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Influences of the land use pattern on water quality in low-order streams of the Dongjiang River basin, China: A multi-scale analysis

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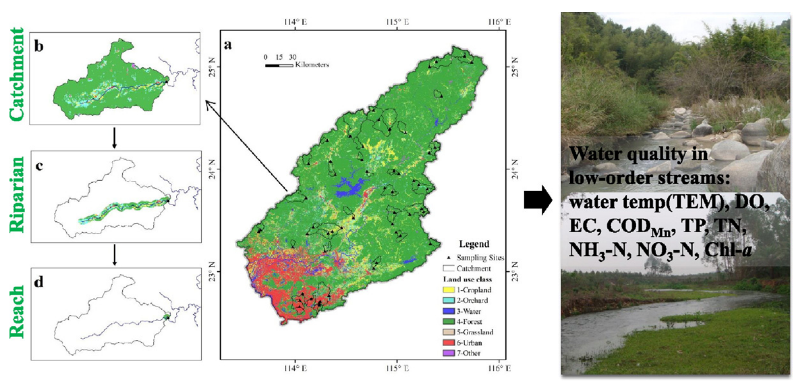
HIGHLIGHTS

- Land use influences on water quality in low-order streams remain elusive.
- Land use influences at geomorphic regions across multi-scales were analyzed.
- Land use configurations had the greatest effects on water quality.
- Water quality management needs to adopt a multi-scale perspective.
- Accurate assessments of land use influences should consider a regional basis.

GRAPHICAL ABSTRACT



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ABSTRACT

Understanding the relationships between land use patterns and water quality in low-order streams is useful for effective landscape planning to protect downstream water quality. A clear understanding of these relationships remains elusive due to the heterogeneity of land use patterns and scale effects. To better assess land use influences, we developed empirical models relating land use patterns to the water quality of low-order streams at different geomorphic regions across multi-scales in the Dongjiang River basin using multivariate statistical analyses. The land use pattern was quantified in terms of the composition, configuration and hydrological distance of land use types at the reach buffer, riparian corridor and catchment scales. Water was sampled under summer base flow at 56 low-order catchments, which were classified into two homogenous geomorphic groups. The results indicated that the water quality of low-order streams was most strongly affected by the configuration metrics of land use. Poorer water quality was associated with higher patch densities of cropland, orchards and grassland in the mountain catchments, whereas it was associated with a higher value for the largest patch index of urban land use in the plain catchments. The overall water quality variation was explained better by catchment scale than by riparian- or reach-scale land use, whereas the spatial scale over which land use influenced water quality also varied across specific water parameters and the geomorphic basis. Our study suggests that watershed management should adopt better landscape planning and multi-scale measures to improve water quality.
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1. Introduction

River drainage networks are hierarchically organized systems in which every large river is formed by a large number of small low-order streams (Vannote et al., 1980). Low-order streams, referred to as first- and second-order streams in this study, dominate the riverine landscape and constitute over 50% of the total stream length (Strahler, 1957; Meyer et al., 2007). These streams transport water, nutrients, organic materials and sediments from terrestrial uplands to downstream systems, thereby supporting or diminishing the ecological functions of downstream systems (Gomi et al., 2002). Due to the close interconnections with the landscape, low-order streams are highly vulnerable to land-disturbing activities, such as deforestation, agriculture and urbanization (Freeman et al., 2007). These anthropogenic activities in low-order streams can increase nutrient loading and reduce nutrient retention, which can result in the eutrophication and hypoxia of distant downstream ecosystems (Dodds and Oakes, 2008; Castillo et al., 2012). Despite their important role in maintaining river health, most low-order streams are not routinely monitored for water quality. Therefore, it is crucial to investigate the impacts of land use on water quality in low-order streams, which offer an effective tool not only for protecting local streams but also for improving downstream water quality (Norton and Fisher, 2000; Brion et al., 2011).

Understanding the relationships between land use and water quality from a landscape perspective is important for watershed planning and management (Lee et al., 2009). The influence of land use on water quality has been a concern since the 1970s (Johnson et al., 1997). Early studies typically correlated water quality with simple measures of land use composition (e.g., the percent of different land use types) within a watershed (Bolstad and Swank, 1997; Donohue et al., 2006; Dodds and Oakes, 2008). However, composition metrics are only coarse predictors of water quality; they do not discriminate between different landscape configurations, such as the patch size, patch shape, edge configuration or spatial interconnection of patches of land use types within a landscape (Alberti et al., 2007). With the rapid development of landscape ecology, the use of landscape metrics provides the ability to quantify land use configurations relatively quickly and easily. Recent studies have shown that simple landscape metrics, such as aggregation, the largest patch index, patch density or shape indices may be more useful as predictors of water quality than as composition metrics in urbanizing watersheds (Uuemaa et al., 2005; Lee et al., 2009; Gemesi et al., 2011; Sun et al., 2014; Bu et al., 2014). New spatially explicit measures of land use patterns are emerging with new developments in spatial data acquisition techniques. For example, several studies have determined that water quality was significantly linked with the distance of land use to the stream networks along hydrologic pathways (King et al., 2005; Zampella et al., 2007; Lyon et al., 2008; Walsh and Kunapo, 2009). Generally, previous studies mainly focus on a single land use factor or landscape metrics at the landscape level (Uuemaa et al., 2007; Sun et al., 2013; Sun et al., 2014; Bu et al., 2014), making it difficult to apply the findings to landscape and land use planning. A few studies have made attempts to further study spatial characteristics for each patch type (land use class), which is at a finer resolution (Lee et al., 2009; Amiri and Nakane, 2009; Gemesi et al., 2011). Therefore, to better evaluate the complex impacts of land use on water quality, it may be necessary to quantify different aspects of land use patterns at the class level.

Land use metrics are sensitive to changes in scale, which refers to the spatial resolution of the data (grain size) or the areal breadth (extent) of analysis (Wu et al., 2002). The relationships between land use and water quality are often reported to change with the spatial extents and ranges from reach buffers and riparian corridors to catchments (Morley and Karr, 2002; Allan, 2004; Ye et al., 2014). Thus, a key question is which land use spatial extent has the strongest influence on water quality.

The proper use of scale will allow managers to make better decisions and use resources efficiently. However, the results are not always consistent. Some studies have shown that land use at the reach or riparian scales was a better predictor of water quality than at the catchment scale (Johnson et al., 1997; Dodds and Oakes, 2008; Tran et al., 2010), while other studies found that land use at the catchment scale accounted for water quality variability better (Gove et al., 2001; King et al., 2005; Dow et al., 2006). Schiff and Benoit (2007) noted that these mixed results were likely attributed to the variations in study designs and geographic locations.

Although the scale effect of land use on water quality has been addressed, few studies have been conducted in low-order streams. Low-order streams generally occur across the range of climatic, geologic, biogeographic and anthropogenic settings in the entire watershed (Montgomery and Buffington, 1998; Meyer et al., 2007). Different geomorphic settings among low-order streams influence the spatial patterns of land use and the mechanisms that link land use to water quality (Basnyat et al., 1999; Strayer et al., 2003). A deeper understanding of scale issues is necessary to subdivide low-order streams by geomorphologic characteristics and conduct separate multi-scale analyses in each of the homogenous regions for accurate assessments of land use impacts.

The Dongjiang River basin, one of the most developed areas in China, has been experiencing rapid urbanization for the last 20 years (Ren et al., 2011). Over 28 million people lived in the basin in 2010 (He et al., 2013). Meanwhile, the Dongjiang River basin plays a key role in supplying drinking water for the Pearl River Delta region and Hong Kong. In recent years, there has been increasing concern regarding the deterioration of the water quality in the downstream portion of the basin (Ho and Hui, 2001; Ding et al., 2015). However, to our knowledge, no previous studies have examined the multi-scale relationships between the land use and water quality of low-order streams in the Dongjiang River basin. This information is of vital importance for regional land use planning and the sustainable use of water resources in the basin.

In this study, we estimated the impacts of land use patterns on water quality of low-order streams at different geomorphic regions across multi-scales in the Dongjiang River basin using multivariate statistical analyses. The land use pattern was quantified by the composition, configuration and hydrological distance of land use types at the reach, riparian and catchment scales. Our objectives were to address the following questions: 1) Which metrics describing the land use pattern were most predictive of water quality in low-order streams; 2) Which spatial scale of land use has the strongest influence on water quality of low-order streams; and 3) Is there a difference in land use influences across different geomorphic conditions within a watershed?

2. Methods

2.1. Study area

The Dongjiang River is mainly located in Guangdong Province in southern China and is one of the three main tributaries of the Pearl River (Fig. 1). The main stem of the Dongjiang River is 562 km long and encompasses a watershed area of approximately 35,340 km^2 (Jiang et al., 2012). The Dongjiang River flows from the mountains in the north to the alluvial plains in the south and discharges into the Pearl River Delta. The plains with an elevation of <200 m account for 50.9% of the river basin. The hilly mountains are approximately 200–500 m high and account for 36.4% of the basin. The mountains with an elevation of >500 m account for 12.7% of the basin. For the period of 1958–2010, the mean annual air temperature is 21 °C, and the mean annual precipitation is 1800 mm. The mean annual runoff of the basin is approximately 296×10^8 m^3, most of which is from precipitation (Wang and Xia, 2004; Jiang et al., 2007). The predominant land use type is forest, which occupies 71.4% of the basin in 2009, although the proportion of urban area has extended to 9.4%. Cropland and orchards cover 8.4% and 5.7% of the basin, respectively (Ren et al., 2011;

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