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Physicochemical conditions and properties of particles in urban runoff and rivers: Implications for runoff pollution

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HIGHLIGHTS

- The physicochemical conditions varied greatly from rainwater to runoff, and to rivers.
- Higher proportion of nano-scale particles was in runoff than in rivers.
- The ratio of turbidity and TSS indicated the size and settleability of particles.

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ABSTRACT

In this study, to gain an improved understanding of the fate and fractionation of particle-bound pollutants, we evaluated the physicochemical conditions and the properties of particles in rainwater, urban runoff, and rivers of Yixing, a city with a large drainage density in the Taihu Lake Basin, China. Road runoff and river samples were collected during the wet and dry seasons in 2015 and 2016. There were significant differences between the physicochemical conditions (pH, oxidation-reduction potential (ORP), and electroconductivity (EC)) of rainwater, runoff, and rivers. The lowest pH and highest ORP values of rainwater provide the optimal conditions for leaching of particle-bound pollutants such as heavy metals. The differences in the physicochemical conditions of the runoff and rivers may contribute to the redistribution of pollutants between particulate and dissolved phases after runoff is discharged into waterways. Runoff and river particles were mainly composed of silt and clay (<63 μm, 88.3%–90.7%), and runoff particles contained a higher proportion of nano-scale particles (<1 μm) but a lower proportion of submicron-scale particles (1–16 μm) than rivers. The ratio of turbidity to TSS increased with the proportion of fine particles and was associated with the accumulation of pollutants and settling ability of particles, which shows that it can be used as an index when monitoring runoff pollution.

1. Introduction

Runoff volumes, runoff coefficients, and pollutant loads have tended to increase in recent decades, as a result of the increases in impervious surfaces caused by rapid rates of urbanization worldwide (Sun et al., 2015). Increases in these indexes exacerbate the risk of urban floods. Therefore, drainage systems are generally designed to ensure rapid discharge of runoff into adjacent waterways. It has been reported that more than 90% of runoff is discharged directly into rivers in districts that have implemented rain and sewage diversion. This means that the increasing number of non-point source pollutants are more widely distributed, and are difficult to control with centralized measures (Loperfido et al., 2014).

Non-point source pollution, recognized as a pertinacious illness of urban rivers because of its ongoing contribution to their pollution, has received considerable attention in previous studies (Reidsma et al., 2012). The concentrations, loads, and first flush effects of runoff pollutants have been investigated, and first flushes of pollutants with high concentrations and loads have also been observed during rainfall events (Kim and Sansalone, 2008; Chow et al., 2013; Zhang et al., 2013; Chow and Yusop, 2014; Gasperi et al., 2014). The processes that control the build-up and wash-off

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of road-deposited sediment (RDS) have been explored to investigate the fate and fractionation of runoff pollutants, including their accumulation, mobility, and fractionation (Sansalone and Ying, 2008; Joshi and Balasubramanian, 2010; Yuen et al., 2012). Studies have shown that particle size plays an important role in the accumulation and mobility of pollutants (Gunawardana et al., 2012; Zhao and Li, 2013; Li et al., 2015). Also, pollutants tend to accumulate in fine particles that can be transported easily by rainfall (Gunawardana et al., 2015; Zhao et al., 2016). Other studies have reported that the fractionation of pollutants between the particulate and dissolved phases is determined by their binding states with particles and the physicochemical conditions (pH, oxidation-reduction potential (ORP) and electroconductivity (EC)) in the water environment (Morselli et al., 2003; Duong and Lee, 2009; Zhang et al., 2016). For example, water environments with low pH, low ORP, and high ORP favor the release of heavy metals (HMs) associated with carbonates, Fe and Mn oxides, and organic matter, respectively (Sutherland et al., 2012; Maniquiz-Redillas and Kim, 2014). These studies provide valuable information about runoff pollution and its control. However, little is known about the fate and fractionation of pollutants contained in runoff once they are discharged into waterways.

The fate and fractionation of runoff pollutants are closely related to their potential impacts on waterways; dissolved pollutants are directly bioavailable, while the sediments may clog waterway beds, smother biota, damage the respiratory systems of organisms, attenuate light, and act as vectors of hydrophobic pollutants (Helmreich et al., 2010; Zuo et al., 2012; McKee and Gilbreath, 2015). Therefore, it is important to analyze the physicochemical conditions and particle characteristics of the main receptors of RDS during runoff events, namely rainwater, runoff, and waterways, to evaluate the fate and fractionation of runoff pollutants. However, previous studies have tended to examine the particle properties and fractionation of particle-bound pollutants in runoff or rivers separately, and have rarely considered the physicochemical conditions. Consequently, we have little appreciation of whether or how the properties of particles in, and physicochemical conditions of, rainwater, runoff, and rivers differ from each other, nor do we have a good understanding of the potential fate of particle-bound runoff pollutants once they are discharged into waterways. A clearer understanding of these processes will facilitate improved management of runoff pollution.

The objectives of this study therefore were to 1) detect the differences in the physicochemical conditions and particle characteristics of rainwater, urban runoff, and rivers, and 2) analyze the potential fate and fractionation of runoff pollutants during rainfall events. We hope that the information produced will support management of runoff pollution and contribute to the preservation of urban waterways.

2. Material and methods

2.1. Study area and sampling sites

We chose Yixing, a city in the Taihu Lake Basin in Eastern China, as our study area. This city is characteristic of the area and, with its extensive waterway network, has a large drainage density. Yixing has a population of approximately 1.24 million and covers a total area of 1996.6 km^2, 16.8% of which is occupied by water bodies. The urban area of 66.3 km^2 is crisscrossed by rivers, with a river density of up to 2.27 km km^{-2}. Yixing has a subtropical monsoon climate. The average annual temperature, rainfall, number of rain days, and evaporation are 15.7 °C, 1177 mm, 136.6 d, and 849 mm, respectively. The drainage is via a rain and sewage diversion system that comprises only main pipes or a few branch pipes that are capable of discharging runoff rapidly in most conditions. When runoff is generated, untreated runoff flows directly into the nearest waterways.

The catchment of the Nanhe River (blue lines in Fig. 1A), one of the three largest rivers in the Taihu Basin, is to the west of Taihu Lake. The rivers flow from west to east and ultimately feed into Taihu Lake after traversing Xijiu, Tuanjiu, and Dongjiu Lakes and other interconnected rivers (Fig. 1A and B). The water input to Taihu Lake from the Nanhe River system accounts for around 25% of the total inputs to the lake. Agriculture, aquaculture, forestry, and urban areas dominate land use in the Nanhe catchment. The central urban area is in the middle reaches and comprises residential, commercial, and industrial areas. River and runoff samples were collected from August 2015 until May 2016. A total of 34 sampling sites, comprising 3 stagnant rivers (blue triangles, Fig. 1B) and 31 flowing rivers (red triangles, Fig. 1B), distributed throughout the Nanhe system were monitored. We collected samples of urban runoff from three road sites (green circles, Fig. 1B) in residential, commercial, and industrial areas.

2.2. Sampling strategy

Six different types of samples, namely rainwater, urban runoff (UR), stagnant rivers during the wet season (SR-W), stagnant rivers during the dry season (SR-D), flowing rivers during the wet season (FR-W), and flowing rivers during the dry season (FR-D), were collected. Individual samples of local rainwater were collected in clean polyethylene vessels in an open area. Runoff samples were collected from the inlet grating at the roadside (Fig. 1C) at 5-min intervals during five rainfall events. The rainfall amounts, rainfall durations, and antecedent dry periods ranged from 5.2 to 26.8 mm, from 72 to 318 min, and from 23.8 to 359 h, respectively. We collected surface water samples from the middle of the river channels (Fig. 1D). River samples were collected once or twice a month during the dry season when the number of antecedent dry days ranged from 2 to 8 d. River samples were collected through two rainfall events in the wet season at time intervals of 0.5, 1, 2, 4, and 6 h. Samples were collected in pre-washed 1-L polyethylene bottles. It should be noted that the sampling program was not designed to identify the cause-and-effect linkages between urban runoff and rivers, but to understand the physicochemical

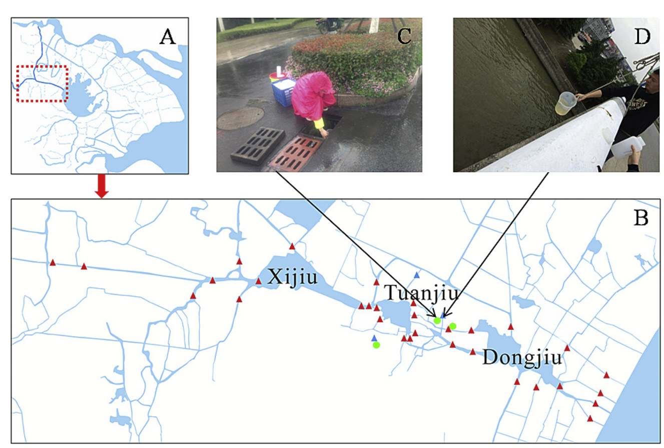

Fig. 1. (A) Geographical position. The blue lines and red virtual frame represent the Nanhe River system and the study area, respectively. (B) River sampling sites. The red and blue triangles represent the sampling sites in the flowing and stagnant rivers, respectively. The green circles represent the road runoff sampling sites in the urban area. (C) and (D) are photographs of runoff sampling and river sampling, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)