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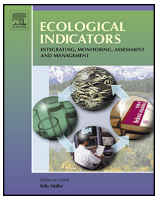

Impact of landscape pattern at multiple spatial scales on water quality: A case study in a typical urbanised watershed in China

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ABSTRACT

Buffer zones along rivers and streams can provide water quality services by filtering nutrients, sediment and other contaminants from the surface. Redundancy analysis was used to determine the influence of the landscape pattern at the entire catchment scale and at multiple buffer zone scales (100 m, 300 m, 500 m, 1000 m and 1500 m) on the water quality in a highly urbanised watershed. Change-point analysis was further applied to estimate the specific locations along a gradient of landscape metric that result in a sudden change in the water quality variable. The landscape characteristics for 100 m buffer zones appeared to have a slightly greater influence on the water quality than the entire catchment. The patch density of urban land and the large patch index of water were recognised as the dominant variables influencing the water quality for a 100 m buffer zone. The result of change-point analysis indicated key interval values of the two landscape metrics within the 100 m buffer zone. When the patch density of urban land was >30–40 n/100 ha and the largest patch index of water was >2.5–3.5%, the watershed water quality appeared to be better protected.

1. Introduction

Buffer zones, with the fundamental purposes of preventing erosion and filtering out contaminants from nonpoint pollution (NPS) and groundwater entering laterally, have been widely used as a typical landscape for water quality services to adjacent waters (Correll, 2005; O'Driscoll et al., 2014; Shan et al., 2014). However, many riparian zones of rivers have not only been denuded of native vegetation, but the adjacent waterways have been channelised, dammed, populated by exotic biota and seriously polluted (Correll, 2005). In the watersheds with a high degree of urbanisation, the situation is more serious due to numerous anthropogenic factors. When planning the restoration or recreation of riparian buffer zones, the landscape design usually varies along with the width of the buffer zones (Fischer and Fischenich, 2000). Therefore, under the premise of limited funds, it is of significance for rational landscape design to understand the relationship between the landscape and the water quality at the buffer zone scale.

It is known that rivers are recipients of pollutants from adjacent landscapes. Thus, the landscape pattern, including the landscape composition and the spatial configuration, is closely correlated with the water quality, as proven by numerous studies (Hopkins, 2009; Mitchell et al., 2013; Xiao and Ji, 2007; Yang, 2012). From an ecological perspective, investigating the relationship between the landscape pattern and water quality variables at multiple spatial scales could provide important information for the optimisation of the buffer zones and the improvement of the water quality (Zhou et al., 2012). Considering the specificity of each catchment, the difference in intensity of human disturbance and the resolution of data sets, it is understandable the research has not yielded a consensus view (Buck et al., 2004; Dodds and Oakes, 2008; Li et al., 2013; Margriter et al., 2014). Although these studies have become more common in recent years, many questions are still unanswered. For example, quantifying the impacts of the landscape at multiple spatial scales on urban receiving water bodies is still lacking in the literature.

A great variety of landscape metrics, such as the quantification of the landscape, have been developed for landscapes and used for elucidating the relationship between the landscape and the water quality for years (Basnyat et al., 2000; Riitters et al., 1995; Uuemaa et al., 2009). For the sake of water quality improvement, it is valuable to investigate the response of the water quality to the gradient of the landscape metrics, and it would be best to indicate the key

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interval values of the landscape metrics for river risk management. Change points, defined as points or zones at which an abrupt change in an ecological quality, property, or phenomenon occurs or where small changes in a driver can produce large responses in the ecosystem, can be used for determining the key interval values (Francesco Ficetola and Denoël, 2009; Groffman et al., 2006). In multiple fields of ecology, the existence of change points have been proven; for example, most papers have focused on the abrupt changes in species richness or occurrence in response to various types of drivers, habitat or landscape connectivity (Petty et al., 2010; Schmidt and Roland, 2006). Several studies have explored the abrupt change in water quality along the landscape pattern; however, most studies only investigated one simple metric, for example, the amount of impervious area (ISA) (Liu et al., 2013; Schueler, 1994). It is known that both the landscape composition and configuration have a significant impact on the water quality, and the relationship is complicated and scale dependent (Shen et al., 2014; Zhou et al., 2012). Thus, combining the scale dependence and change-point analysis to relate the landscape to the water quality is important to provide valuable information for landscape design in riparian buffer zones and for river water quality improvement.

The Beiyun River watershed bears 90% of the flood relief task of the municipality of Beijing, and its water quality has a significant impact on the urban environment and downstream areas. However, the water quality of the Beiyun River watershed exceeds grade V, which is the worst score in the national surface water quality standards of China (BMEPB, 2011). A few riparian zones existed in the watershed, if at all, have limited ecological function as a result of narrow single type of vegetation cover and large slope. The reconstruction and repair of riparian buffer zones has been recognised as an urgent and effective way for filtering runoff and land based pollutants. Our previous study has characterised the relationship between the water quality and the landscape pattern of the watershed, including both the composition and the spatial configuration at the landscape and the class levels (Shen et al., 2014). The results showed that the landscape characteristics are significantly correlated with this highly urbanised watershed in the rainy season. The landscape indices at the class level and those that represent the configuration have substantial impacts on the water quality. The relationship between the landscape characteristics and the water quality after the rainy season was poor compared with that in the rainy season. Therefore, in the present study, the further exploration at multiple buffer zones was only conducted in the rainy season. Based on a previous study, the objectives were therefore (1) to examine the relationships between the water quality and the landscape variables at multiple spatial scales and to determine the most effective riparian width and (2) to evaluate whether there is an abrupt change in the water quality with changes in the landscape metrics in the most effective riparian zone.

2. Methods

2.1. Site description

The Beiyun River, located in the northern section of the Chinese Grand Canal, originates in the northern Yan Mountains in the territory of Beijing, flows through Xianghe County, Hebei Province and drainages into the Tianjin Haihe River. The river system we examined is the portion inside the municipality of Beijing with a drainage area of 4348 km^2 and a total length of 89.4 km (Fig. 1). The watershed drains a region of warm and semi-humid continental monsoon climate, and its annual mean temperatures range between 10 and 12 °C. The average annual rainfall is 500–600 mm, as much as 80% of which falls in the rainy season, generally from June to August. During the period 1961–1998, the average annual surface water outflow in the Beiyun River basin was approximately 0.93 billion m^3/a, including 0.462 billion m^3 fresh water and 0.469 billion m^3 wastewater discharge (Pan et al., 2013).

The Beiyun River watershed flows through the downtown area of Beijing and is the most important drainage system of Beijing. The Qing River and the Ba River are the major drainage channels in the urban areas, and the Wenyu River and the Beiyun River are the drainage channels of the suburban areas in the downstream. Artificial projects for flood control and agricultural irrigation have diversely impacted the river ecosystems and intensified the water degradation. The dominant land use category in the river system is forest, followed by urban area and agricultural land, which comprise 37.18%, 28.76% and 19.97% of the total area, respectively.

2.2. Data sets

Samples were collected at 25 sites throughout the Beiyun River watershed (Fig. 1) in July, 2011. Two or three parallel samples at each sampling site were collected to effectively avoid the risk of obtaining random results. Sample collection occurred a day after a rain event (daily rainfall: 48 mm) to represent the contribution of the NPS pollution of storm water runoff. Five chemical water quality indicators, the total suspended solids (TSS), chemical oxygen demand (CODcr), ammoniacal nitrogen (NH_4–N), total nitrogen (TN), and total phosphorus (TP), were measured within 6 h of sampling following standard methods (SEPA, 2002).

The subcatchment boundaries for each monitoring site were delineated from a digital elevation model (DEM) (30 m × 30 m data resolution) using SWAT (Soil and Water Assessment Tool) (Arnold et al., 1998). The land use/land cover of the basin was derived using Landsat SPOT5 1A images in 2009 with a hybrid of supervised and unsupervised classification algorithms. The resolution of the remote sensing image may affect the results of the studies because it directly affects the accuracy of the land use classification. Thus, two data sets with different resolutions, including panchromatic images of the downtown area of Beijing (2.5 m resolution) and multispectral images of the Beiyun River watershed (10 m resolution) were used for more accurate extraction. Eight land use and land cover types were classified (Table 1): urban land (URB), industrial land (IND), road (ROA), water body (WAT), grassland (GRA), forest (FOR), agricultural land (AGR), and unused land (UND). Five spatial scales within the regional watershed, consisting of 100 m, 300 m, 500 m, 1000 m, and 1500 m buffer zones, were created by buffering along the streams using ArcGIS9.3 (Fig. 1).

The landscape metrics representing the patch size, shape, structure, and landscape diversity were selected at the both landscape and class levels. Contagion (CONTAG) and Shannon's diversity index (SHDI) were calculated at the landscape level only; the patch density (PD), landscape shape index (LSI), edge density (ED), interspersion and juxtaposition index (IJI) were calculated at both levels; and the percent of landscape (PLAND) and large patch index (LPI) were calculated at the class level only. These metrics not only reflect the land use and the land cover but also represent the spatial structure of the landscape. The land use shapefiles of the multiple buffer zones and the entire catchment were transferred to raster data (10 m × 10 m), and the landscape metrics at the multiple scales were then calculated using FRAGSTATS3.3 software (McGarigal et al., 2002).

2.3. Statistical analysis

The water quality data were imported into Canoco4.5 (Braak and Šmilauer, 2002) to test the DCA gradient axis, and the result showed that the DCA gradient shaft length was less than 3. Therefore, redundancy analysis (RDA) was selected for the gradient analysis of