baseflow). The event mean concentration of storm A was the highest likely due to the first flush effect mobilizing accumulated waste. The flux of DOP and DRP was controlled by discharge as DOP in storm B and DRP in storm C with a relatively simple hysteresis effect with higher fluxes on the rising limb being diluted by rainfall on the falling limb. DOP in storm B remained relatively constant due to delay in DOP flushed from upstream areas balancing dilution by rainfall down stream. DRP in storm C also remained relatively constant caused by successive release of soil DRP to the river from previous unsaturated surface layers. TPP export was greatest towards the early to high stages of the storm events suggesting that most of the eroded sediment and resuspended sediment-bound P are exported during the early stages of the storm. The total flux of P is elevated in watersheds with high levels of human perturbation while climate change is predicted to increase the frequency of major storms. The results of this study are important in predicting the ecosystem response of estuarine and coastal regions to major storms in the riverine catchment area.
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1. Introduction

Global climate change is likely to increase the number, duration and intensity of tropical/subtropical cyclones and accompanying heavy storms, especially in East Asia (Webster et al., 2005; Wu et al., 2005; Knutson et al., 2010). The IPCC's Fourth Assessment Report concluded that substantial increases in heavy precipitation events are likely as a result of climate change (Qin et al., 2007). Studies using the integrated Global NEWS model have predicted increased riverine export of dissolved nutrients (mainly nitrogen (N) and phosphorus (P)) from watersheds to the coast by the year 2030, particularly in Asian basins such as China if economic development continues (Qu and Kroeze, 2010; Seitzinger et al., 2010). The cumulative effects of global environmental and climate change will likely cause an increased inflow of freshwater and nutrients to coastal waters in many areas of the globe, intensifying the eutrophication of estuarine and coastal waters (Rabalais et al., 2009; Hung et al., 2013; Shih et al., 2013; Chen et al., 2013a). Increasing nutrient losses from terrestrial to aquatic ecosystems are frequently associated with intensification of agriculture, application of animal wastes and chemical fertilizer to farmland, as well as uplands and channel erosion. Understanding riverine nutrient dynamics and key factors controlling the delivery of nutrients from watershed to coast under various hydrological conditions is essential to develop appropriate nutrient management strategies to protect the aquatic ecosystem.

Major changes in river nutrient concentrations and loads often occur during storm events (Gouze et al., 2008; Cornelis et al., 2011; Hubbard et al., 2011). A number of studies of nutrient dynamics during storm runoff have been performed in small rivers or streams (Correll et al., 1999; Borah et al., 2003; Li et al., 2007; Wang et al., 2010a; Gurumurthy et al., 2012; Williams and Kimball, 2013). By contrast there are only limited observations on large rivers

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(Mitchell et al., 1997; Brunet and Astin, 1998). Given the predicted increasing nutrient yields by Seitzinger et al. (2010), research on nutrient dynamics and export under storm conditions becomes scientifically important in Asia basins. Many coastal areas in China have a large population and fast-growing economy, which together result in declining water quality, enhanced eutrophication and algal blooms, loss of biodiversity and widespread degradation of aquatic ecosystem services. Direct measurement of nutrient dynamics during storms in China coastal river is very limited (Yang et al., 2009; Wu et al., 2012), although several scientists have conducted similar biogeochemical research after strong storm events in Chinese coastal waters (Gong et al., 2011; Hung et al., 2013; Shih et al., 2013; Chen et al., 2013a). Insufficient knowledge of how storm alter riverine nutrient supply impedes our ability to understand the regional changes that affect coastal ecosystems, and limits our ability to guide management and decision making.

The Jiulong River and adjacent estuary is located in a highly human perturbed area in southeast China, and has suffered nutrient (N and P) enrichment and eutrophication problems in the past 30 years (Li et al., 2011; Yan et al., 2012; Chen et al., 2013b). A previous analysis of riverine N dynamics suggests that extreme storm runoff (rainfall intensity > 50 mm d^{-1}) causes a four-fold increase in dissolved inorganic N (DIN) fluxes, with a greater fraction of ammonium (up to 30% of DIN) compared with smaller storm (rainfall intensity < 50 mm d^{-1}) and background flow conditions (less than 15%). Storm-driven sharp increases of N loads and changes in nutrient stoichiometry (relatively more ammonium) might be associated with algal blooms in the adjacent estuary and Xiamen Bay (Chen et al., 2012a). Besides N, P is an important bioelement. It is often the limiting nutrient to productivity and the concentration of P governs eutrophication of both the river and estuary. However, the riverine P dynamics during storms and its impacts on aquatic ecosystem are still unknown because P data were not available in the previous study. P discharge since the 1990s has increased rapidly due to livestock breeding and overuse of phosphate fertilizers by farmers (Chen et al., 2013b). Therefore, in this study the response of dissolved and particulate P forms as well as suspended particulate matter to storm events in this human impacted watershed is described. Based on the temporal variability of P concentration, flux and composition during the three largest storm events in 2013, we focus our discussion on the effects of storms size and hydrological conditions on riverine P dynamics, and how the hydrological conditions and watershed characteristics (rainfall, antecedent soil moisture, and P sources) are coupled in controlling riverine P export. This study provides the first assessment of how storms alter P dynamics supplied to a subtropical estuary in the fast developing China.

2. Materials and methods

2.1. Description of study site

The Jiulong River is a river in southeast China, with a subtropical climate and a drainage area of 14,740 km^2 (Fig. 1). Three tributaries (North River, West River, and South River) discharge water into Xiamen Bay through the estuary. The North Jiulong River was selected as the study site because it is the main tributary; it has a drainage area of 9570 km^2 and a mean annual discharge of 82.3×10^8 m^3, approximately two-thirds of the total runoff. Annual precipitation is in the range of 1400–1800 mm, with 75% occurring in the wet season from April to September. The length of the main channel to the outlet (Jiangdong) is approximately 274 km, traversing an elevation difference of 325 m. The topography in the North Jiulong River watershed is mostly hilly (91% of the catchment area has an altitude greater than 200 m, and 40% has a slope greater

Fig. 1. Map of the Jiulong River Basin showing the study area, sampling site (square), the hydrological station furthest downriver (star) and weather stations (triangle). S15 (Jiangdong) at the outlet of North Jiulong River watershed was selected as the sampling site for continuous measurements during storm events.

than 25°). Land use comprises 78% forest (mostly artificial), 16% arable land, 3% urban and residential land, 2% water, and 1% bare and grassland (2007 Landsat Thematic Mapper image). Over 120 hydropower stations and reservoirs have been constructed in Jiulong River Watershed (Wang et al., 2010b). The North Jiulong River watershed covers four cities/counties (Longyan, Zhangping, Hua'an and Changtai) and a part of Zhangzhou city. The total population is 1.5 million, 43% of whom live in urban areas. Longyan city (upstream area) has experienced a rapid increase in animal farming in recent years. The other counties are predominantly agricultural and forest land and have a relatively low population intensity, with the exception of the more densely populated downriver area close to the estuary (Changtai and Zhangzhou). Significant nutrient (N and P) enrichment and a declining N:P ratio have been observed in both the Jiulong River and estuarine waters since the 1990s; P loadings have increased as a consequence of waste discharge from the proliferation of livestock farming and the application of excessive phosphate fertilizers to cash crops (Chen et al., 2013b). Recent water quality degradation and eutrophication in Jiulong River and Xiamen Bay have been attributed to poor treatment of animal and human wastes and diffuse pollution from agricultural land. Various human activities have substantially impacted nutrient biogeochemistry from watershed to coast (Chen et al., 2008; Chen and Hong, 2012).

2.2. Storm characteristics

Three typical storm events which occurred in May 2013 (storm A), June 2013 (extreme storm B) and July 2013 (extreme storm C, caused by Typhoon Soulik) were analyzed (Table 1). Storm A occurred on May 18th and was the first heavy rainfall event in 2013, but had a lower rainfall intensity compared with storms B and C. Storm B began on June 10th was the largest flooding event in 2013. Rainfall was prolonged and peak discharge (4130 m^3 s^{-1}) was the

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