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Research article

Phosphorus retention along a typical urban landscape river with a series of rubber dams

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ABSTRACT

Small dams are widely constructed in urban rivers as landscape engineering practice, which increasingly cause eutrophication problems. Phosphorus retention in dammed rivers is a critical factor driving eutrophication, but it is little known in urban landscape river systems controlled by small dams. In this study, we investigated the retention of different phosphorus species along an urban landscape river with 30 rubber dams. We found that 42.5% (7.69 metric tons/yr) of the total phosphorus (TP) was trapped within dams, of which total particulate phosphorus (TPP) retention load accounted for 81.5%. From first river segment BBF-4# to the segments further downstream, the TP retention rate sharply decreased from 47.6% to −8.3%-9.2%, and phosphorus was mainly retained in the uppermost segment of the dammed river. The retention rate of dissolved reactive phosphorus (86.3%) was higher than that of TPP (40.3%) because of biological uptake. Further, with a retention rate of −11.3%, the dammed river was a net source of dissolved organic phosphorus. Different hydrological regimes, due to seasonal events and dam management, greatly influenced phosphorus retention within the dammed river, resulting in higher retention loads in the rainy season than in the dry season, and very low retention loads in the snowmelt season, with 1.48, 0.55 and 0.06 t/month, respectively. Our findings imply that management practices should focus on reducing the phosphorus export from the upper watershed and improving the hydrodynamic conditions of the dammed urban landscape river with regard to eutrophication.

1. Introduction

During the rapid progress of urbanization, more and more small dams are constructed in urban rivers as landscape engineering practice, which may cause eutrophication due to hydrodynamic attenuation and nutrients accumulation (Hilton et al., 2006; Némery et al., 2016). Phosphorus plays an essential role in the limitation of primary production and eutrophication in freshwater system (Guildford and Hecky, 2000; Hilton et al., 2006). It is important to understand phosphorus transport and fate in dammed urban landscape rivers for phosphorus management and eutrophication control.

The construction of reservoir dams, which is the most common hydraulic engineering practice in river systems, has significantly changed the global phosphorus cycle and increased phosphorus retention (Maavara et al., 2015). Researches have revealed that reservoir dams often trap amounts of phosphorus in rivers, while the natural rivers without artificial dams showed negligible annual net phosphorus retention and sometimes could be phosphorus sources due to bank erosion (Schulz and Köhler, 2006; Svendsen et al., 1995). For instance, the annual yield of total phosphorus (TP) was 20%–30% lower in the dammed than in the natural river systems (Powers et al., 2015; Sferratore et al., 2008). In large river systems, like the Yangtze River in China, the construction of series of large reservoirs have decreased the discharge of TP by 84% (Ouyang et al., 2011). Single reservoir also have large capacities to retain phosphorus. In the Three Gorges Reservoir of the Yangtze River (Ran et al., 2016) and in the Kafue Gorge Dam of the Kafue River in Zambia (Kunz et al., 2011b), for instance, 44% and 60% of the TP were retained, respectively.

Nowadays, in addition to large reservoir dams, more and more small dams, like rubber dams and concrete weirs, are being built worldwide, especially as part of urban river landscapes. Similar to large reservoirs, small dams also change the morphology and hydrology of rivers. It has, for example, been reported that nutrients (Gao et al., 2017) and antibiotics (Guo et al., 2017) efficiently accumulate within small dams. Other studies related to small dams in urban river systems are focused on the effects of dam construction on river habitat quality (Cochero et al., 2016; Ding et al., 2015). Therefore, the knowledge about the global phosphorus cycle and phosphorus retention in dammed rivers

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(Filippelli, 2008; Maavara et al., 2015) is incomplete, while it is scarcely studied about the phosphorus transport in urban river systems with small dams.

Riverine phosphorus is cycling both as particulate and dissolved species. Dissolved reactive phosphorus (PO_4-P) has the highest bioavailability (McCall et al., 2017). Dissolved organic phosphorus (DOP) can be either directly taken up by phytoplankton or remineralized into PO_4-P (Llebot et al., 2010). Particulate phosphorus consists of metals-bound inorganic phosphorus and mineralizable organic phosphorus, with different release potential into water (Ye et al., 2017). Different phosphorus species, however, have different retention characteristics, and thus would show different contribution to eutrophication. Ran et al. (2016) reported that the Three Gorges Reservoir acted as a 'converter' for dissolved reactive phosphorus and a 'filter' for particulate phosphorus, causing in more particulate phosphorus to settle in the reservoir. Therefore, in order to control the eutrophication, it is necessary to fully understand the transport and fate of different phosphorus species in dammed urban landscape rivers.

The phosphorus trapped in dams mainly accumulates in the sediments (Maavara et al., 2015; Vo et al., 2014), which become an intrinsic source (Liu et al., 2013). The trapped phosphorus can only be transported to the lower water bodies when runoff increases, e.g., due to flooding events or dam collapse (Avilés and Niell, 2007; Jung et al., 2014). Generally, riverine flow changes with the seasonal precipitation variations, resulting in more phosphorus retained during low flows than during high flows (Morris et al., 2014; Pulley et al., 2016). Increasing flow release or improving hydrodynamic condition by dam operation can also reduce phosphorus retention (Jung et al., 2014). Besides flow variations, which has the most direct and profound effect on phosphorus retention in river systems, the hydrological regimes include inflow loads of phosphorus and suspended particles (Mao et al., 2015). In the dammed urban landscape rivers, how the variations of the hydrological regimes influence the transport of phosphorus needs further study.

Tens of thousands of rubber dams have been constructed in river systems around the world since first developed in 1957 and installed in the Los Angeles River, USA (Manning et al., 2005), especially as landscape engineering practice of urban rivers in water shortage areas. Therefore, a typical urban landscape river, with 30 rubber dams in the city of Zhangjiakou in northern China, was studied in order to examine how phosphorus behaves in small dams. We hypothesized that: (1) the phosphorus retention loads and retention rates sharply decrease along the gradient dammed river; (2) the retention rate of particulate phosphorus is higher than that of dissolved phosphorus; and (3) seasonal hydrological regimes greatly influence the phosphorus retention load.

2. Materials and methods

2.1. Study area

The dammed urban landscape river studied here is located in the main channel of the lower reaches of the Qingshuihe catchment (Fig. 1). The river flows into the Yang River and ultimately discharges into the Guanting Reservoir (a possible auxiliary drinking water source for Beijing). The area has a temperate continental monsoon, semi-arid climate with hot summers and cold, windy, and dry winters. The river is frozen in the winter from November to February. The annual rainfall is about 400 mm and most abundant from June to September (http://www.zjk.gov.cn/zjzjk.html). The studied river passage is 22 km long and has been under strict management since 2008 with completely hardened channels, allowing only water from the upper watershed to empty into it. Meanwhile, 30 rubber dams (numbered 1# to 30#) filled with tap water have been constructed along the urban landscape river (Fig. 1). The dams, which are 120 m long and 3.5 m deep on average, have transformed the 3–10 m wide waterway, with a mean flow velocity of 0.82 m/s, into a fluvial impoundment with a sheet flow of less than 0.01 m/s. The dammed urban landscape river has a maximum water storage capacity of 5.3 million m^3 and an average residence time of 38 days. In the frozen period, about one-fourth of the rubber dams are collapsed to facilitate convenient riverbed management (between December 2015 and March 2016, rubber dams 1#, 4#, 6#, 13#, 20#, 21#, 23# and 26# were collapsed). All dams are designed to collapse in case of extreme flooding, which has not happened yet.

2.2. Sampling and field measurements

Five monitoring sites were selected along the dammed urban landscape river (Fig. 1): site Beibengfang (BBF) is located at a relatively natural part of the river and coincides with the inlet of the river; site 4# coincides with the outlet of the 4th rubber dam and the Zhangjiakou Hydrological Station; sites 13#, 21# and 30# coincide with the outlets of the 13th, 21st and 30th rubber dams, respectively; site 30# is the outlet of the entire dammed river. The characteristics of the different river segments are shown in Table 1.

Water samples were collected monthly from March to November in 2016 (no samples were collected during the frozen period from December to February). The collected water samples were analyzed within 48 h. The velocity and flow were measured on-site using a portable flow meter (FLOWWATCH, Switzerland). Turbidity was measured by a HACH 2100Q portable turbidimeter (USA), and used as a proxy measure of suspended particles.

2.3. Phosphorus species in water samples

The phosphorus species in the water samples were measured according to national standard methods (SEPA, 2002). The concentrations of TP and total dissolved phosphorus (TDP; total phosphorus in the water sample filtered by a 0.45 μm membrane) were determined using the molybdenum blue method. Total particulate phosphorus (TPP) was estimated as the difference between TP and TDP, and DOP was estimated as the difference between TDP and PO_4-P. The concentration of PO_4-P was measured using a Smartchem 200 automatic chemical analyzer. Chlorophyll *a* (*Chl a*) in the river water was extracted by 90% acetone and tested by a spectrophotometer.

2.4. Phosphorus mass balance calculations

The phosphorus mass budget was calculated using the monthly discharge and concentration values at the inlet and outlet of the different river segments (Bowes and House, 2001; Jossette et al., 1999). The monthly retention load of phosphorus within each of the four river segments, M_R, was calculated according to Equation (1), where M_{in} is the monthly load of phosphorus entering each river segment, and M_{out} is the corresponding load leaving each river segment (all terms are in metric tons (t) per month).

$$M_R = M_{in} - M_{out} \tag{1}$$

The annual phosphorus sedimentation rate (S_R, g/m^2/yr) was calculated according to Equation (2) (Némery et al., 2016), where Y_R is the annual phosphorus retention load in t/yr (i.e., the sum of all monthly retention loads), and the Surface-parameter is the surface area of the entire impoundment (2.47 km^2).

$$S_R = Y_R/\text{Surface} \tag{2}$$

The phosphorus retention rates in each river segments were calculated according to Equations (3) and (4) (Maavara et al., 2015), where R_L (t/km·month) is the retention efficiency based on the transport distance, R_P (%) is the retention rate of phosphorus, i.e., the phosphorus retained as a percentage of the load entering the urban landscape river from BBF, and M_{BBF} (t/month) is the load of phosphorus entering the urban landscape river in BBF.