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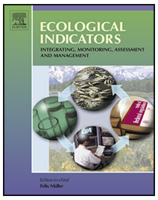

Water displacement by sewer infrastructure and its effect on the water quality in rivers

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ABSTRACT

Water quality is affected by a complex combination of natural and anthropogenic factors. To assess watershed integrity on a larger scale and for an optimal, cost-effective integrated watershed management, defining linkages between upstream watershed land cover and riverine water quality is essential. A correct upstream area calculation is an absolute necessity to reach conclusive results, but remains problematic in human influenced catchments. Especially sewer infrastructures (including wastewater treatment plants) are difficult to incorporate. We developed a method that allows us to integrate the sewer system in the upstream calculations and applied it on the Nete catchment in Belgium. Our results show strong changes in results compared to standard runoff methods. We conclude that if sewer systems are not incorporated in upstream area calculation, the impact of human activities on the water quality at a catchment scale estimates will be severely biased. A thorough understanding of the evaluated catchment and a correct translation of the different hydrological flow paths in the upstream area calculation is absolutely necessary to gain reliable results.

1. Introduction

Water quality is affected by a complex combination of natural and anthropogenic factors (Allan, 2004; Baker, 2003). Understanding the anthropogenic impacts is important to implement effective measures to improve water quality and stream ecosystem health (Booth et al., 2004). To assess watershed integrity on a larger scale, defining linkages between watershed land cover and river characteristics can provide interesting insights leading to cost-effective measure programs (Gergel et al., 2002; Oneill et al., 1997). Upstream landscape metrics are widely used as predictors of stream ecosystem health and water quality, biodiversity and river functioning (Jones et al., 2001; Stanfield et al., 2009; Van Hulle et al., 2010). The developed methods are frequently improved to better represent the different catchment processes (e.g. Baker et al., 2007; Sponseller et al., 2001; Strayer et al., 2003; Van Sickle, 2005; Van Sickle and Johnson, 2008).

Upstream urban and impervious areas are important contributors to anthropogenic impact on both landscape and aquatic ecosystems (Arnold and Gibbons, 1996; Booth and Jackson, 1997; Jacobson, 2011). Usually, urban and impervious land uses encompass only a low percentage of the catchment area. Still, they have a disproportionately large influence on both the hydrology and biogeochemistry of receiving streams (Cunningham et al., 2009; Feminella and Walsh, 2005; Paul and Meyer, 2001; Vrebos et al., 2014). Urbanization changes hydrological flow paths in many different aspects (Carey et al., 2013). An accurate integration of urban areas and their specific hydrological processes in upstream area calculations is hence an absolute requirement to study human influence on nutrient balances of catchments (Brabec et al., 2002).

Upstream area calculations that represent the actual catchment are dependent on correct incorporation of hydrological flow paths and solute deliveries (Gergel et al., 2002). Catchment areas are generally delineated based on computer rendered upstream areas that reflect the natural runoff conditions (Baker et al., 2006), while manmade structures are usually neglected. As a result, upstream areas are often inaccurately delineated (Hammond and Han, 2006). One of the most important artificial structures is the sewer infrastructure: it drastically impacts the water flow paths in sub-urban catchments (Bernhardt and Palmer, 2007). Rain and

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Abbreviations: EIA, effective impervious area; WWTP, wastewater treatment plant; NGI, National Geographic Institute; FEA, Flemish Environmental Agency.

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wastewater run through underground pipes, crossing streams above and beneath: water is pumped upstream, downstream and between sub-catchments. Areas that, under natural conditions, used to be part of one (sub-)catchment have become part of another. Such manmade hydrological changes have profound effects on different explaining variables, like impervious area, used in land use indicator tests.

Instead of integrating sewer infrastructure in the upstream area calculation, most land use indicator studies incorporate sewer infrastructure and wastewater treatment plants (WWTP) as a separate factor with proper mean discharges and not as part of the upstream land use classes (e.g. Meynendonckx et al., 2006; Rothwell et al., 2010). A limited number of studies have considered connected or "effective" impervious areas (EIA) as a separate factor (e.g. Hatt et al., 2004; Wang et al., 2000). Still, the potential impact of the sewer system on upstream area calculation and land use distributions has been overlooked. The incorrect estimation of land use impacts can thus lead to erroneous conclusions. Yet, a correct calculation of upstream areas is an absolute necessity. Because of the large amount of explaining variables (e.g. upstream land uses, soil characteristics) used in statistical models, significant results are likely to be obtained, even if some explaining variables are incorrect.

In this paper, we assessed the effect of sewers and WWTPs on the upstream area calculation and the associated impact on land use indicator studies, in a case-study for the Nete catchment (Belgium). We compared the classic method of upstream area calculation with an adapted approach in which the sewer system complexity was incorporated. Both methods were used to explore correlations between upstream watershed characteristics and chloride and nitrogen concentrations over a time period of 8 years.

2. Materials and methods

2.1. Study area

The Nete catchment (approximately 1.673 km^2) is situated in the central Campine region in Northern Belgium (Fig. 1). It has a marine, temperate climate with an average precipitation of 800 mm/year. The dominant soil type is sand, with loamy sand occurring in the floodplains and a small area in the south that mainly consists of sandy loam and loamy sand. Topographic height ranges between 3 m and 82 m above sea level.

A major part of the streams within the catchment have been straightened, deepened and embanked. As a result these streams no longer follow their natural flow path. At the same time large obstructions like canals and high ways have been constructed. These constructions are bypassed by siphons, which allow water to run under obstructions in the ground.

The Nete yearly discharges on average 389 million m^3 water into the Rupel. Water chemistry is, spatially and temporally, highly variable because of different anthropogenic activities like agriculture, households, industry, etc. Land use in the Nete catchment consists mainly of cropland (20%), pasture (22%), broadleaved woodland and evergreen needle leaf forests (23%) and impervious area (8%). The other 27% mainly consists out of open water, gardens, bare land, etc. The land cover is highly fragmented with a median parcel of 0.10 ha.

In total 55 cities and municipalities are fully or partially located within the catchment. Population densities for these ranged in 2010 between 152 inh/km^2 and 1530 inh/km^2 with an average of 420 inh/km^2 for the entire catchment. The urbanized areas are mainly situated around the town centers. Typical ribbon development is present between the different villages, making the development of sewer systems costly and time consuming (De Decker, 2011).

At the moment 29 WWTPs are situated within the catchment. In 2008 74% of the households in the catchment were connected to a WWTP. Only during the 90s and the beginning of the 21st century most of these WWTPs have been expanded with tertiary treatment systems. Wastewater treatment zones do not coincide with the natural catchments and wastewater is actively transported from one (sub) catchment to another for treatment. Although the Nete catchment is considered to be one of the most natural catchments within Flanders (northern part of Belgium), almost none of the rivers and streams within the catchment meet the European Water Framework Directive standards and more investments to reach these standards are needed.

2.2. Water quality data

Water quality data from 2003 until 2010 were obtained from the Flemish Environmental Agency (FEA). During this period, nitrate ($NO_3{}^-$-N, mg/l), nitrite ($NO_2{}^-$-N, mg/l), ammonium ($NH_4{}^+$-N, mg/l) and chloride (Cl^-, mg/l) concentrations in streamflow were measured at 345 different locations in the catchment. Sampling frequency differs between the sample locations. Some points were sampled monthly for all parameters, others only once a year for one parameter. For nitrate 16,762 samples were available for analysis, for nitrite 14,836 samples, ammonium 14,646 samples and for chloride 13,877 samples.

Seasonal means, i.e. winter (December–February), spring (March–May), summer (June–August) and autumn (September–November) were calculated per year for each sample point, only when at least 2 samples were present for each season. As a consequence incorporated data points vary for the different variables and between years. Because of the origin of the data, detection limits varied between years and location and some measurements were below a relatively high detection limit. In order to take these measurements into account and incorporate also the sample points with low concentrations in the analysis, measurements below the detection limit, were given a value half of the detection limit.

2.3. Wastewater treatment plants

There are 29 active WWTPs situated in the catchment. The oldest dates back to 1957, the most recent was built in 2007. While most of the WWTPs have been renovated in last 15 years, large parts of the sewer infrastructure are relatively old and most of the sewer system still collects waste as well as rain water, but also parasitic groundwater (Dirckx et al., 2009). Yearly WWTPs influent and effluent data were obtained from the FEA for the period 2003–2010. For one, small, WWTP (Leopoldsburg) no data were available. These influent and effluent data encompass the following information: yearly flow (m^3/year), $NO_3{}^-$-N load (kg/year), $NO_2{}^-$-N load (kg/year), $NH_4{}^+$-N load (kg/year) and chloride load (Cl^- kg/year).

2.4. Geographic analysis

2.4.1. Land use map

Land use maps (1:10,000 vector-layers) were obtained from the National Geographic Institute (NGI) and consist of 49 different categories (NGI, 2007). They have a high accuracy and are based on aerial photographs from 1998 (1:21,000) and on site verification and adjustment in the following years until 2007. The land use vector layer was converted to a 1m-raster and the land use categories were aggregated to 8 different classes: woodland (VE111, VE113, VE114, VE120, VE131, VE132, VE133, VE140, VE150, VE220), cropland (VE340), pasture (VE320),