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Research Paper

Assessing how spatial variations of land use pattern affect water quality across a typical urbanized watershed in Beijing, China

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A R T I C L E I N F O

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A B S T R A C T

Understanding the relationship between land use patterns and water quality in urbanized areas can provide insight into urban water quality management. In this study, a self-organizing map (SOM) and a linear mixed effects (LME) model were applied to explore the spatiotemporal patterns of nutrients and their relationship with land use characteristics in the highly urbanized Beiyun River watershed. The SOM classified 324 sampling data from 2014 to 2015 at 25 typical river sampling sites into nine clusters, with differences in land use patterns and seasonal (rainy and dry seasons) distributions. In the urbanized upstream reach of the river, concentrations of most pollutants were low, while in downstream sites the concentrations were higher for these pollution parameters. Nitrate-N ($NO3^{-}$-N), however, exhibited the opposite pattern, probably due to the sources of pollutants and biochemical processes. The explanatory ability of the LME model in the established urbanized area and newly developed area in the upstream portion of the watershed was much better than in the downstream area, probably due to the influence of upstream nutrient contributions and the point source inputs in the downstream area. These statistical results indicated that sewage disposal and the main urbanized land use types were the most important drivers of river contamination. Forest land positively or negatively influenced river water quality depending on its spatial location as well as the water quality indicators. Therefore, sewage disposal as well as spatial non-stationarity of land-use impacts should be taken into consideration to reduce water pollution in the Beiyun River watershed.

1. Introduction

River water chemistry is influenced by multitudinous natural and anthropogenic point sources (PS) and nonpoint sources (NPS) of pollution. Land use patterns within a watershed affect water quality through NPS pollutants, which have posed a severe threat to the river water quality, especially in urban areas (Jia, Yao, & Yu, 2013). With the intense urbanization in developing countries, natural landscapes have been fragmented and converted into impervious surfaces (Su, Gu, Yang, Chen, & Zhen, 2010; Han & Jia, 2017), resulting in increased peak flows and increased volumes of runoff. These modifications of the hydrological process make pollutants on the surface of a catchment much easier to be transported into rivers by storm water, causing great degradation problems (Barbosa, Fernandes, & David, 2012). Therefore, identifying the quantitative relationships between land uses and water pollution parameters is essential for integrated water resources management in urban watersheds.

Many researches have provided compelling evidence that the stream hydrological process and water quality variations are associated with land use changes (Wan et al., 2014; Alvarez-Cabria, Barquin, & Penas, 2016; Bu, Zhang, Meng, & Song, 2016). Expansion of impervious surface areas accelerates the transport of nutrients from the source areas to receiving waters, resulting in the increased nutrient concentrations in river systems (Liu, Egodawatta, Guan, & Goonetilleke, 2013). Sewage effluents could also contribute to the spatiotemporal variations of nutrient fluxes from urbanized watersheds due to the varying wastewater treatment technologies and nutrient removal efficiencies (Hale, Grimm, Voeroesmarty, & Fekete, 2015; Xian, Ouyang, Li, Xiao, & Ren, 2016). Forest usually functions as sink of nutrients to rivers due to its fixation and adsorption effects for pollutants (Nakagawa & Iwatsubo, 2000; Bu et al., 2016). Water bodies can provide direct effects on nutrient biological cycles. For instance, the processes of nitrogen cycle, composed by nitrogen assimilation, ammonification, nitrification and denitrification, are controlled by the water conditions. These influencing factors include pH value, temperature, redox conditions and so on (Köln, Ferguson, & Newton, 2007). However, the relationships are usually area-specific and non-stationary, especially in urban areas that are impacted by human activities (Griffith, 2002). The spatial and temporal

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variations in pollution sources and transportation factors could be the main reason. Intense human activities can cause the uneven distributions of NPS pollution sources within a watershed, and the PS pollution may bring about uncertainties concerning the relationship between urban land use types and river water quality (Ahearn et al., 2005; Zhou, Huang, Pontius, & Hong, 2016). The linkage of land use types and riverine water quality, and the degree to which pollution indicators can be interpreted by land use types still need to be further studied.

Researchers have applied various statistical methods, for example, correlation analysis (Yu, Xu, Wu, & Zuo, 2016), multiple regression and redundancy analysis (Shen, Hou, Li, & Aini, 2014), to investigate the relationships between land uses and water quality. These researches are usually focused on the overall relationships in an entire study area. However, because pollution sources may change through a study area, a global approach may miss this spatial variation and hide local relationships between land use patterns and water quality, which are more practical for making appropriate management strategies. A plausible way to overcome this shortcoming is to recognize similar watershed and pollution characteristics through spatiotemporal analysis, and then analyze the associated land use-water quality relationships. Cluster analysis attempts to arrange dataset into multiple clusters so that objects within a cluster have similar characteristics and different from those in other clusters (Thuy Thanh et al., 2015). These representative clusters can be helpful to provide insight into watershed heterogeneity as well as physicochemical processes which control river water chemistry (Park, Kwon, Hwang, & Park, 2014). Because environmental data are usually bulky, non-linear and “noisy”, and because complex interactions exist between explanatory and response variables, non-linear clustering analyses are preferable to linear analyses when examining these data. In particular, the self-organizing map (SOM) method has been employed as a versatile tool for information extraction and classification of various ecological and environmental data, and has been widely used in water research, such as for surface water (Zelazny, Astel, Wolanin, & Malek, 2011), biological indicator taxa in aquatic systems (Milosevic et al., 2016), storm water monitoring (Ki et al., 2011) and groundwater assessment (Thuy Thanh et al., 2015).

Despite great efforts to explore relationships between land use pattern and water quality, it is still challenging to link various water quality parameters to land use types in the highly heterogeneous urbanized watershed. The objective of this study was to examine which land use types can best explain the observed water quality variables in response to urbanization levels in a typical urbanized watershed. In this study, water quality variables were surveyed at 25 sampling sites throughout the Beiyun River watershed in Beijing from 2014 to 2015. A hierarchical framework of SOM, cluster analysis, and a linear mixed effect model was used to investigate the variation of river water quality and its linkage with land use patterns across the Beiyun River watershed. Specifically, we aimed (1) to examine the spatiotemporal variation of the pollutant dynamics in the urbanized river system; (2) to identify the relationships between land use types and urban river water quality; and (3) to recognize the spatial variation of the effect of land use pattern on water quality in the urbanized area.

2. Materials and methods

2.1. Study site

The Beiyun River originates in the south of Yan Mountains in Changping District of Beijing, flows successively through the major urban area of Beijing, Xianghe Country of Hebei province, and finally drains into the Hai River. The river basin examined in this study is located in the municipality of Beijing. In the study watershed, the total river length is 89.4 km and the basin area is 4348 km^2. Bounded by the Beiguan floodgate, the upstream of the basin is named as the Wenyu River, and the downstream is called as the Beiyun River. The Beijing metropolitan area exhibits the rural–suburban–urban gradient. With

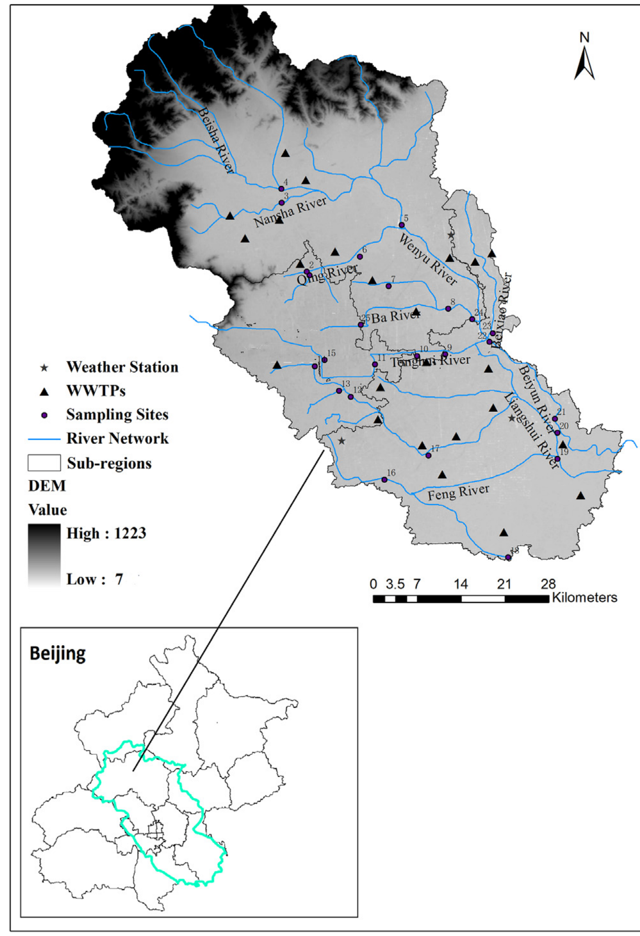

Fig. 1. Location of the sampling sites in the Beiyun River Watershed.

the rapid economic development, the new urban functional areas in Beijing are conducted in the rural and suburban region. The annual average temperature of the study area is 10–12 °C, and the annual precipitation is 500–600 mm. Approximately 80% of the rainfall takes place during the period from June to August. As an important drainage channel, the flood relief responsibility of the Beiyun River accounts for 90% for Beijing, and it receives increasing urban sewage by way of the main tributaries, namely, Qing River, Ba River, Tonghui River and Liangshui River etc… The river is currently affected by serious pollution, generally exceeding grade V, which is the worst grade defined by the national surface water quality standard.

In this study, 25 water quality sampling sites were selected along the mainstream and its tributaries based on mainstream characteristics, the influence of tributaries and the land use patterns. The exact location of each sampling sites was determined using Global Position System (GPS) (Garmin, GPSMAP 62sc) during the field study. The watershed boundaries and river network were delineated using SWAT (Soil and Water Assessment Tool) based on the digital elevation model (DEM, 30 m resolution), the given river map and the selected sampling sections (Fig. 1). Specifically, the river networks were built using the extraction method for flat regions described by previous studies (Zhang & Huang, 2009; Lou, Su, Li, Yuan, & Zhang, 2011). Each sampling section was specified to be the outlet point of a delineated catchment, and the catchment areas of the sampling sites were determined for further analysis.

2.2. Sample collection and analysis

River water samples were taken at monthly intervals from July 2014