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The impact of land use and spatial mediated processes on the water quality in a river system

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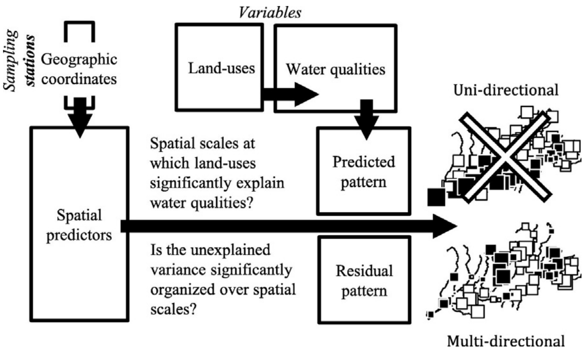
HIGHLIGHTS

- Water quality in rivers is affected by different pollution sources and pathways.
- Eigenvector maps were used to assess spatial changes in water chemistry.
- Land use and spatial descriptors of diverse scales were related to water quality.
- Unidirectional, upstream-downstream changes were not found.
- Management is required on different scales incorporating the predominate pathways.

GRAPHICAL ABSTRACT



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ABSTRACT

River systems are highly complex, hierarchical and patchy systems which are greatly influenced by both catchment surroundings and in-stream processes. Natural and anthropogenic land uses and processes affect water quality (WQ) through different pathways and scales. Understanding under which conditions these different river and catchment properties become dominant towards water chemistry remains a challenge. In this study we analyzed the impact of land use and spatial scales on a range of WQ variables within the Kleine Nete catchment in Belgium. Multivariate statistics and spatial descriptors (Moran's and Asymmetric Eigenvector Maps) were used to assess changes in water chemistry throughout the catchment. Both land use and complex mixes of spatial descriptors of different scales were found to be significantly associated to WQ parameters. However, unidirectional, upstream-downstream changes in water chemistry, often described in river systems, were not found within the Kleine Nete catchment. As different sources and processes obscure and interact with each other, it is generally difficult to understand the correct impact of different pollution sources and the predominant pathways. Our results advocate for WQ management interventions on large and small scales where needed, taking the predominate pathways in to account.

1. Introduction

River systems are complex and patchy systems which are greatly influenced by both catchment surroundings and in-stream processes (Poole, 2002). This results in a hierarchical system, ranging from the largest spatial scale of landscape or basin to successively smaller scales

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Abbreviations: WQ, Water quality; RCC, River Continuum Concept; PCAIV, Principal Component Analysis on Instrumental Variables; MEM, Moran's Eigenvector Map; RDA, Redundancy Analysis; AEM, Asymmetric Eigenvector Maps.

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such as the valley segment, channel reach and sediment pools and riffles (Allan, 2004; Townsend et al., 2003). Different geomorphological, ecological and anthropogenic factors affect river water quality (WQ), with changing influence over temporal and spatial scales (Baker, 2003; Poole, 2010). Under natural conditions, river systems already demonstrate a high level of complexity which has increased further due to land development. Anthropogenic activities have disrupted and changed existing processes and/or included new water and pollution sources through different pathways (sewers, runoff, seepage, etc.). As a result, carbon, nutrient and other contaminants, such as chloride and calcium, have become more dynamic (Kaushal and Belt, 2012; Kaushal et al., 2014; Steele and Aitkenhead-Peterson, 2011).

Since the beginning of the 20th century, scientists have attempted to translate these dynamics into theoretical concepts (Melles et al., 2012). Vannote et al. (1980) observed that physical variables changed along a continuous gradient from headwaters to river mouth, determining stream communities (River Continuum Concept: RCC). In the following decades, additional concepts were developed that increased our understanding of the rivers complexity, among others: the serial discontinuity concept (Wards and Stanford, 1983), nutrient spiraling (Webster and Patten, 1979), catchment hierarchy (Townsend, 1996) and patch dynamics (Townsend, 1989). Which were later integrated and extended by Poole (2002), Thorp et al. (2006) and Humphries et al. (2014) to explain different types of discontinuities in natural systems. Statzner and Higler (1986) evidenced the universal influence of hydraulics on the longitudinal river gradient, and mentioned that natural zonation patterns over long stream reaches are usually obscured by human influences. The integration of anthropogenic influences in these concepts is still progressing; e.g. “Urban Stream Syndrome” by Walsh et al. (2005) and “Urban Watershed Continuum” by Kaushal and Belt (2012). Under what conditions these concepts can be applied is often less clear.

Many river processes occur at different spatial scales, taking directional movements into account. Both natural and anthropogenic patterns and processes in river systems are generally strongly oriented to downstream reaches (longitudinal connectivity vectors) (Ward, 1989). But also lateral (e.g. runoff) and vertical (e.g. seepage) vectors can have important effects (Stanford and Ward, 1993; Townsend, 1996). The relative magnitude of these vectors can differ among river systems and investigating which of these vectors are predominant within a river system remains challenging.

Catchment characteristics like land uses and geomorphological properties are connected to a river system through all three vectors and have profound effects on the river characteristics. These characteristics are therefore widely used as landscape metrics to explain WQ variation and applied as predictors for ecosystem health and river functioning (Jones et al., 2001; Stanfield et al., 2009). As these landscape metrics depend on a good delineation of the upstream area and correct incorporation of the hydrological flow paths and solute deliveries (Gergel et al., 2002), much research has gone to improve their calculation (e.g. Baker et al., 2007; Van Sickle and Johnson, 2008; Vrebos et al., 2015). Nevertheless, landscape metrics can only explain part of the observed variation, as they describe only a limited portion of all processes present in a catchment. For example, in-stream processes can have a profound impact on different WQ parameters (e.g. (Caissie, 2006; Withers and Jarvie, 2008) and also ground water contributions to stream chemistry can be scale dependent (Peralta-Tapia et al., 2015). Up to now, it remains difficult to define and select structures, connectivity vectors and scales on which these processes take place and to translate them into functional indicator metrics.

In general, ecological variables strongly depend on environmental conditions which change often gradually in space (Dray et al., 2012; Legendre, 1993). Although a catchment can extend over a large area and can be marked by strong upstream-downstream gradients, subgradients at smaller scales can result from sub-catchment properties, local pollution sources or in-stream processes. As a result, the WQ pattern of the whole catchment might encompass various spatial scales. In this respect, WQ descriptors can exhibit different “spatial waves”, where these descriptors increase and decrease along a river stretch. These changes depend on particular physical, chemical or human-mediated drivers and/or local independent processes. Basically, there is no single scale at which ecological phenomena should be studied as the observer imposes a perceptual bias (i.e. the spatial extent of his work) through which the system is viewed (Levin, 1992). Many scales can be perceived in any spatial extent and recent developments in spatial analysis enlarged exploratory perspectives in scale-dependent processes (Dray et al., 2012). Scales can be materialized by spatial variables derived from geographic coordinates of sampling units in order to explore the spatial nature of ecological variables by a correlative approach. Two types of spatial predictors were recently developed: those accounting for spatial patterns resulting from multi-directional processes (Griffith and Peres-Neto, 2006) and those accounting for unidirectional ones (Blanchet et al., 2008b). Both types can be combined within one analysis, to test a community or species for both directional and non-directional processes and flows at different spatial scales (Blanchet et al., 2011).

Natural lotic systems are expected to generate longitudinal gradients. However, intensive land uses should strongly disrupt the spatial extent of natural processes and these longitudinal gradients. Focusing on a strongly anthropogenically affected river system in northern Belgium, we hypothesized that (1) land use should drive a substantial amount of WQ variance; (2) spatial variables accounting for unidirectional processes should weakly predict WQ patterns; and (3) human-mediated processes should take place over complex mixes of spatial scales.

2. Methodology

2.1. Study area

The Kleine Nete Catchment (approximately 780 km^2) is situated in Northern Belgium and is a sub-catchment of the Scheldt river basin (Fig. 1). It has a marine temperate climate with an average precipitation of 800 mm/year. Topographic heights range between 3 m and 57 m above sea level. As a result of weak elevation gradients, average water current velocities are limited (0.2 m/s in winter, 0.06 m/s in summer) (De Doncker et al., 2009). The catchment consists mainly of sandy soils, with loamy sand soils in the floodplains. Due to permeable soils, the river system is mainly groundwater fed and natural surface runoff takes only place during wet periods when the soils are water saturated. Some of the upstream geophysical characteristics of the catchment, used in the analysis, are summarized in the Supplementary material (Fig. S1).

Land use within the catchment is dominated by pasture (24%), croplands (20%), broadleaved woodland and evergreen needle leaf forests (22%) and houses and roads (13%). The other 21% consists mainly out of open waters, gardens, shrubs, etc. In total 27 cities and municipalities are fully or partially located within the catchment, with a total population of +/−524,000 inhabitants in 2012 and an average population density of 455 in./km^2. Typical ribbon development is present between villages in the catchment (De Decker, 2011).

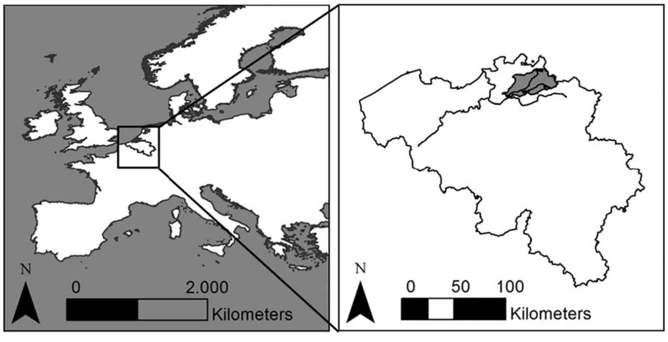

Fig. 1. Location of the study area.