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Exploring the dynamic correlation of landscape composition and habitat fragmentation with surface water quality in the Shenzhen river and deep bay cross-border watershed, China

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ABSTRACT

The dynamics of land cover and landscape structure are important variables that influence the environmental and ecological quality of a watershed. In this study, a complex hypothesis was proposed that assumed water quality was closely correlated with landscape composition and habitat fragmentation and that this relationship varied at different spatial scales, namely, in riparian buffers with different widths. This hypothesis was tested using a case study in the Shenzhen River and Deep Bay watershed, which is the border region between the Hong Kong Special Administrative Region and Shenzhen in China. To effectively explore the correlation of habitat fragmentation with surface water quality, a compound indicator was proposed that can be used to disentangle the effect of habitat fragmentation from that of habitat loss alone. The results of the redundant analysis suggested that the surface water quality in our study area was strongly correlated with landscape composition and habitat fragmentation, and the correlations varied with riparian buffer widths. Compared to habitat fragmentation, landscape composition seemed to be the dominant contributor to the variation in water quality. The cross-border comparison between Hong Kong and Shenzhen suggested the riparian buffers with the strongest linkages were different for the two sides of the watershed, likely due to their special combinations of landscape characteristics and other socio-economic contexts. Whether habitat loss and fragmentation had negative effects on water quality depended on the habitat types and water quality variables that were examined. These findings can be helpful in offering useful information for future watershed management and landscape planning.

1. Introduction

Water quality is considered to be affected by a wide range of factors, including local topography, soil permeability, stream density, temperature, and land-use activities (Sliva and Williams, 2001; Didham et al., 2012; Aronson et al., 2014; Tanaka et al., 2016). Landscape characteristics have critical influences on hydrological processes, energy flows and nutrient cycles (Grimm et al., 2000; Lee et al., 2009). The importance and effectiveness of landscape approaches in studies on water quality dynamics have been increasingly recognized (Uuemaa et al., 2007; Amiri and Nakane 2009; Liu et al., 2012; Zhou et al., 2012; Shen et al., 2015; Clément et al., 2017). The variations in landscape characteristics are believed to most likely affect hydrological conditions and ecological processes by altering the types and amounts of pollutants entering aquatic systems (Griffith, 2002; Xiao and Ji, 2007; Shen et al., 2015). Habitat loss and fragmentation are essential processes that occur during landscape change in terms of both composition and configuration (Fahrig, 2003; Smith et al., 2009). Intense modification of the landscape, increased consumption and pollution of ecosystems have directly and indirectly resulted in habitat loss, fragmentation and degradation (Maron and Fitzsimons, 2007; Giam et al., 2010).

Landscape composition has been widely reported to have a strong correlation with water quality change. The increase in forest land (a type of natural habitat area) could contribute to the reduction of water pollution (Lee et al., 2009; Liu et al., 2012), whereas the increase in urban area (*i.e.*, the decline in habitat area) is suggested to be positively correlated with the degradation of water quality in terms of all pollutants (Uuemaa et al., 2007; Lee et al., 2009). Habitat fragmentation is defined as the process of breaking up a large, intact area of a habitat type into smaller, intact units that are separated by a matrix of human-converted land cover (Forman and Godron, 1986; Haddad et al., 2015). Some landscape metrics related to habitat fragmentation, such as patch

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density, patch edge, and contagion, have been evaluated in terms of their correlation with water quality. It was reported that the nutrient and organic parameters (e.g., TN, NO_3-N, TP, and COD_{Mn}) were positively correlated with the patch density of cropland, orchard and grassland (Ding et al., 2016). A negative correlation between contagion and water pollution was detected (Bu et al., 2014), which indicates that degraded water quality usually occurs in highly fragmented landscapes (Uuemaa et al., 2005). Although these metrics used to measure certain aspects of habitat fragmentation are related to water quality, to date, the direct correlation between habitat fragmentation and river water quality has been poorly addressed.

Indeed, the process of habitat fragmentation is not independent of habitat loss (loss of habitat amount). Habitat loss could cause an increase in the distances (isolation) between habitats within a landscape (Goodsell and Connell, 2002), and habitat fragmentation will inevitably produce a loss of habitat (Andrén, 1994). Although habitat loss and fragmentation have been considered so tightly linked that disentangling their effects is meaningless (Didham et al., 2012), they are two distinct processes that are not always independent of one another (Fahrig, 2003; Fahrig, 2017). The impacts of habitat loss can sometimes be mitigated by connectivity with the surrounding habitat (Fahrig, 2003). Therefore, it is crucial to distinguish the effects between habitat loss alone and true fragmentation in terms of their different effects on species and ecosystems (Fahrig, 1998; Schmiegelow and Mönkkönen, 2002; Mortelliti et al., 2011). Many landscape metrics adopted for measuring habitat fragmentation in a study might have high correlations with each other (Hargis et al., 1998). However, few studies have been able to differentiate the effect of habitat fragmentation from habitat loss. Therefore, an indicator that can disentangle the process of fragmentation from that of habitat loss alone should be developed. This could contribute to the determination of whether habitat fragmentation is actually correlated with water quality, respectively. Furthermore, a study investigating the relationship between landscape configuration and water quality in a large number of watersheds (590) suggested that, for smaller watersheds ($< 250\,km^2$), landscape configuration explained most of the variation in water quality; however, for larger watersheds ($> 250\,km^2$), the proportions of different land-cover types become more important (Clément et al., 2017). An indicator measuring pure habitat fragmentation could also contribute to examine whether landscape composition or habitat fragmentation has a stronger correlation with water quality.

The relationship between water quality and landscape characteristics can be evaluated at different spatial scales, including the watershed, sub-watershed, buffer zone and other smaller proportions of the watershed (Griffith, 2002; Smith et al., 2009; Zhou et al., 2012; Shen et al., 2015). Riparian buffer landscapes, composed of patches or corridors of vegetation, wetlands, agricultural crops and urban settlements, are interfaces between terrestrial and aquatic environments (Apan et al., 2002; Shen et al., 2015). Variation in the riparian landscape plays a significant role in influencing entire ecological and hydrological conditions, including surface water quality, soil erosion and wildlife and fish habitat (Apan et al., 2002; Xiao and Ji, 2007). Some studies maintain that the explanatory ability of the landscape characteristics of riparian buffer zones would increase with the width of the buffer, e.g., from 100 m to 200 m, 400 m, 800 m or 1500 m (Zhao et al., 2015), whereas other studies recognize that the landscape characteristics of 100-m-wide buffer zones have the greatest influence on water quality (Shen et al., 2015). A consensus has not yet been achieved due to the specificity of each watershed and the variables of both human disturbance and the collected datasets (Shen et al., 2014; Shen et al., 2015). Although an increasing number of studies have been conducted in recent years, many questions remain unanswered, e.g., quantifying and disentangling the impact of habitat fragmentation on water quality at multiple spatial scales.

Cross-border or trans-boundary studies are very popular in Europe and North America, and this issue has attracted a large range of researchers from different disciplines, such as geography, political science, environmental science, and sociology (Perkmann, 2003; Nelles and Durand, 2014). In China, one of the most notable cases of a cross-boundary study is the one between Hong Kong and mainland China (Chan, 1998; Lee, 2002). Many scholars have shed light on cross-boundary policy integration, environmental problems, and transportation development (Shen, 2004; Gu and Yim, 2016; Lam et al., 2017). However, the understanding of the effects of habitat fragmentation on water quality in the border region is still very poor. This study attempts to investigate the correlations of landscape composition and habitat fragmentation with water quality degradation in the Shenzhen River and Deep Bay watershed, which is located in the border region between the Hong Kong Special Administrative Region and Shenzhen, China. The entire watershed has an area of approximately $726.72\,km^2$. To examine this issue, this study tested the following working hypotheses: 1) landscape composition and habitat fragmentation were closely related to surface water quality, and the effects of landscape composition had a stronger correlation with variation in water quality than did habitat fragmentation (independent of habitat loss); 2) the correlation of landscape composition and fragmentation with water quality varied with the widths of riparian buffers, and the riparian buffers with the strongest linkages were different for the Shenzhen and Hong Kong sides of the watershed; and 3) the most significant effects of habitat loss and fragmentation on water quality were negative.

2. Materials and methods

2.1. The Shenzhen river and deep bay cross-border watershed

The city of Shenzhen and Hong Kong SAR, located in the southeast of the Pearl River Delta, China, are neighbors along the Shenzhen River and the Deep Bay area. The Shenzhen River and Deep Bay cross-border watershed (abbreviated as the Shenzhen River cross-border watershed) is a border region, as shown in Fig. 1. The whole area extends from 22°23′10″ to 22°40′47″ N and 113°51′39″ to 114°12′54″ E. The Shenzhen River cross-border watershed neighbors Dapeng Bay (Mirs Bay) to the east and the Pearl River Estuary to the west, connecting the Shenzhen Special Economic Zone (SEZ) to the north and the SAR to the south. The northern area of the Shenzhen River cross-border watershed covers most of the Shenzhen SEZ and a small portion of the town of Buji in the Longgang district, whereas the south lies in the northern part of the New Territories of Hong Kong, primarily including the Yuen Long and North Districts. Approximately $412.95\,km^2$ of the watershed is in the city of Shenzhen, which is equivalent to almost 60% of the total area. The Shenzhen River is not only the major river but also the natural border within this watershed. It originates near Niuweiling in the Wutong Mountains and flows approximately 37 km westward into its estuary in Deep Bay. Its major tributaries include the Liantang, Shawan, Buji, Futian, and Huanggang rivers on the Shenzhen side, and the River Indus, River Beas, and River Ganges on the Hong Kong side. The Yuen Long River, Kam Tin River, Tin Shui Wai River and the Dasha River drain directly into Deep Bay. Two ecologically important wetlands exist in the estuary of the Shenzhen River. The Mai Po and Inner Deep Bay Ramsar Site on the Hong Kong side of the watershed is a wetland of international importance that provides habitat for East Asian migratory birds.

Since the late 1970s, the Shenzhen River cross-border watershed has experienced serious habitat loss and fragmentation (Ng et al., 2011; Xie and Ng, 2013). Nearly 50% of the wastewater on the Shenzhen side of this watershed never reaches the sewage system, and substantial non-point wastewater inputs from agriculture eventually enter Deep Bay, which has significantly impacted the water quality there. The data from the Environmental Protection Department of Hong Kong (2003) indicate that the water quality of the major rivers and nullahs in the Inner Deep Bay watershed are generally poor. In 2003, the Inner Deep Bay area had the poorest water quality, characterized by high ammonia and