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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.

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

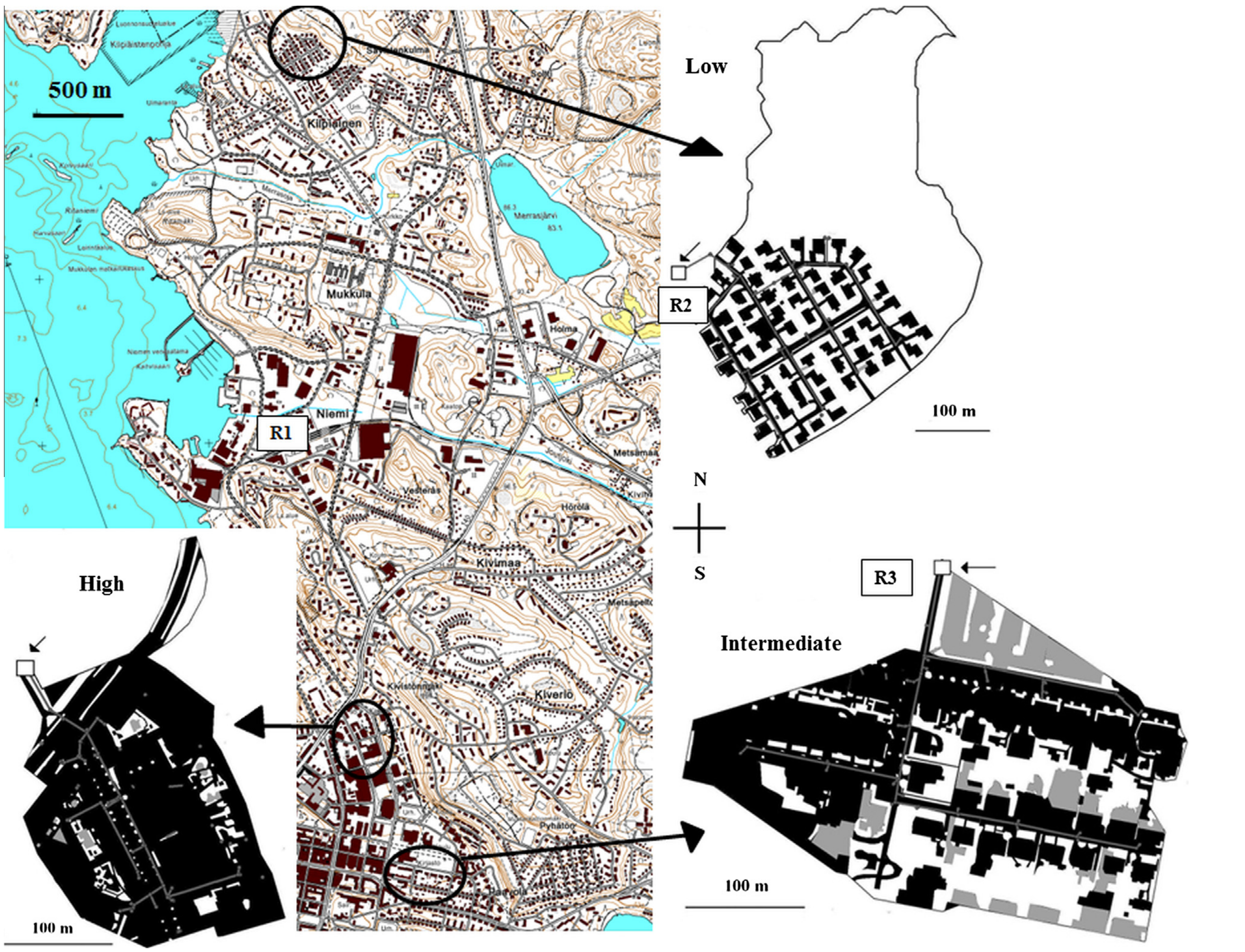

Fig. 1. The three study catchments located in the city of Lahti: a low-density residential area with total impervious area (TIA) of 19% (the Low catchment, total area = 12.6 ha) and two city centre catchments with TIA of 62% (the Intermediate catchment, 6.5 ha) and 89% (the High catchment, 6.1 ha). In each catchment: black areas = impermeable surfaces, light grey areas = gravel surfaces, white areas = urban green areas. Dark grey lines = stormwater pipe lines (PVC or concrete). Small black arrows point to locations of the measuring stations (white squares). R1 = weather station at the University campus, R2–R3 = rain gauges at the study catchments.

lasting until the flow rate had returned to the pre-event baseflow rate. Cold period events were separated from the data based only on the flow record. For each event the following event variables were calculated: runoff duration (Dur [h]), total runoff volume (R, [mm]), peak flow (Qmax, [L/s, L/s/ha]), length of antecedent dry period (ADP, [h]), mean runoff intensity (Int, [mm/h]), event mean pollutant concentration (EMC, [μg/L, mg/L]) and event mass load (EML, [g, kg]). Event rainfall depth (P, [mm]) and maximum 10-min rainfall intensity (Pmax, [mm/10 min]) were calculated for each warm period rainfall-runoff event. During warm periods, ADP was defined as the time (h) of no rainfall between two runoff events. During cold periods, ADP was defined as the time (h) since last snowmelt that was indicated by hydrographs and steady base flow rates or totally dry stormwater pipes between snowmelt events. The same methods were also used to determine duration, i.e. starting and ending, of the snowmelt event.

EML (Eq. (1)) was calculated for all sampled events as the sum of pollutant mass loads determined by multiplying each discrete concentration (C_i) within an event with its corresponding runoff volume (V_i), (see Huber, 1993; Charbeneau and Barrett, 1998):

$$EML = \sum_i C_i V_i \tag{1}$$

EMC (Eq. (2)) was defined as the ratio of EML to total event runoff volume (V):

$$EMC = \frac{EML}{V} = \frac{\sum_i C_i V_i}{\sum_i V_i} \tag{2}$$

For the regression analysis, EMLs were normalized by catchment area [g/ha, kg/ha].

For statistical analyses, the results from both study years (2009 and 2010) were combined and runoff events were divided into two groups: cold period events covering winter and spring seasons (snowmelt and rain-on-snow events) and warm period events covering summer and autumn seasons (rainfall-runoff events). Normality of the event variables was tested using the Kolmogorov–Smirnov and Shapiro–Wilk tests and by inspecting histograms. All data were $\log_{10}$-transformed to obtain approximately normal distributions. Simple linear relationships between the $\log_{10}$-transformed event variables (Dur, R, Qmax, ADP, Int, P, Pmax) were tested using Pearson correlation. Stepwise multiple linear regression (SMLR) analysis was applied to detect those variables that best explain variation in EMLs (g, kg) at each study catchment – separately for cold and warm periods. Another SMLR analysis that merged the data off all the study catchments was carried out to assess whether catchment type variables explain EML (g/ha, kg/ha) and EMC during the cold and warm periods. For this combined analysis, besides EMLs, peak flows (l/s) were divided by catchment areas (ha). Catchment type variables included total impervious area (TIA, [%]) and land use type (LU) as a dummy variable

Table 1
Median and range (min–max) of the runoff event variables of sampling events during warm and cold periods (precipitation variables measured only during the warm period) at the three study catchments of varying land use (High, Intermediate, Low). *R* = total runoff volume, Qmax = peak flow, Int = mean runoff intensity, Dur = runoff duration, ADP = antecedent dry period, P = precipitation, Pmax = maximum 10-min rainfall intensity, No. of samples = the number of samples taken during one sampling event.

	High		Intermediate		Low	
	Cold	Warm	Cold	Warm	Cold	Warm
R (mm)	1.5 (0.29–11)	3.5 (0.76–14)	1.7 (0.27–38)	2.5 (1.0–17)	3.0 (0.27–142)	0.73 (0.29–8.1)
Qmax (L/s/ha)	1.4 (0.19–16)	10 (1.8–29)	2.4 (0.11–7.6)	7.2 (0.02–76)	0.95 (0.06–5.3)	1.6 (0.11–12)
Int (mm/h)	0.08 (0.01–0.94)	0.60 (0.13–2.4)	0.09 (0.02–0.44)	0.47 (0.14–3.3)	0.01 (0.01–0.11)	0.05 (0.02–0.28)
Dur (h)	8.3 (0.13–60)	4.9 (1.3–12)	8.3 (0.12–351)	3.4 (0.14–23)	14 (3.4–1275)	5.5 (1.1–200)
ADP (h)	2.9 (0.13–197)	14 (0.13–393)	26 (4.7–618)	18 (2.6–300)	42 (15–1319)	66 (3.0–271)
P (mm)		4.6 (1.2–17)		3.2 (1.5–24)		4.6 (1.2–21)
Pmax (mm/10 min)		0.6 (0.2–9)		0.8 (0.2–9)		0.6 (0.2–4.6)
No. of samples	4 (3–25)	5 (3–13)	4 (3–40)	4 (3–23)	5 (3–51)	4 (3–12)

(0 = low density residential, 1 = city centre commercial–residential). Model residuals were inspected as plots against the predicted value and normal P–P plots of the residuals. Serial correlations of the residuals were tested using the Durbin-Watson test for first-order autocorrelation. Eigenvalues were checked for multicollinearity of the variables and for outliers. Outliers were also investigated using the Mahalanobis Distance, Cook's distance and Leverage-values and if outliers were found, the SMLR was also conducted without them to evaluate whether their removal changes the outcome. If so, outliers were deleted from the SMLR analysis.

3. Results

3.1. Runoff event characteristics

Typical to local runoff events, the sampled runoff events were relatively short in duration and small in volume (Table 1). During the warm period, the smallest sampled storm was 4.6 mm, which produced 0.3 mm of runoff. For the cold period, the smallest sampled runoff depth was also 0.3 mm. However, particularly at the Low catchment, at least one longer melt period, lasting from a few days to weeks, occurred during spring snowmelt**.** Runoff was less intense during the cold than the warm period (Table 1). However, during the cold period, variation in peak flow (coefficient of variation, CV 1.2–2.7) and mean runoff intensity (CV 1.1–1.7) were larger than during the warm period (peak flow, CV 0.37–1.2; mean runoff intensity, CV 0.67–0.97). Antecedent dry weather periods varied considerably during both warm (CV 1.4–2.1) and cold (CV 2.2–2.9) periods. Moreover, at the High catchment, minimum ADPs were very short due to runoff event characteristics being short in duration and high in runoff intensity.

The number of sampling events reflects inherent differences in the number of runoff events generated between catchments and seasons: more events occur at the city centre catchments than at the Low catchment (Table 2) due to the fact that at the city centre catchments, runoff is generated even during small storm events (see Valtanen et al., 2014a). Additionally, due to the longer catchment lag, consecutive storms that would have been treated as separate runoff events at the city centre catchments produced only one prolonged runoff event at the Low catchment. As TOC was measured only during the first study year (2009), fewer samples were taken for TOC.

The normalized EMLs exhibited large temporal and spatial variation, especially during the cold months (Fig. 2) when runoff volumes also varied (CV 0.98–2.6) more than during the warm period (CV 0.74–1.6), which possibly explain the variation in event loads. Most event loads reached their maxima during the cold period, which relates to high wintertime emissions and pollutant load accumulation over a long time period, particularly concerning end-of-spring snowmelt (see Valtanen et al., 2014b). However, similarly to median runoff volumes at the city centre catchments (Table 1), median EMLs were usually higher during the warm than the cold period with some exceptions: nutrients at the Low and Intermediate catchment and metals especially at the High catchment (Fig. 2). This also relates to pollutant sources and emissions that vary between seasons and are derived from catchment characteristics (e.g. traffic density, population density, imperviousness). Median EMLs at the Low catchment were often an order of magnitude smaller than those at the city centre catchments, in particular EMLs of TSS. This arises from lower pollutant concentrations (for EMCs see Valtanen et al., 2014b) at the Low catchment, which likely originates from its low-density land use and, consequently, less pollution from traffic-related sources in comparison to the city centre catchments. However, median values of the tot-N EMLs during the cold period were equal at the Low and High catchments.

Table 2
Number of sampling events (nr. of EMLs and EMCs) selected for water quality analysis during warm and cold periods at the three study catchments (High, Intermediate, Low). TSS = total suspended solids, tot-N = total nitrogen, tot-P = total phosphorus, TOC = total organic carbon.

	High		Intermediate		Low	
	Cold	Warm	Cold	Warm	Cold	Warm
TSS	35	28	28	22	8	18
tot-N	35	21	23	19	7	15
tot-P	34	18	21	18	7	14
TOC	29	17	14	12	7	8
Al	31	22	27	24	7	17
Cr	31	22	27	24	5	17
Mn	30	22	27	24	7	17
Co	24	21	27	24	6	17
Ni	31	21	20	24	4	17
Zn	31	22	27	24	7	17
Cu	31	22	26	24	7	17
Pb	31	21	26	24	7	17

As with EMLs, EMCs also (see Valtanen et al., 2014b) exhibited large temporal and spatial variation, particularly during the cold period. However, at the two city centre catchments (High and Intermediate), median EMCs were highest during the cold period but at the Low catchment, median EMCs of TSS, tot-P, Mn, Zn and Cu were highest during warm months. This indicates that at the Low catchment, during the cold period, large pollutant loads were also controlled by large runoff volumes while at the city centre, cold period loads were strongly related to high pollutant concentrations.

3.2. Relationships between event variables

Before conducting the SMLR analysis, simple relationships between the event variables (Dur, Int, Qmax, *R*, ADP, *P*, Pmax) were

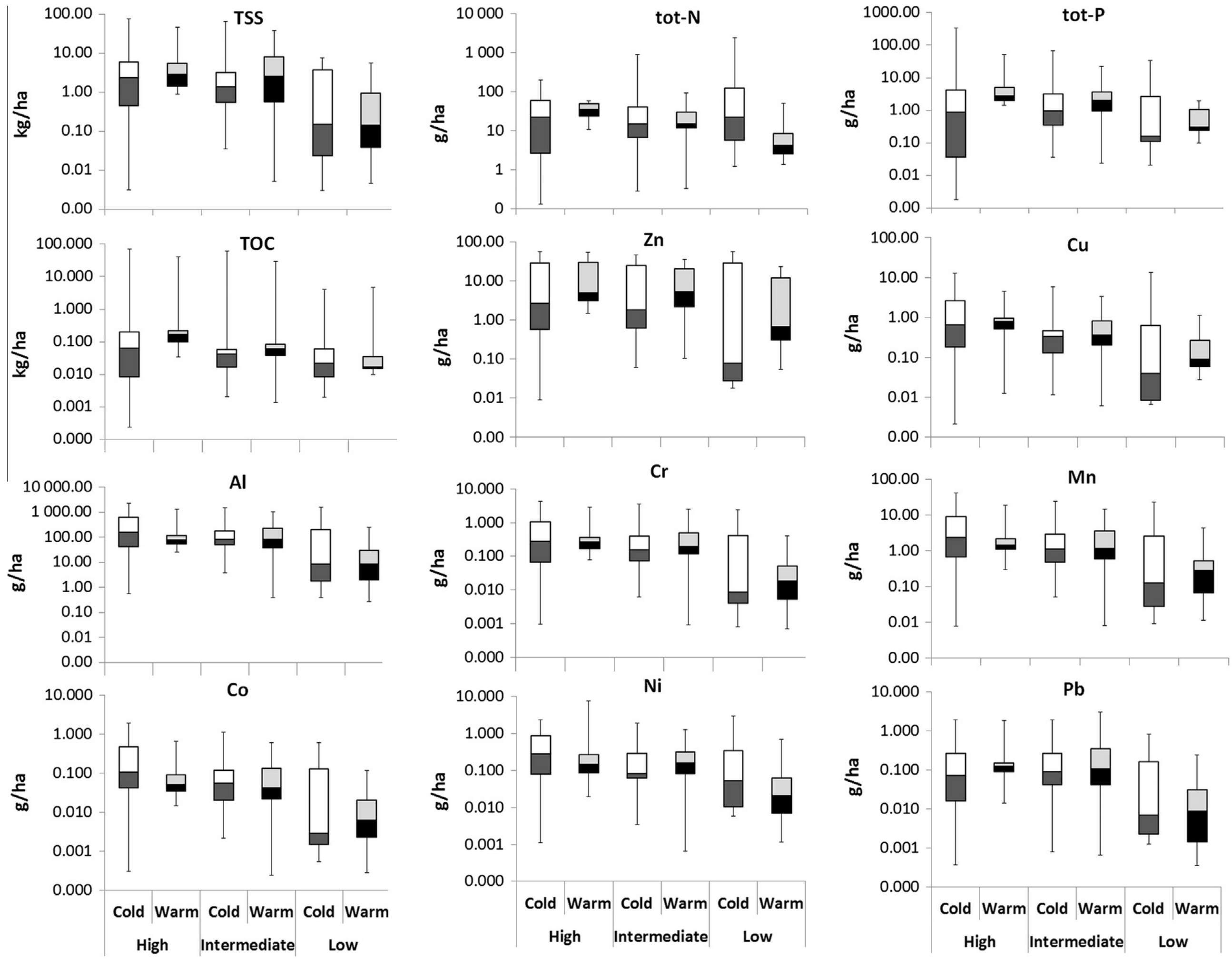

Fig. 2. EMLs normalized by catchment area during warm and cold periods at the three catchments (High, Intermediate, Low). TSS = total suspended solids, tot-N = total nitrogen, tot-P = total phosphorus, TOC = total organic carbon. Boxplots represent medians (horizontal lines), quartiles (white, dark grey, black and grey boxes), and minimum and maximum values (horizontal lines). Note the logarithmic scale of the *y*-axis.

evaluated based on their bivariate correlations. This correlation analysis indicates whether the independent event variables (used also in the SMLR analysis) are related to each other, and hence may explain why certain variables are selected by the SMLR. Considering the entire study project and cold climate hydrology, these relationships can be applied to link the hydrological runoff event characteristics to each other. The correlation analysis showed that event variables were often insignificantly (Pearson correlation, $p > 0.05$) related. Yet, when the length of the antecedent dry period is excluded, total runoff volume correlated with most variables, particularly strongly with runoff duration (Fig. 3). Strong and year-round correlations also occurred between variables reflecting the intensity of runoff, peak flow and mean runoff intensity, especially at the city centre catchments (Pearson correlation coefficients, $r = 0.449–0.817$, $p < 0.05$ in all cases).

Simple relationships between runoff event variables (Dur, Int, Qmax, *R*, ADP, *P*, Pmax) and runoff event quality (EMLs and EMCs) were investigated based on their bivariate correlations. Substantial variation existed among significantly correlating variables that were sensitive to season and depended on whether concentrations or loads were studied. This also causes variation between EMLs and EMCs and between cold and warm periods in variables affecting runoff quality in the SMLR analysis. For example, correlations between runoff duration and runoff volume and EMLs of most of the studied pollutants occurred year-round, but particularly during the cold period as is shown by the EML of TSS (Fig. 4). This results from the accumulation of pollutants (particularly towards large spring melt), snowfall and rain-on-snow during cold months. During the warm period, instead, correlations between EMLs and runoff intensities (peak flow, mean runoff intensity) were stronger than during the cold period. This may result from runoff intensities that are larger during the warm compared to the cold period (Table 1). Positive correlations between peak flow rates and EMCs also occurred for some pollutants during the warm period. However, most of the studied pollutant EMCs correlated differently with runoff event variables. As for EMC, positive correlations with runoff duration and volume occurred during the cold period but these were weak; during the warm period correlations were mostly negative, e.g. for TSS (Fig. 5). Runoff quality correlated rarely with ADP but positive correlations were found particularly with warm period EMCs.

3.3. Model building and residual considerations

Event variables used in the SMLR analysis were: runoff duration, mean runoff intensity, peak flow and antecedent dry period because these variables were not used in the calculation of the dependent variables. Moreover, these variables were measured

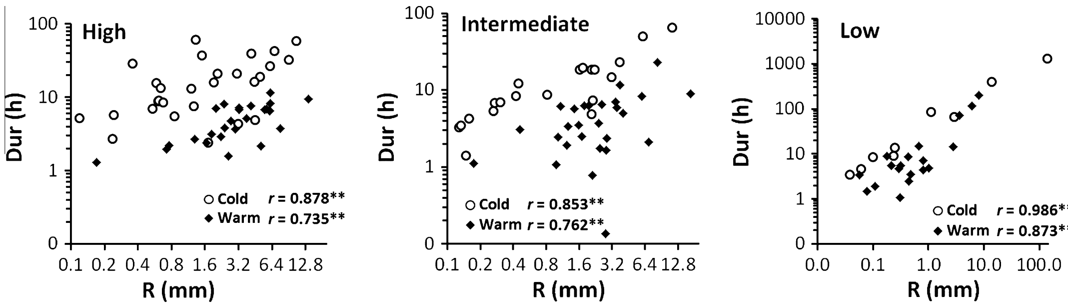

Fig. 3. Relationship between total runoff volume (*x*-axis) and the duration of runoff (*y*-axis) during cold and warm periods at the three study catchments of varying land use (High, Intermediate, Low). Note the logarithmic scale of the axes. *r* = Pearson correlation coefficient, $^{**}p < 0.01$.

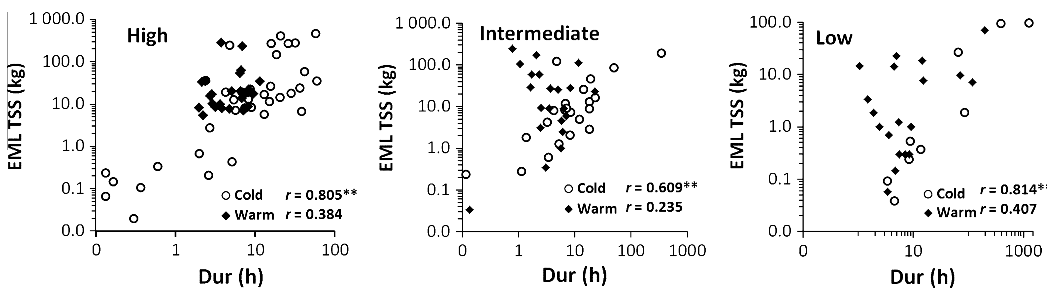

Fig. 4. Relationship between runoff duration (*x*-axis) and EML of TSS (*y*-axis) during cold and warm periods at the three study catchments of varying land use (High, Intermediate, Low). Note the logarithmic scales of the axes. *r* = Pearson correlation coefficient, $^{**}p < 0.01$.

year-round, hence their usage enabled comparisons between the warm and cold periods. None of the rainfall variables were selected as independent variables because rainfall was not measured during the cold period.

The SMLR models presented in Tables 3–6 are statistically significant at $p < 0.05$ with residual assumptions commonly fulfilled. A few outliers were removed based on the data of the residual plots and Mahalanobis Distance, Cook's distance and Leverage-values. No multicollinearity was observed in the established models. Here the SMLR model represents a tool to detect important and multiple relationships between the hydrological runoff event variables and runoff event quality variables, rather than an actual model or predictor for runoff quality.

3.4. Key variables selected by the SMLR analysis for cold period event loads

In most of the multiple linear regression models, runoff variables explained 60–90% of variation in the event loads during the cold seasons. The variables affecting runoff quality were similar between the study catchments: runoff duration was the key explanatory variable in the SMLR models (Table 3) explaining up to 99% of loads at the Low catchment. At the two city centre catchments, mean runoff intensity, combined with event duration, was commonly the second most influential variable. There were no specific patterns between certain pollutant groups, however, some exceptions in selected variables were found: ADP affected tot-N loads at the Intermediate catchment and Zn, Al, Mn loads at the Low catchment. This may relate to the dissolved form of the pollutant. It has previously been reported that at the Low catchment, a larger percentage of the metals are dissolved compared to the city centre catchments (Valtanen et al., 2014a). Some exceptions also occurred concerning model performance. At the Intermediate catchment, R^2-values for nutrient and TOC models were low (0.28–0.41) indicating poor performance of the regression models. At the Low catchment, none of the runoff event variables explained tot-P and Cu loads as regression equations could not be established for them when using the stepwise method.

Combined models for runoff event variables and catchment variables regarding normalized EMLs are shown in Table 4. For the cold period, these models explained 50–80% of the variation in EML. Overall, as in the SMLRs conducted for each site separately, runoff duration and mean runoff intensity, when combined, were often the main variables that increased EMLs during the cold

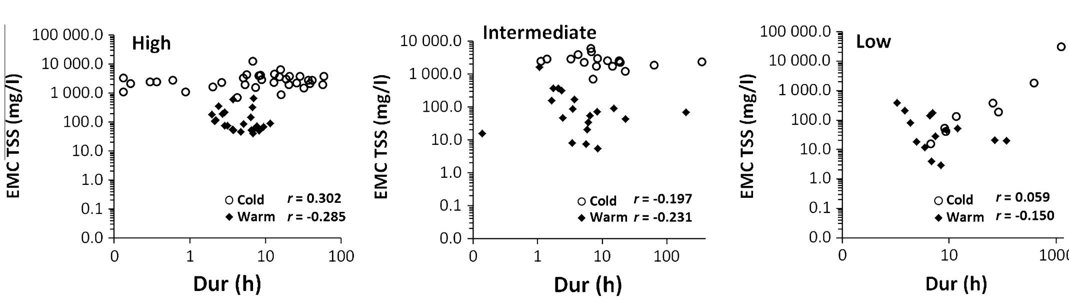

Fig. 5. Relationships between runoff duration (*x*-axis) and EMC of TSS (*y*-axis) during cold and warm periods at the three study catchments of varying land use (High, Intermediate, Low). Note the logarithmic scale of the axes. *r* = Pearson correlation coefficient, $p > 0.05$ in all cases.

Table 3
Multiple linear regression equations for estimating runoff event pollutant loads (EML) during the cold (winter and spring) period at the three study catchments of varying land use (High, Intermediate, Low). Equations follow the form: $\log_{10}(\text{EML}) = \text{Constant} + \Sigma\ a_i \log_{10}(\text{predictor variable})$ where a = the first explanatory variable, b = the second explanatory variable. A hyphen (-) indicates that an equation could not be established for the pollutant. In case of Zn, Mn, Al and Co for the Low catchment, the two entries indicate that two equations of similar R^2 value were returned for the pollutants. Dur = runoff duration, Qmax = peak flow, ADP = antecedent dry period, Int = mean runoff intensity, TSS = total suspended solids, tot-N = total nitrogen, tot-P = total phosphorus, TOC = total organic carbon. R^2 = the coefficient of determination, SEE = standard error of the estimate, p = probability.

	EML	Constant	Dur	Qmax	ADP	Int	R^2	SEE	p
High	TSS	1.198	1.185 a			1.147 b	0.854	0.455	<0.001
	tot-N	1.671	1.101 a			0.603 b	0.945	0.231	<0.001
	tot-P	−0.953	0.893 a	1.040 b			0.694	0.729	0.004
	TOC	−2.064	0.904 a	0.953 b			0.915	0.318	<0.001
	Zn	1.106	1.153 a			1.065 b	0.654	0.328	<0.001
	Cu	0.161	1.344 a			0.933 b	0.694	0.619	0.001
	Al	2.688	1.274 a			1.057 b	0.630	0.703	0.001
	Cr	0.440	1.145 a			1.040 b	0.577	0.730	0.001
	Mn	0.894	1.250 a			1.036 b	0.633	0.686	0.001
	Co	−0.572	1.468 a			1.049 b	0.751	0.579	<0.001
	Ni	−2.201	1.069 a			1.075 b	0.455	0.713	0.010
	Pb	−2.281	0.809 b	1.112 a			0.631	0.647	0.002
Intermediate	TSS	−0.683	0.623 b	0.932 a			0.628	0.517	0.001
	tot-N	2.085	1.092 a		−0.736 b		0.412	0.584	0.031
	tot-P	2.274				1.248 a	0.281	0.775	0.024
	TOC	−1.237	0.604 a				0.352	0.415	0.042
	Zn	1.281	0.798 a			0.881 b	0.796	0.354	<0.001
	Cu	0.309	0.782 a			0.697 b	0.732	0.388	<0.001
	Al	2.833	0.723 a			0.717 b	0.661	0.407	<0.001
	Cr	0.132	0.734 a			0.746 b	0.665	0.441	0.001
	Mn	0.940	0.726 a			0.693 b	0.638	0.454	0.002
	Co	−0.412	0.722 a			0.687 b	0.631	0.456	0.002
	Ni	−1.615	0.484 b	0.838 a			0.538	0.465	0.037
	Pb	−0.114	0.756 a			0.817 b	0.642	0.455	0.001
Low	TSS	−2.489	2.084 a				0.923	0.306	0.002
	tot-N	0.569	1.156 a				0.915	0.178	0.011
	tot-P	-	-	-	-	-	-	-	-
	TOC	−2.075	1.124 a				0.842	0.267	0.010
	Zn	−1.649	1.684 a				0.917	0.257	0.003
		2.315			1.253 b	2.315 a	0.943	0.191	0.038
	Cu	-	-	-	-	-	-	-	-
	Al	−0.469	2.057 a				0.902	0.305	0.002
		3.532			1.798 b	2.588 a	0.920	0.274	0.038
	Cr	−2.980	1.904 a				0.879	0.411	0.019
	Mn	−2.162	1.967 a				0.930	0.243	0.001
		2.269		2.633 a	1.509 b		0.957	0.189	0.023
	Co	−3.127	1.683 a				0.800	0.427	0.016
		3.433				2.705 a	0.708	0.516	0.036
	Ni	−0.427	−0.763 a				0.992	0.136	0.040
	Pb	−2.750	1.538 a				0.714	0.493	0.034

period. Furthermore, larger metal loads were associated with high peak flows. Based on the SMLR equations, particularly TSS, tot-N, TOC and some selected metal (Mn, Co, Ni, Cu) loads increased with increasing imperviousness (the TIA variable), and the city centre catchments exhibited larger Al, Cr and Zn loads compared with loads at the Low catchment. On average, TIA and land use type raised the R^2 value by 10% and 7%, respectively.

3.5. Key variables selected by the SMLR analysis for warm period event loads

Performance (R^2 values) of the warm period regression models (Table 5) did not differ substantially from those of the cold period models (Table 3). However, average R^2 values of the High catchment indicated 25% better model performance for winter conditions than for warm conditions.

Similarly to the cold period models, the same explanatory variables appeared in the regression models irrespective of catchment type. Variation in the explanatory variables between pollutants was also rare indicating that pollutant load build-up during rainfall-runoff events does not depend on pollutant type. Contrary to the cold period, peak flow was the key explanatory variable in the warm period EML models and alone or when combined with runoff duration explained 50–95% of the variation in EMLs during rainfall-runoff events (Table 5). Only in the case of metals at the High catchment, loads were weakly explained (R^2 value range 0.25–0.45), with peak flow rate being the only explanatory variable in the models. Furthermore, regression equations could not be established for Zn and Cu.

The regression models combining catchment and runoff event variables showed that 60–80% of the normalized EMLs were explained by the runoff event variables and catchment characteristics (Table 4). On average, catchment variables improved the explanatory power (R^2) of the models by 8%. Land use type was associated with higher warm period loads for Cr, Co, Zn and Pb in the city centre catchments, whereas an increase in TIA increased the loads of tot-N, tot-P and TOC.

3.6. Key variables for event concentrations selected by SMLR analysis

In general, the combined SMLR models failed to explain variation in the EMCs (Table 6) compared to the EML models (Table 4). During cold months, variables of the combined SMLR explained 25–40% of the variation in EMCs (Table 6), except for Pb concentra-

Table 4
Multiple linear regression equations for estimating runoff event pollutant loads (normalized EML) during cold (winter and spring) and warm (summer and autumn) periods for all the study catchments combined. Equations follow the form: $\log_{10}(\text{EML}) = \text{Constant} + \Sigma\ a_i\ \log_{10}(\text{predictor variable})$ where a = the first explanatory variable, b = the second explanatory variable, c = the third explanatory variable, etc. In case of cold period Cr, the two entries indicate that two equations of similar R^2 value were returned for the pollutant. Land use (LU) dummy variables: 0 = low density residential (Low catchment), 1 = city centre (High and Intermediate catchment). TIA = total impervious area. See Table 3 for other abbreviation explanations.

EML	Constant	Dur	Qmax	ADP	Int	LU	TIA	R^2	SEE	p
Cold period										
TSS	−0.827	1.115 a			0.728 b		0.014 c	0.836	0.43	<0.001
tot-N	0.971	1.031 a			0.649 b			0.904	0.265	<0.001
tot-P	0.203	1.017 a			1.087 b			0.609	0.734	<0.001
TOC	−2.091	0.888 a	0.453 d		0.772 b		0.007 c	0.250	0.298	0.003
Zn	−0.203	0.983 b			1.025 a	0.652 c		0.735	0.512	0.012
Cu	−1.802	0.826 b	0.510 a		0.537 d		0.014 c	0.695	0.560	0.017
Al	0.838	0.927 b	0.461 a		0.657 d	0.856 c		0.701	0.679	0.004
Cr	−1.506	0.956 a			0.916 b	0.800 c		0.630	0.619	0.150
	−0.762	0.851 b	0.366 a		0.894 c			0.604	0.640	<0.001
Mn	−1.037	0.810 b	0.506 a		0.642 d		0.012 c	0.691	0.581	0.005
Co	−2.275	1.042 a			0.814 b		0.130 c	0.734	0.512	<0.001
Ni	−2.517	0.544 b	0.791 a				0.011 c	0.478	0.634	0.160
Pb	−1.204	0.809 b	0.456 a		0.829 c			0.662	0.538	<0.001
Warm period										
TSS	−1.088	0.556 b	1.257 a		0.467 c			0.821	0.378	0.009
tot-N	0.233	0.650 b	0.261 a	0.146 d	0.146 e		0.005 c	0.772	0.260	0.011
tot-P	−1.158	0.524 b	0.702 a				0.007 c	0.596	0.403	0.009
TOC	−2.690	0.748 b	0.319 c				0.012 a	0.777	0.264	0.027
Zn	−0.922	0.622 b	0.598 a			0.634 c		0.697	0.344	<0.001
Cu	−1.02	0.492 b	0.511 a		0.412 c			0.574	0.394	0.028
Al	0.565	0.574 b	1.081 a		0.443 c			0.795	0.360	0.010
Cr	−2.588	0.466 b	1.146 a			0.523 c		0.807	0.348	<0.001
Mn	−1.351	0.400 b	1.210 a					0.703	0.380	<0.001
Co	−3.033	0.486 b	1.109 a			0.365 c		0.768	0.357	0.009
Ni	−1.802	0.760 b	0.674 a		0.609 c			0.672	0.427	0.007
Pb	−2.876	0.449 b	1.313 a			0.416 c		0.776	0.405	0.008

tion which was explained up to 65%. Only the concentrations of TSS, tot-P, Al, Cr and Mn were explained better (40–60%) by the studied variables during the warm period than during the cold one.

As with loads (EMLs), pollutant concentrations were also related to the duration of the runoff event throughout the year (Table 6). During the warm period however, concentrations were diluted by long durations and large runoff volumes. During the cold seasons, event duration was often the most important variable increasing concentrations. This further indicates that pollutant concentrations can affect pollutant loads during cold months when both variables have similar built-up patterns. Catchment properties had a strong effect on cold period EMCs, showing higher EMCs at the city centre catchments compared with the Low catchment (Table 6). Land use was the most important variable influencing TSS concentrations, the second most important variable explaining concentrations of most metals (Cr, Mn, Co, Ni, Zn, Cu), and the third most influential variable in terms of tot-P concentrations, increasing model performance on average by 11%. Metals are commonly in particulate bound forms in urban runoff, particularly during winter months (see Valtanen et al., 2014b) and hence related to TSS concentration showing similar behaviour. Therefore, these pollutants are strongly related to land use type as shown by the considerable difference in TSS event loads between the land use types (Fig. 2). TIA was associated with increasing Al and Pb concentrations and increased R^2 by 6% as a second best explanatory variable during the cold period. However, catchment variables did not have any role in explaining the warm period EMCs, except in the regression equation of Zn. Similarly to EML regression models, during warm months, the most important variable increasing concentrations was peak flow, particularly for many metals and TSS. This suggests that these pollutants also behave similarly during rainfall-runoff. Besides peak flow, duration of the antecedent dry period increased concentrations of many metals and tot-N. This is surprising considering that tot-N is mainly in dissolved form in urban runoff while metals are in particulate bound form (see Valtanen et al., 2014b).

In contrast to the EML regression models, runoff event and catchments variables in EMC models diminished runoff pollutant concentrations surprisingly often particularly during the warm period. This indicates that the same variables may reduce warm period concentrations but also increase total event loads. The most common variable diminishing warm period EMCs was runoff duration that impacted nutrient, TSS and most metal concentrations. Hence, contrary to the cold period EMLs that were affected by runoff duration and EMC, warm period EMCs were not related to warm period EMLs. However, also during the cold period, Pb concentrations were reduced by TIA, tot-N and TOC concentrations by mean runoff intensity and tot-N by ADP.

4. Discussion

4.1. Seasonal variation of key runoff event variables affecting runoff quality

It is well known that rainfall and runoff volumes control loads of various urban runoff pollutants (nutrients, TSS, VSS, COD, metals, ions) during summer storms (LeBoutillier et al., 2000; Brezonik and Stadelmann, 2002; Dougherty et al., 2006; McLeod et al., 2006; Kayhanian et al., 2007; Brodie and Dunn, 2010; Sillanpää and Koivusalo, 2015b). SMLR analysis is commonly used to detect relationships between urban runoff factors and water quality. This method enabled us to compare our findings to those reported in previous studies from warm climates. In our study, runoff duration – which correlated strongly and positively with runoff volume (Fig. 3) – can be considered a surrogate for runoff volume. Hence, supporting earlier warm period findings, we showed that event pollutant loads always increased as runoff duration and volume increased. In addition, runoff duration was among the most powerful variables in explaining runoff quality (hereafter

Table 5
Multiple linear regression equations for estimating runoff event pollutant loads (EML) during the warm (summer and autumn) period at the three study catchments of varying land use (High, Intermediate, Low). Equations follow the form: log10(EML) = Constant + Σ ai log10(predictor variable) where a = the first explanatory variable, b = the second explanatory variable, c = the third explanatory variable. A hyphen (-) indicates that an equation could not be established for the pollutant. See Table 3 for abbreviation explanations.

	EML	Constant	Dur	Qmax	ADP	Int	R^2	SEE	p
High	TSS	−1.341	0.529 b	1.267 a			0.646	0.308	0.044
	tot-N	0.695	0.447 b	0.697 a			0.594	0.236	0.042
	tot-P	−1.351	0.859 b	1.143 a			0.799	0.236	0.001
	TOC	−0.301	0.273 a				0.274	0.247	0.037
	Zn	-	-	-	-	-	-	-	-
	Cu	-	-	-	-	-	-	-	-
	Al	1.063		0.913 a			0.333	0.345	0.006
	Cr	−1.208		0.759 a			0.452	0.233	0.002
	Mn	−0.537		0.834 a			0.252	0.349	0.012
	Co	−2.507		1.134 a			0.440	0.335	0.001
	Ni	−2.430		1.316 a			0.339	0.480	0.007
	Pb	−2.265		1.202 a			0.395	0.399	0.003
Intermediate	TSS	−0.627	0.802 b	0.888 a		1.295 c	0.857	0.385	0.007
	tot-N	0.538	0.479 b	0.677 a			0.518	0.382	0.029
	tot-P	−1.176	0.664 b	1.089 a			0.748	0.339	0.001
	TOC	−2.107	0.816 a	0.716 b			0.791	0.291	0.036
	Zn	−0.118	0.644 b	0.691 a			0.628	0.591	0.001
	Cu	−1.556	0.558 b	0.939 a			0.663	0.353	0.004
	Al	−0.090	0.661 b	1.390 a			0.765	0.390	0.002
	Cr	−2.485	0.621 b	1.284 a			0.726	0.401	0.004
	Mn	−1.557	0.621 b	1.210 a			0.699	0.407	0.005
	Co	−3.036	0.635 b	1.240 a			0.709	0.407	0.004
	Ni	−2.374	0.679 b	1.125 a			0.638	0.449	0.005
	Pb	−3.005	0.622 b	1.460 a			0.784	0.383	0.003
Low	TSS	−1.825		1.554 a			0.661	0.458	<0.001
	tot-N	0.496	0.562 a	0.343 b	0.233 c		0.925	0.129	0.001
	tot-P	−0.409	0.392 b	0.571 a			0.740	0.215	0.003
	TOC	−1.645	0.814 a	0.307 b			0.946	1.336	0.031
	Zn	−0.448	0.691 a	0.526 b			0.710	0.368	0.009
	Cu	−0.712	0.360 b	0.440 a			0.652	0.267	0.005
	Al	−0.166	0.484 b	1.205 a			0.777	0.356	0.005
	Cr	−2.471	0.410 b	0.992 a			0.684	0.376	0.018
	Mn	3.445		−1.891 a			0.513	0.897	0.020
	Co	−2.799	0.481 b	0.871 a			0.738	0.319	0.002
	Ni	0.030	1.121 a			1.328 b	0.773	0.336	<0.001
	Pb	−2.910	0.433 b	1.112 a			0.640	0.456	0.036

referring to both pollutant loads and concentrations), particularly during the cold period.

Moreover, our study showed that the importance (if selected as the first, second or third best explanatory variable) and role (a negative or positive impact) of runoff event characteristics affecting urban runoff quality varied between cold and warm periods, which supported our hypothesis about the season-dependent differences in the SMLR models. In the city centre catchments, the best explanatory variable affecting pollutant loads was peak flow rate during the warm period, but event duration during snowmelt events. The importance of peak flow in city centre catchments is explained by the fact that the runoff response to summer storms is more sensitive to maximum rainfall intensity at highly developed catchments compared to less developed urban areas, as also observed by Sillanpää (2013). In addition, Vaze and Chiew (2003) reported that under warm climatic conditions, the intensity of runoff and rainfall explained nutrient and total suspended solid loads better than total runoff volume. The reason why peak flow rate is not an important explanatory variable during cold months in our study likely results from different runoff event characteristics during cold months: smaller peak flows and mean runoff intensities in comparison to summer storms. However, during the cold period, runoff volumes clearly vary more than during the warm period and pollutants (high concentrations) are accumulated in the snow over a long period of time. This may explain why runoff duration, connected to runoff volume, was a powerful explanatory variable during snowmelt seasons.

In the present study, seasonality strongly affected the key variables explaining pollutant concentrations (EMC). Pollutant concentrations during the warm season were influenced by runoff intensity as well as the length of the antecedent dry period, as previously observed by, e.g. Melanen (1981), Brezonik and Stadelmann (2002), McLeod et al. (2006) and Brodie and Dunn (2010) for nutrients, TSS, VSS, COD, ions and metals. Yet, during the cold period, our study showed that runoff duration was the most important runoff variable increasing EMCs as was observed for EMLs. Hence, the built-up patterns for cold period EMCs and EMLs were similar, and EMLs were also clearly increased by the EMCs during the cold period, particularly at the city centre catchments. Moreover, during snowmelt, the event magnitude (i.e. event duration and volume) tends to increase towards the end-of-spring snowmelt whereas runoff during the warm period occurs frequently during small storms (Sillanpää, 2013). Hence, contrary to cold period concentrations, the dilution effect of the duration of the event was observed for warm period EMCs even though EMLs increased.

Additionally, pollutant build-up and wash-off are influenced by seasonal differences in runoff patterns: during the warm period, pollutant build-up during dry weather is washed off during the following rain event but, during the cold period, pollutant storage within the catchment can build up over time until the onset of spring snowmelt (Oberts, 1994; Marsalek et al., 2000a; Westerlund and Viklander, 2006). Together, these temporal differences in the accumulation of runoff and pollutants explain why

Table 6
Multiple linear regression equations for estimating runoff event pollutant concentrations (EMC) during cold (winter and spring) and warm (summer and autumn) periods for all study catchments combined. Equations follow the form: $\log_{10}(\text{EML}) = \text{Constant} + \Sigma\, a_i \log_{10}(\text{predictor variable})$ where a = the first explanatory variable, b = the second explanatory variable, c = the third explanatory variable, etc. Land use (LU) dummy variables: 0 = low density residential (Low catchment), 1 = city centre (High and Intermediate catchment). TIA = total impervious area. See Table 3 for other abbreviation explanations.

EMC	Constant	Dur	Qmax	ADP	Int	LU	TIA	R^2	SEE	p
Cold period										
TSS	1.246	0.006 b				1.020 a		0.374	0.466	0.013
tot-N	3.071	0.005 a		−0.136 c	−0.300 a			0.256	0.396	0.036
tot-P	1.954	0.012 a						0.219	0.628	<0.001
TOC	0.344	0.031 a			−0.271 b			0.384	0.307	0.006
Zn	1.681	0.009 a				0.605 b		0.365	0.424	0.002
Cu	0.879	0.010 a				0.709 b		0.357	0.485	0.001
Al	3.235	0.010 a					0.730 b	0.312	0.519	0.002
Cr	0.552	0.010 a				0.675 b		0.275	0.540	0.010
Mn	1.452	0.010 a				0.679 b		0.318	0.513	0.003
Co	0.201	0.010 a				0.612 b		0.349	0.475	0.004
Ni	0.991	0.010 a						0.248	0.514	<0.001
Pb	1.507	0.009 c				2.937 b	−0.056 a	0.713	0.448	<0.001
	1.130			0.115 a		2.454 c	−0.045 b	0.646	0.500	<0.001
Warm period										
TSS	0.952	−0.350 b	1.192 a		−0.408 c			0.614	0.365	0.017
tot-N	2.861	−0.178 b		0.178 a				0.209	0.288	0.049
tot-P	1.718	0.332 a						0.187	0.313	0.001
TOC	-	-	-	-	-	-	-	-	-	-
Zn	2.031					0.259 a		0.099	0.360	0.013
Cu	1.905			0.078 a				0.080	0.422	0.028
Al	2.814	−0.228 c	0.648 a	0.178 b				0.552	0.358	0.024
Cr	0.527	0.300 b	0.608 a					0.540	0.355	0.003
Mn	1.276	−0.270 c	0.430 a	0.193 b				0.398	0.378	0.012
Co	−0.247	−0.253 c	0.517 a	0.190 b				0.492	0.349	0.011
Ni	0.204		0.409 a	0.172 b				0.254	0.417	0.034
Pb	−0.052	−0.308 b	0.730 a	0.192 c				0.567	0.402	0.013

runoff duration had a positive (winter) or negative (summer) impact on EMCs and also explain why the antecedent dry period did not impact EMCs during snowmelt. In addition, the impact of antecedent dry periods during winter is likely diminished by winter-specific pollutant sources and pollutant transport related to street maintenance, snow removal, the heating of buildings and the use of anti-skid material and studded tyres (Amrhein et al., 1992; Hautala et al., 1995; Semádeni-Davies and Bengtsson, 1999; Bäckström et al., 2003).

The current study included several pollutants for which sources may vary, depending on the specific pollutant and land use type (House et al., 1993; ĎArcy et al., 2000; Moy et al., 2003) Yet, the main result is that irrespective of the pollutant, runoff quality is primarily influenced by same runoff generation processes, which depend on season (either cold or warm season) and whether loads or concentrations were of interest.

4.2. The importance of catchment type in explaining runoff quality

In addition to hydrological variables, catchment variables were important in explaining runoff quality variation in the current study since land use type and imperviousness increased the explanatory power (R^2 values) of the regression models by approximately 10%. Previous studies have also emphasized the fundamental role of land use in explaining urban water quality (Driver and Tasker, 1990; McLeod et al., 2006; Dougherty et al., 2006; Kayhanian et al., 2007; Helmreich et al., 2010; Liu et al., 2013). In our study catchments, pollutant loads increased as catchment imperviousness increased. Yet, particularly for loads, systematic similarities in the regression models considering catchment variables were not observed between different pollutants. In addition, runoff quality models in terms of the selected explanatory runoff variables were mostly similar between catchment types.

Land use type was an important variable in the cold period pollutant concentration (EMC) models, reflecting differences in pollutant sources between the city centre and residential areas. It should be noted, however, that the hydrological impact of land use/land-cover is primarily incorporated into the runoff variables used; hence, the inclusion of catchment variables to the regression models likely required substantial differences in the type or magnitude of pollution sources between the study catchments. For instance, Sillanpää and Koivusalo (2013) suggested that the amount of different urban snow types explained differences in pollutant concentrations between low-density and medium-density residential catchments during spring snowmelt. In previous studies, TIA and land use type have been important in, e.g. explaining concentrations and loads of TSS and tot-N (Melanen, 1981; Driver and Tasker, 1990) that was also detected in our study during the warm (tot-N load) and cold (TSS concentration and load) periods. In the current study, metal loads and concentrations responded more often to land use than to TIA, emphasizing the importance of land use type particularly in predicting metal content in runoff (Melanen, 1981; Driver and Tasker, 1990).

Obviously, certain urban land use types such as city centres can generate high runoff pollutant concentrations and large pollutant loads, warranting special attention when water quality protection is concerned. However, our results imply that, regardless of land use type, increased imperviousness will also lead to water quality degradation. Consequently, urban land use characteristics and activities that increase pollutant loads should be taken into consideration in sustainable water protection in urbanized areas.

4.3. Overall performance of SMLR models in explaining rainfall and snowmelt runoff quality

A number of studies have shown the usefulness of multiple linear regression in explaining urban runoff quality under warm conditions and rainfall-runoff (e.g. Brezonik and Stadelmann, 2002; Vaze and Chiew, 2003; McLeod et al., 2006; Kayhanian et al., 2007; McCarthy et al., 2007; Brodie and Dunn, 2010; Sillanpää and Koivusalo, 2015a), yet there are no such studies for snowmelt events. Our analysis showed for the first time that water quality regression models, using catchment and runoff characteristics, can predict runoff equally well in the winter- and summertime. This observation lends little support to our hypothesis that runoff quality is particularly difficult to explain using cold season runoff variables.

In general, runoff event variables used in the current study were successful in predicting urban runoff pollutant export in cold climates and explained 50–90% of the variation in pollutant loads. A similar level of model performance has previously been achieved with runoff event and catchment characteristics for rainfall-runoff events (LeBoutillier et al., 2000; Brezonik and Stadelmann, 2002; Dougherty et al., 2006; McLeod et al., 2006; Maniquiz et al., 2010; Sillanpää, 2013). However, predicting pollutant concentrations (nutrients, TSS, COD, BOD, DOC, Pb, Zn) appears to be less straightforward than predicting pollutant loads, since variables affecting concentrations are more numerous and site specific than for loads (Brodie and Dunn, 2010; Maniquiz et al., 2010; Sillanpää and Koivusalo, 2015b). This was also the case in our study in which the regression models explained only 30–60% of the variation in pollutant concentrations, suggesting that a more appropriate set of explanatory variables related to, e.g. pollutant sources are required. This is corroborated by Joannis et al. (2014) who concluded that even though mass loads between events can be estimated with flow rate, they are hard to predict within events where pollutant concentrations play a crucial role in affecting mass discharges. Hence, concentrations and loads appear to behave differently between and within events.

In the current study pollutant load SMLR model performance during the cold period did not, on average, differ between catchments of different levels of urbanization. It is likely that similar model performances between the study catchments reflect previous observations that differences in runoff generation between urban catchments are not as distinct during the cold period as during the warm period (Valtanen et al., 2014a; Sillanpää and Koivusalo, 2015b). Instead, during the warm period the R^2 values for the highly impervious city centre catchment were 30% lower than for the less urbanized catchments, particularly in the metal load models. Possible reasons for differences in warm period R^2 values are difficult to explain but may be related to land use activities (Driver and Tasker, 1990; McLeod et al., 2006; Kayhanian et al., 2007; Helmreich et al., 2010), in addition to differences in the runoff response to summer storms due to catchment characteristics (Valtanen et al., 2014a). In the present study, the catchments differed from each other particularly in traffic quantities, population densities and in the type of buildings (detached housing or blocks of flats) (see Valtanen et al., 2014b).

5. Conclusions

The main objective of this study was to examine seasonal relationships between runoff event variables, catchment characteristics and runoff quality to fill gaps in catchment-based cold climate research on urban runoff pollutant transport. We provide hitherto lacking knowledge on the mechanisms and key runoff/-catchment characteristics that control pollutant transport during snowmelt and rainfall seasons. Previous studies carried out in cold climates have not modelled runoff quality based on empirical measurements, hence, the mechanisms controlling runoff quality during snowmelt and rainfall periods have remained obscure.

Our study revealed that the mechanisms that control runoff quality differ between pollutant loads (EML) and concentrations (EMC), and that the behaviour of these two variables are not necessarily linked to each other. The study also showed that the controlling mechanisms are season dependent warranting the need for year-round stormwater monitoring and for the cold period to be studied on its own. The impact of seasonality became manifested, e.g. as altered (whether being the first, second or third best explanatory variable) importance of explanatory runoff event variables. For example, runoff duration was largely responsible for regulating cold period loads, while peak flow was a powerful factor in explaining pollutant load built-up during the warm period. Also, the impact of runoff variables depended on season. For example, opposing (positive and negative) effects of runoff duration in explaining EMCs occurred between cold and warm seasons. These changes occurred due to differences in runoff generation patterns (runoff intensities, volumes, durations and snow accumulation) that vary and are seemingly different between cold and warm periods. Furthermore, imperviousness and/or land use type played an important role in affecting runoff quality. In particular, land use type affected cold period metal concentrations, while imperviousness controlled most of the pollutant loads during either warm or cold periods.

Our study provides evidence that regression models explaining pollutant loads using runoff event and catchment characteristics perform well for both warm and cold seasons. Yet, these models cannot depict variation in runoff pollutant concentrations as well as variation in loads during any of the seasons. Furthermore, a more accurate evaluation of the factors controlling pollutant concentrations in urban areas may require data on pollutant sources – traffic intensity being one of such sources (e.g. Petrucci et al., 2014).

Patterns affecting runoff pollution did not depend on land use type. However, based on land use type alone, city centres require special attention with regard to water quality protection because of high pollutant concentrations and loads. Additionally, an increase in imperviousness of any urbanized area results in the simultaneous increase in pollutant loads. However, the importance of individual summer storms, winter snowmelt or rain-on-snow events should always be evaluated together with long-term pollutant load generation.

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