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Key factors affecting urban runoff pollution under cold climatic conditions

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SUMMARY

Urban runoff contains various pollutants and has the potential of deteriorating the quality of aquatic ecosystems. In this study our objective is to shed light on the factors that control the runoff water quality in urbanized catchments. The effects of runoff event characteristics, land use type and catchment imperviousness on event mass loads (EML) and event mean concentrations (EMC) were studied during warm and cold periods in three study catchments (6.1, 6.5 and 12.6 ha in size) in the city of Lahti, Finland. Runoff and rainfall were measured continuously for two years at each catchment. Runoff samples were taken for total nutrients (tot-P and tot-N), total suspended solids (TSS), heavy metals (Zn, Cr, Al, Co, Ni, Cu, Pb, Mn) and total organic carbon (TOC). Stepwise multiple linear regression analysis (SMLR) was used to identify general relationships between the following variables: event water quality, runoff event characteristics and catchment characteristics. In general, the studied variables explained 50–90% of the EMLs but only 30–60% of the EMCs, with runoff duration having an important role in most of the SMLR models. Mean runoff intensity or peak flow was also often included in the runoff quality models. Yet, the importance (being the first, second or third best) and role (negative or positive impact) of the explanatory variables varied between the cold and warm period. Land use type often explained cold period concentrations, but imperviousness alone explained EMCs weakly. As for EMLs, the influence of imperviousness and/or land use was season and pollutant dependent. The study suggests that pollutant loads can be – throughout the year – adequately predicted by runoff characteristics given that seasonal differences are taken into account. Although pollutant concentrations were sensitive to variation in seasonal and catchment conditions as well, the accurate estimation of EMCs would require a more complete set of explanatory factors than used in this study.

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1. Introduction

Urban runoff, considered as one of the most important diffuse pollution sources in urbanized settings, can cause water quality degradation leading to ecological and health risks (Davis et al., 2001; Kim et al., 2003; Blecken et al., 2012; Fletcher et al., 2013). Various pollutants, such as nutrients, metals, solids, microbes, oils and organic contaminants, are exported via runoff from urban sites to receiving water bodies (Pitt et al., 1999; Foster et al., 2000; Ellis and Mitchell, 2006; Lee et al., 2011; Lundy et al., 2012). These pollutants appear in different forms (e.g. dissolved and particulate bound forms) (Amrhein et al., 1992; Sansalone and Buchberger, 1997; Hallberg et al., 2007), and differ in origin not only based on the pollutant type but also according to land use type (Mitchell, 2001, 2005; Göbel et al., 2006; Clark and Pitt, 2012). Urban runoff quality and pollutant transport mechanisms have been more frequently studied in warm and temperate climates, where local weather conditions and catchment properties play a decisive role (Schueler, 1994; Brezonik and Stadelmann, 2002; Dougherty et al., 2006; Göbel et al., 2006; Sillanpää, 2013; Valtanen et al., 2014b), but are less understood for cold climates characterized by strong seasonal patterns (Dougherty et al., 2006; Westerlund and Viklander, 2006).

In warm and temperate climates, much is known about the main hydrological variables that affect runoff quality during rainfall-runoff events. For example, the intensity and depth of runoff and rainfall, as well as antecedent weather conditions are known to influence runoff pollutant concentrations and mass loads (LeBoutillier et al., 2000; Brezonik and Stadelmann, 2002; Marsalek, 2003; Kayhanian et al., 2007; Brodie and Dunn, 2010). However, the impacts of key variables that best explain variation in runoff quality can be site and pollutant-specific (Vaze and Chiew, 2003; Crabtree et al., 2006; McLeod et al., 2006;

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Helmreich et al., 2010; Hathaway et al., 2012; Sillanpää and Koivusalo, 2015a) depending e.g. on catchment imperviousness, land use type and land use activities (Driver and Tasker, 1990; McLeod et al., 2006; Dougherty et al., 2006; Kayhanian et al., 2007; Helmreich et al., 2010; Liu et al., 2013). Therefore, a complete understanding of the factors that control runoff pollutant transport requires several years of study in which data comprising various study sites and pollutants are collected (Semádeni-Davies and Titus, 2003; Hatt et al., 2004; Groffman et al., 2004; Sillanpää, 2013).

In cold climates, pollutant input and especially the transport of pollutants via runoff are far less understood than in warm climatic regions due to peculiarities and challenges related to the accumulation of snow, pollutant built-up in the snow-pack, snowmelt and frozen soils (Buttle and Xu, 1988; Bengtsson and Westerström, 1992; Oberts, 1994; Matheussen, 2004). The export mechanisms of runoff pollutants during cold seasons are further affected by anthropogenic activities, such as snow ploughing and snow transportation (Bengtsson and Westerström, 1992; Semádeni-Davies and Bengtsson, 1999). Moreover, the typical pollutant sources of urban areas differ between warm and cold periods (Oberts, 1994; Marsalek, 2003; Hallberg et al., 2007) and wintertime pollutant emissions are generally higher in comparison to summer conditions due to control utilized to increase human and vehicular traction (Amrhein et al., 1992), high emissions of gaseous impurities by traffic and heating (Hautala et al., 1995) and increased erosion by the use of studded tyres (Bäckström et al., 2003). During cold periods, runoff event duration and event volume increase towards the end-of-spring snowmelt in contrast to summer storms that frequently occur in small volumes (Sillanpää, 2013). Hence, given high seasonal variation in runoff generation and pollutant transport mechanisms, it may not be possible to model and predict runoff quality using the same hydrological variables that are commonly applied to warmer months (Buttle, 1990; Marsalek et al., 2000b). Also Dougherty et al. (2006) concluded that annual water quality models do not adequately describe the associations between runoff variables and runoff quality at the seasonal scale. This is supported by other studies under cold climate, showing that runoff generation patterns and water quality differ between seasons (Roseen et al., 2009; Helmreich et al., 2010; Valtanen et al., 2014a,b; Sillanpää, 2013). However, evidence of the factors that determine transport patterns during cold seasons are limited due to the lack of analyses between hydrological factors and runoff quality of the snowmelt period in cold climate studies (e.g. Westerlund and Viklander, 2006; Sillanpää, 2013).

The aims of the present study were (i) to identify key urban runoff event variables that control event mass loads (EMLs) and event mean concentrations (EMCs), and (ii) to investigate variation in these key variables in terms of season and catchment characteristics under cold climatic conditions. We hypothesized that variation in runoff event quality is better explained by runoff variables during the warm season than during the cold season due to winter-specific pollutant sources and transport mechanisms. Furthermore, we expected that key influential variables are season-dependent due to seasonal differences in runoff and pollutant transport mechanisms. This study, focusing on event-scale pollutant export, forms part of a long-term urban runoff study programme in which annual and seasonal runoff characteristics are being investigated (Valtanen et al., 2014a,b).

2. Methods

2.1. Study sites

The three study catchments are located within the city of Lahti (60°59′00″N, 25°39′20″, population 102,000 in 2011) in Finland. Lahti is located in a boreal climate with a mean annual precipitation of 633 mm (Kersalo and Pirinen, 2009) with rather evenly distributed precipitation throughout the year. During the current study, 65% of annual precipitation (480 mm) occurred during the warm period in the first study year (2009) when summer was the wettest season (Valtanen et al., 2014a). During the second year, annual precipitation (460 mm) was evenly distributed between the warm and cold periods. Winter in Lahti lasts for 135–145 days and the summer period for 110–120 days, giving two distinct periods for runoff events. Precipitation during winter and spring mostly falls as snow while from summer to mid-autumn precipitation occurs as rainfall. In Lahti, average monthly temperatures from November to March vary between −0.8 and −7.3 °C and from April to October between 2.8 and 16.6 °C. Hence, the winter period enables the accumulation of snow on surfaces and this snow storage is mostly released during spring snowmelt. Rainfall events typically last a few hours, with 1–10 mm of precipitation depth (Sillanpää, 2013). At urban catchments in southern Finland, mean dry weather periods between rainfall-runoff events last from a few hours to a few days and for snowmelt events from a few days to more than twenty days (Sillanpää, 2013).

The study catchments represent different levels of imperviousness and two land use types (Fig. 1). The sewer pipes at the catchments are mostly dry during dry weather periods. During cold months, de-icing with road salts (NaCl) and traction control with sanding are common procedures in the study catchments (The city of Lahti, personal communication), but accurate statistics on the amounts of salt and sand applied at the study catchments are not available (The City of Lahti, 2015).

2.2. Measurements

Monitoring took place between October 2008 and the end of August 2010. At each study catchment, runoff was measured continuously at 1 min intervals using an ultrasonic flow sensor (Nivus PCM4) placed at stormwater sewer pipes. Precipitation was measured with 0.2 mm volume precision (a tipping bucket rain gauge, Rainew 111) at 1 min intervals during the warm periods in the Low (R2) and Intermediate (R3) catchments (Fig. 1). Precipitation data for the High catchment were obtained from the Intermediate catchment. During occasional failure in precipitation measurements at the study catchments, precipitation recorded at 10 min intervals and 0.1 mm precision at the roof top of the University Campus (R1) was used for each catchment.

At each catchment, an automatic sampler (ISCO 3700) was programmed to take 1 L samples at irregular time intervals based on the accumulated runoff volume: Sampling frequency varied between 10 and 200 m^3 of runoff (i.e. a sample was taken at minimum after 10 m^3 of accumulate runoff based on flow measurements). The sampled events (3–51 samples/event) included rainfall events, snowmelt events, and rain-on-snow events. From the samples, total nitrogen (tot-N), total phosphorus (tot-P), total heavy metals including both dissolved and particulate bound metals (Cr, Mn, Co, Ni, Zn, Cu, Pb, Al), total organic carbon (TOC) and total suspended solid (TSS) concentrations were analysed. For a detailed description of the chemical analyses, see Valtanen et al. (2014b).

2.3. Data analysis

All runoff events were separated from the continuous two year runoff data and divided into cold and warm period events. Separation of the two periods was based on meteorological data. The cold period started from the first snowfall and freezing temperatures (November–December) and ended at the termination of spring snowmelt (April–May). For the warm period, a runoff event was defined as starting from the first observation of precipitation and

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