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Effects of land use and spatial processes in water and surface sediment of tropical reservoirs at local and regional scales

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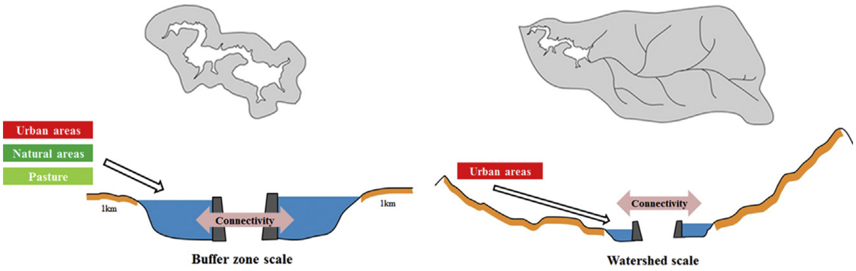
HIGHLIGHTS

- Land uses have effects in water and sediment quality in tropical reservoirs.
- Different land uses have different relationships with water/sediment variables.
- Effects of land use vary between buffer zone and watershed scale.
- Connectivity can explain some of variation of water and sediment characteristics.
- Sediments are an effective tool to assess reservoir quality.

GRAPHICAL ABSTRACT



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ABSTRACT

The effects of land use and connectivity on the characteristics of aquatic ecosystems are thought to be scale-dependent. This study aimed to evaluate the relationships between land use and reservoir characteristics at two spatial scales, after controlling for spatial processes. Water and surface sediment samples were collected from 31 sites (7 reservoirs) in the Paiva Castro and Piracicaba River basins (Cantareira System, São Paulo State, Brazil), during austral summer and winter. The dataset included 15 water quality variables and 6 surface sediment variables. Land use variables (natural areas, pasture, agriculture and urban areas) were obtained at two spatial scales (buffer and watershed) in each reservoir. Spatial variables were calculated using Moran's Eigenvectors Maps and Asymmetric Eigenvector Maps. The strengths of the relationships between land use and sediment variables were stronger than those between land use and water quality variables. The strengths of some of the relationships were scale-dependent. Finally, spatial processes, mostly hydrological connectivity, play an important role in water-sediment quality and should be considered in landscape management programs.

1. Introduction

Changes in land cover occur due to the interaction among multiple processes, including natural and human-driven ones (Lambin et al., 2003). These changes, in turn, may alter different characteristics of aquatic ecosystems (El-Khoury et al., 2015; López-Moreno et al., 2014;

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Stendra and Johnson, 2006). In theory, the effects of land use on aquatic ecosystems are accounted for by an increase in erosive processes, which increase the input of allochthonous material to aquatic ecosystems (Likens and Bormann, 1974). For example, increasing agricultural areas leads to increased runoff rates, which leads to higher stream flows variability (Lin et al., 2015). Owing mainly to point sources of organic pollution, urbanization often results in increased nutrient levels in rivers (Bu et al., 2014), which accelerates eutrophication and reduces the services that aquatic ecosystems provide (Taranu and Gregory-Eaves, 2008; Zedler and Kercher, 2005). To inform conservation planning and watershed management and because of the high rates of watershed conversion to agricultural and urban areas (Keatley et al., 2011) and other forms of land use, it is important to understand the impacts of these anthropogenic processes on water quality.

Pure effects of land use on water quality are difficult to detect because they are confounded with other anthropogenic impacts (Stendra and Johnson, 2006) and natural processes. The lake landscape-context (LLC) framework (Soranno et al., 2009) recognizes three sets of landscape features that interact to determine chemical, physical and biological characteristics of lakes at multiple spatial scales: human activities, terrestrial features and aquatic connections. Land use is one of the variables (related to human activities) in the LLC framework and the analyses of its relationship with water quality and sediment often include other LLC variables such as lake morphometry (Liu et al., 2011), precipitation (Yu et al., 2016), and climate change (El-Khoury et al., 2015). However, aquatic connection, the third set of landscape features in LLC framework, has been neglected in most studies relating land use and water quality.

Aquatic connectivity, in terms of the present work, can be understood as the connection between two sites through the hydrological network. This link allows the exchange of biotic and abiotic components between aquatic environments (e.g. macroinvertebrates, fish, and sediments; see Pan et al., 2011; Lynch et al., 2011; and Wright, 1977, respectively). Thus, it is likely that water quality in one site may be dependent on the water quality in the site upstream. Zorzal-Almeida et al. (2017) found that most of the variation in diatom community structure was accounted for by the spatially structured environmental variation. Thus, connectivity (represented by spatial variables) should be included in analyses relating land use to water quality, especially when reservoirs are the object of study. This is so because these artificial ecosystems are distributed in networks and can integrate and accumulate material and pollutants from watersheds (Burford et al., 2012; Shivoga et al., 2007). Despite the large literature on land use, only few studies considered the effects of spatial variables (derived from eigenfunction analysis; e.g. Dray et al., 2006) to assess variation in water quality (Vrebos et al., 2017).

The effects of land use in water-sediment characteristics may be scale dependent (Wagner et al., 2011), and it is not clear whether local effects are stronger than regional effects and vice-versa (Sliva and Williams, 2001). Local scales can be represented by buffer areas surrounding rivers and reservoirs (Ding et al., 2016). Regional effects can be represented by watershed scale variables (Tang et al., 2005) that consider the land use of the entire catchment.

This study aims to evaluate the influence of land use on water and surface sediment characteristics at two spatial scales (buffer zone and watershed) taking the effects of the spatial dependence into account. The following predictions were made (i) the strength of relationship between land use, at watershed scale, and reservoirs' water quality will be higher during rainy seasons (i.e., summer in Southern hemisphere), when runoff increases, than during dry seasons (winter); (ii) sediment variables will have a clearer response to land use variation than water variables as the sediment variables accumulate information across time and space (Smol, 2008; Fontana et al., 2014); (iii) most of the variation in water and sediment variables will be explained by spatially structured land use variables.

2. Materials and methods

2.1. Study area

This study was conducted at the Cantareira System (CS), a pivotal water supply system in the State of São Paulo (Paiva Castro and Piracicaba River basins, Brazil, Fig. 1). This system encompasses five reservoirs interconnected by tunnels and waterways: Jaguari, Jacareí, Cachoeira, Atibainha and Paiva Castro. The system can produce 33 m^3 of water per second: 31 m^3 from Piracicaba River basin and 2 m^3 from the Paiva Castro basin, supplying >9 million people in the Metropolitan Region of São Paulo (Whately and Cunha, 2007). Two other hydropower reservoirs (Salto Grande and Tatu reservoirs) were also studied. These reservoirs differ in purpose (water supply and power generation) and morphometric features, such as maximum depth, retention time and maximum volume (Fig. 1).

2.2. Sampling design

Samples were carried out during the austral summer and winter of 2010 (Jaguari and Jacareí reservoirs) and 2013 (Cachoeira, Atibainha, Paiva Castro, Salto Grande and Tatu reservoirs). Sampling sites were selected considering the influence of the main tributaries and outflows. Number of sampling sites per reservoir varied between two and seven (Fig. 1).

Water samples were collected with a van Dorn bottle at three depths (sub-surface, middle of the water column, and 1 m above bottom). The mean values of the three values were used in all data analyses. Surface sediments were sampled only during winter because they integrate a large temporal scale, usually one or two years (Smol, 2008). A UWITEC gravity corer was used to collect the first two centimeters of the sediment.

2.3. Land use

Land use variables were quantified using three data sources: (1) SPOT images 2007–2009 interpretation maps (1:25,000 – São Paulo, 2013), (2) IKONOS images 2002 interpretation maps (1:25,000 – São Paulo, 2005), and (3) IBGE information maps (1:5,000,000 – IBGE, 2010). Land use was classified into four categories: "natural" areas (forests, reforestation, riparian areas, and water courses), pasture, agriculture (permanent and semi-permanent crops), and urban areas (urban area and bare ground). Percentage cover of these categories were generated by ArcGIS 10.2 at two scales: (1) buffer zone (1 km from reservoir shoreline), and (2) watershed (entire area of the basin upstream the reservoir). At the buffer zone scale, land use data associated to each site were weighted by its maximum distance to the main tributary in the reservoir. At watershed scale, the percentages of land uses were divided by the distance between a sampling site to the main tributary, assuming that nearby sites receive greater influence of land use than more distant sites (Zorzal-Almeida et al., 2017).

2.4. Water and surface sediment

Temperature, pH and conductivity were measured in situ (Horiba U-53). Water transparency was determined using a Secchi disk. Following APHA (2005), we also measured dissolved oxygen, alkalinity, inorganic carbon species, nitrate, nitrite, ammonium, total nitrogen, reactive soluble phosphorus, total dissolved phosphorus, total phosphorus, and soluble reactive silica concentrations. Samples for analysis of dissolved nutrients were filtered on Whatman GF/F filters, under low pressure (<0.50 atm). Chlorophyll-*a* concentration (corrected for pheophytin) was determined after extraction with 90% ethanol (Sartory and Grobbelaar, 1984), using the methods described by Golterman et al. (1978).