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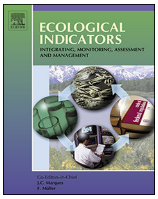

Identifying the critical riparian buffer zone with the strongest linkage between landscape characteristics and surface water quality

Kun Li[a], Guangqing Chi[b], Ling Wang[c], Yujing Xie[a,*], Xiangrong Wang[a,*], Zhengqiu Fan[a]

[a] *Department of Environmental Sciences and Engineering, Fudan University, Shanghai 200433, PR China*
[b] *Department of Agricultural Economics, Sociology, and Education, Pennsylvania State University, University Park, PA 16802, USA*
[c] *Faculty of Resources and Environmental Sciences, Hubei University, Wuhan 430062, PR China*

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ABSTRACT

Influence of landscape pattern on water quality is complex and scale dependent. Existing literature mainly focuses on examining this influence at a wide range of spatial scales from local to basin level or to eco-regional scales. Studies on identifying the critical riparian zone, with certain buffer width and length that exhibit the strongest association between landscape characteristics and stream water quality, are still limited. Such identification is helpful for better understanding the influence of the adjacent landscape on stream water quality and is critical for effective landscape planning and local river management. In this study, the urban area of Xiangyang City along the Hanjiang River was selected as a case study. Water quality samples were collected at eight sites in the examined river system of the Hanjiang River from 2009 to 2014. Landscape pattern analysis, redundancy analysis and stepwise multiple linear regression analysis were used to explore the quantitative associations between landscape patterns and water quality. The results indicate that the landscape metrics that were selected explain approximately 63–87% of the variations in stream water quality at multiple buffer widths in 2009 and 2014. The strongest linkage between landscape characteristics and water quality occurred in the riparian zone with the buffer width of 300 m where the explanatory ability of the landscape metrics still varied at different buffer lengths and increased from 500 m to 8 km. Urban built-up land was more positively associated with degraded water quality at the smaller buffer widths than at the larger buffer widths, whereas forest land exhibited a stronger contribution to water quality improvements at wider buffer widths than at narrower buffer widths. The situation was different for the different buffer lengths. Urban built-up land was more correlated with water quality at longer buffer lengths, and forest land had a stronger contribution at shorter buffer lengths. Overall, landscape configuration seemed to have stronger effects on the water quality than landscape composition. These findings provide important information regarding multi-scale measures for sustainable landscape management to improve surface water quality.

1. Introduction

Freshwater bodies near cities, especially urban rivers, are often used as evacuation routes for all types of waters polluted by domestic and industrial waste products (Brion et al., 2015). Urban rivers, closely interconnecting with the landscape pattern, are easily influenced by human activities (Freeman et al., 2007). Urban expansion, landscape modification and population growth within the river basins increase the stress on urban rivers, and the wastes and pollutants transported into urban rivers cause a series of environmental problems such as water quality deterioration (Li et al., 2012; Volo et al., 2015). Although urban areas only account for approximately 3% of the global land use, these areas contain more than 50% of the total global population (Grimm et al., 2008). Landscapes have substantially changed with the growth of the human population and urban expansion over the past several decades (Su et al., 2010), and these changes are strongly related to water pollution (Gonzales-Inca et al., 2015). Globally, the ecological integrity of river systems is becoming threatened due to the changes in landscape patterns (Miserendino et al., 2011). However, the international scientific literature that quantifies the impacts of landscape changes on water bodies in urban areas is still limited (Shen et al., 2014; Zhao et al., 2015).

Studies on the relationship between surface water quality and landscape patterns began in the late 1960s (Kuehne, 1962). These studies, initially investigating the effect of morphometric features and identifying pollutant sources, have evolved to the modern landscape

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* Corresponding authors at: Department of Environmental Sciences and Engineering, Fudan University, 220 Handan Road, Shanghai 200433, PR China.
E-mail addresses: 14110740007@fudan.edu.cn (K. Li), gchi@psu.edu (G. Chi), xieyj@fudan.edu.cn (Y. Xie), xrxrwang@fudan.edu.cn (X. Wang), zhqfan@fudan.edu.cn (Z. Fan).

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approach (Amiri and Nakane, 2009). Numerous studies have been conducted to explore the impacts of landscape patterns on the water quality in lakes and rivers (Hassan et al., 2015; Uriarte et al., 2011), and most of them have reported that landscape characteristics are vital to water quality (Beckert et al., 2011; Turner, 1989). Initially, studies often focused on the composition of the landscape patterns to explain the variation in water quality indicators (Townsend et al., 2003; Zampella et al., 2007). Landscape types that are associated with human development activities generally have negative effects on water quality, whereas undeveloped lands (*e.g.,* forest land) are often associated with good water quality (Tu, 2011). Recently, more attention has been paid to the importance of the spatial arrangement of the landscape for the receiving watersheds (Stryjecki et al., 2016; Zhou et al., 2012). The landscape metrics of large patch index, landscape shape index and patch density are analyzed to explain the correlation with water quality (Rajaei et al., 2017; Teixeira and Marques, 2016) and have become a useful approach by combining methods of landscape ecology and geographic information system (GIS) techniques. A great variety of landscape indicators (*e.g.*, patch density, large patch index, contagion) have been reported to be significantly associated with river water quality (Bu et al., 2014; Campagnaro et al., 2017; Sun et al., 2013). Indeed, both compositional attributes (*e.g.*, the proportion of different landscape percentages) and spatial attributes (*e.g.*, the fragmentation degree of landscape and aggregation index) have been increasingly used to explain the relationship between landscape characteristics and water quality (Awoke et al., 2016; Gonzales-Inca et al., 2015; Untereiner et al., 2015). It is necessary to identify whether landscape composition or landscape configuration has a greater effect on water pollution for better understanding the influence of the adjacent landscape on stream water quality (Campagnaro et al., 2017).

The influence of landscape patterns on water quality is complex and area specific (Griffith, 2002), and this relationship varies in different river watersheds dominated by various landscape types, such as agricultural land or forest land (Shi et al., 2017). Several studies have provided evidence for the different roles of landscape characteristics in receiving water at various spatial scales ranging from the local or basin level to eco-regional scales (Goldstein et al., 2007). However, the answers have not been consistent for the question regarding which spatial scale landscape characteristics are most closely related to water quality (Shi et al., 2017). Some studies have shown that the whole basin was crucial in determining the impacts of human activities on water quality (Ding et al., 2016; Meneses et al., 2015); however, other studies reported that the landscape patterns at riparian buffer zones are more powerful to explain the variations in water quality (Mcmillan and Scientist, 2014; Uriarte et al., 2011). These inconsistent results are understandable, as each catchment has unique characteristics and is influenced by different human activities that impact the water quality (Sun et al., 2014). However, none of these studies have examined the spatially explicit buffer lengths that also have important impacts on the water quality. It has been reported that the roles of landscape characteristics in the explanation of the total variations of the water quality in a river vary with different buffer zone lengths (Feld, 2013; Shen et al., 2014; Vikman et al., 2010). River water quality was found to vary along the direction of flow due to human activities and the changing size of the buffer zone (Shen et al., 2015), and the self-purification ability of the water was influenced by the landscape patterns in the river basin. However, studies that investigate the dynamic influences of various buffer lengths on water quality are still lacking. Thus, it is necessary to identify the critical area, *i.e.*, a riparian zone with a certain buffer width and length, where the strongest linkage between landscape characteristics and surface water quality occur. This result would provide significant information for water pollution management and landscape planning.

Our goal in this study was to identify the critical area where landscape characteristics had the greatest contribution to the explanation of the variation in water quality. We investigated how the landscape pattern was functionally linked to the stream water quality of the Hanjiang River inside the urban area of Xiangyang City in central China. Landscape analyses, redundancy analysis (RDA) and stepwise multiple linear regression (MLR) analysis were adopted to examine the influence of landscape characteristics on water quality. The landscape analyses were quantified in terms of landscape composition and configuration metrics at various buffer widths and lengths. Four research questions were explored: 1) which landscape types are positively associated with water quality degradation, and which landscape types are negatively associated with water pollutants? 2) Do the landscape metrics affect the water quality in similar ways at different buffer widths and lengths? 3) To what extent do landscape characteristics mostly affect water quality, and which buffer zone landscape characteristics have the strongest effects? 4) Does landscape composition or landscape configuration make a higher contribution to water quality?

2. Materials and methods

2.1. Study area

The Hanjiang River is the largest tributary of the Yangtze River, and the main stream is 1,577 km long with a total drainage area of 159,000 km^2. The river system examined in this study is the portion inside Xiangyang City that is located in the middle reaches of the Hanjiang River in central China. The total area of Xiangyang City is approximately 19,774 km^2. The Xiangyang urban area is located along the Hanjiang River from the monitoring sections of Baijiawan (sampling site 1) to Yujiahu (sampling site 4) as shown in Fig. 1. The main stream of the Hanjiang River examined in this study is 49 km in length, and the surrounding urban area is approximately 3,557 km^2, which is our total study area. The Xiaoqinghe River and Tangbaihe River are two tributaries of the Hanjiang River. The Hanjiang River in the Xiangyang urban area (HRXUA) is an important water source for more than 1.6 million people in our study area. Rapid urban sprawl has occurred in Xiangyang City since 2004, and the rate of urbanization increased from 37.8% to 57.3% from 2004 to 2015. The study area experiences the north subtropical monsoon climate with the mean annual temperature of approximately 14 °C. The mean annual precipitation ranges from 800 mm to 1200 mm, which mainly happens from July to September.

2.2. Data collection and processing

2.2.1. Water quality data collection and processing

To study the water quality in the HRXUA, eight sampling sites were selected, including four sampling sites in the mainstream of the Hanjiang River and four sampling sites in its tributaries, as shown in Fig. 1 and Table 1. The sampling sites labeled S1 and S2 in Table 1 are in the drinking-water sources for Xiangyang City. Eight water quality parameters, including 5-day biological oxygen demand (BOD_5), chlorophyll a (Chl-a), dissolved oxygen (DO), total nitrogen (TN), chemical oxygen demand (CODcr), total phosphorus (TP), ammonia nitrogen (NH_4^+-N) and permanganate index (COD_{Mn}), were collected from July 2009 to 2014. The water quality parameters from July 2009 to July 2013 were collected and analyzed by the Environmental Monitoring Center (EMC) of Xiangyang City, and the water quality data in 2014 were collected on July 16, 2014, and analyzed on July 18, 2014, in the Analysis and Testing Center of Fudan University. Other data, such as population and economic development, are from the Xiangyang Statistical Yearbook from 2009 to 2015. Wastewater discharge data are from the Environment Quality Bulletin of Xiangyang published by the Xiangyang Environmental Protection Bureau from 2007 to 2015.

The methods of sampling, preservation, transportation, and analysis of the water data from 2009 to 2014 referred to standard methods suggested by State Environmental Protection Administration of China (SEPA, 2002).