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Landscape diversity and forest edge density regulate stream water quality in agricultural catchments

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ABSTRACT

It is well known that the composition of land cover within a watershed plays a large role in regulating stream water quality. However, there remains significant uncertainty regarding the effect of spatial configuration of different types of land cover on water quality. Using periphytic algae (diatoms) as indicators of stream trophic state, we investigated the relationship between landscape configuration and water quality in a large number of watersheds (590) at varying catchment scales in Eastern Canada. Variation partitioning analysis showed that landscape configuration explained 48% of the variation in water quality. However, since the physiographic setting constrains most agricultural activities, most of the variation was attributed to the shared influence of surficial deposits, land cover and landscape configuration (34%). The results from regression models showed that the geomorphological setting of watersheds (surficial deposits and slopes) and the proportion of different land cover types (mainly forests, wetlands, crops and urban areas) have a major impact on stream water quality. Nevertheless, a few configuration metrics emerged as important factors. Landscape diversity appeared to have a negative impact on water quality, whereas forest and wetland edge densities had a positive impact. Moreover, the influence of these lanscape metrics seems to occur at certain thresholds. In areas of intensive farming, streams with a forest area that covers at least 47% of the watershed have a better water quality. Below this threshold, eutrophic and meso-eutrophic conditions are more frequent in streams and rivers. The shape and location of forested patches were also found to be relevant. Woodlands and wetlands with an edge density higher than 36 m/ha and located along streams and gullies have a positive impact on water quality. For the same proportion of forest, complex patches will be more efficient filters than large regular patches. Forest edge density seems to control the extent of the interface with the agricultural sources and thus promotes the "sink" effect of forests on nutrients.

1. Introduction

It is well known that the composition of land cover within a watershed plays a large role in regulating stream water quality (e.g. Omernik, 1977; O'Neill et al., 1997). Agricultural and urban land covers act as sources, while woodlands and wetlands act as sinks of non point-source pollution. For example, nutrient and sediment inputs to a basin are positively correlated with the percentage of agriculture and urban cover types and negatively with percentage of forest in a watershed (e.g. Johnson et al., 1997). More recently, a number of studies have employed both lansdcape composition (land cover in%) and configuration in order to link the spatial arrangement of sources and sinks relative to flowpaths with river water quality. For the characterization of landscape configuration, two categories of metrics are used, namely class-level landscape metrics (e.g. forest edge density, urban patch density) and watershed-level landscape metrics (e.g. diversity, contagion). Landscape composition has usually been identified as the most important parameter of water quality, and it demonstrates closer relationships with water quality parameters than configuration does (e.g. Gergel, 2005; Griffith et al., 2002; Moreno-Mateos et al., 2008; Snyder et al., 2005; Uuemaa et al., 2007).

There remains significant uncertainty regarding the effect of landscape configuration on water quality. This uncertainty stems partly from the fact that the studies conducted so far 1) were carried out in various contexts which are difficult to compare, from

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landscapes dominated by rice production to urban landscapes or wetland environments; 2) involved a highly variable number of watersheds, and sometimes very few (<30); 3) covered a wide range of watershed sizes, which may lead to some scale effect issues; 4) did not use the same landscape metrics and sometimes used very few metrics, at the landscape level only; 5) used a wide range of indicators of water quality; 6) used land use data at different spatial resolutions, from 0.5 to 200 m, which again may lead to some scale effect issues; and finally, 7) did not take into account other factors that may have a strong influence on water quality, such as the physical setting of watersheds (surficial deposits, soils, slopes) and point source pollution (wastewater treatment plants and industries). For example, Hunsaker and Levine (1995) were among the first to analyse the impact of landscape structure on stream water quality. Their study focused on two datasets containing a total of 59 catchments in Illinois. They used a land-cover resolution of 200 m to analyze the impact of 6 configuration metrics at the class level on total phosphorus (TP) and nitrogen (TN). One of their conclusions was that landscape contagion had a positive impact on water quality. Seventeen years later, one of the latest studies published on the subject (Liu et al., 2012) focused on 16 catchments in China. They used a land-cover resolution of 30 m to analyze the impact of 20 configuration metrics at the landscape and class levels on 12 water chemistry variables. At the landscape level, they concluded that edge and patch densities had a positive impact on water quality. There is, so far, little consistency in correlations between stream conditions and landscape metrics. Moreover, Griffith et al. (2002) have shown that there is a strong correlation between landscape metrics and land use proportions and very few studies have thoroughly investigated the variation in water quality explained by landscape configuration when the shared contribution is excluded.

As far as we can assess from the published literature, this study represents the most extensive analysis on the impact of landscape configuration on water quality to date. It was designed to overcome the previously identified difficulties: 1) a large number of catchments were analysed; the study area encompasses 590 catchments of the St. Lawrence River Basin (Eastern Cannada), ranging in size from 0.5 to 2 000 km^2 and stratified into four catchment size groups in order to reduce the effect of size on patch shape variables (Griffith et al., 2002); 2) a large number of landscape metrics were tested (44) at both landscape and class levels; 3) the variation in water quality was partitioned between four groups of explanatory variables (population data, land cover, landscape configuration and physical setting) to test the unique contribution of landscape configuration; 4) only one biotic index (IDEC) of water quality was used, which integrates temporal variations in water chemistry and provides an evaluation of the mean trophic state of a stream; 5) surficial deposits and slopes were added as exploratory variables and the 590 catchments were stratified into four physiographic groups that encompass a wide range of physical settings and land cover types; and 6) population data were included, subdivided into three sets; the total population, the population connected to a wastewater treatment plant (point source pollution) and the population not connected to a plant (nonpoint source pollution).

The study is organized around four questions:

1) What is the relative influence of landscape configuration on stream water quality?
2) Which landscape metrics are best related to water quality?
3) Does the relationship between landscape configuration and water quality depend on catchment size?
4) Does the relationship between landscape configuration and water quality vary between ecoregions?

2. Materials and methods

2.1. Water quality

Biomonitoring based on various organisms is nowadays included in water quality management protocols in numerous countries. The use of bioindicators provides an integrated measurement of water quality as experienced by the aquatic biota, and offers a useful alternative to chemical based water quality assessment. Among the biota used, benthic diatoms are common because they lie at the base of aquatic food webs and are among the first organisms to respond to environmental changes (Lowe and Pan, 1996). They are diverse and have a wide distribution across ecosystems and geographic areas allowing for a continuous spatial distribution across regional monitoring (Stevenson and Pan, 1999). Benthic diatoms have long been recognized as reliable indicators of organic pollution, eutrophication and general pollution and as such, they are seen as reliable indicators of the impacts of different land use practices on stream ecosystems (Hering et al., 2006; Pan et al., 2004; Walsh and Wepener, 2009).

Numerous diatom-based indices have been developed in various countries and are integrated into water quality monitoring programs as an additional tool for assessing ecosystem health (e.g. Kelly and Whitton, 1995). In Canada, the Eastern Canadian Diatom Index (IDEC: Indice Diatomées de l'Est du Canada) was developed as a tool for biological monitoring of stream water quality, and to supplement traditional stream monitoring protocols (Grenier et al., 2006, 2010; Lavoie et al., 2006, 2010, 2014). The IDEC is a diatom-based index that integrates the effects of multiple stressors on streams, most particularly those related to eutrophication in agricultural and urban areas. The index value generated by the IDEC indicates the distance, on a scale of 0–100, of each diatom assemblage from its specific reference assemblage, with 100 representing reference conditions. The IDEC version 3.0 was developed based on 648 diatom assemblages, including 150 reference sites (Lavoie et al., 2014). More than 400 watercourses were sampled, allowing for a better coverage of the various environmental characteristics in Eastern Canada. The index has been used mainly by water agencies, provincial and federal governments, universities and municipalities. The Quebec Ministry of the Environment (MDDELCC) routinely uses the IDEC to monitor a set of one hundred streams undergoing restoration.

The use of a biological index instead of physicochemical parameters has several advantages; 1) the IDEC integrates changes in water quality over a period of weeks, allowing, with one sample collected in August or September, to obtain an integrated picture of the state of water quality at the end of summer (Lacoursière et al., 2011); 2) the index reflects the trophic state of a river, which avoids having to analyze several physicochemical parameters (e.g. P, N, Chl *a*); 3) since 2002, more than 1000 stations, located in 600 streams in Eastern Canada, have been sampled. It would have been difficult to obtain physicochemical data on such a large number of stations, especially in mid-size catchments; 4) the correlation between the IDEC and chemistry-based indices is generally good (Lavoie et al., 2014) and the correlation is also strong with other biological indicators (Lavoie et al., 2009).

Samples collected during late summer in 2002 and 2003 constitute the bulk of the data used to develop the IDEC. However, over the 10 years of IDEC development, additional diatom data issued from several projects conducted between 2004 and 2012 were subsequently incorporated into the database. These studies were conducted in collaboration with water agencies, provincial and federal governments, as well as universities. Diatom assemblages were collected and analysed using standard protocols (Lavoie et al., 2014). Diatoms were collected by scraping the biofilm from the top surface of rocks using a toothbrush. One composite sample per