A catchment-scale assessment of pollution potential of urban snow at two residential catchments in southern Finland

Une estimation à l'échelle du bassin hydrographique du potentiel de pollution de la neige dans un environnement urbain, sur deux bassins résidentiels du sud de la Finlande

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RÉSUMÉ

En dépit du rôle crucial de la neige dans le cycle hydrologique en climat froid, les études de contrôle de la qualité de la neige en milieu urbain manquent souvent de discussions concernant le rôle de la neige dans la gestion du ruissellement à l'échelle du bassin versant. Dans cette étude, des mesures de la qualité de la neige ont été effectuées simultanément dans deux bassins versants résidentiels à Espoo, en Finlande, avec des mesures continues du ruissellement. Les résultats concernant la qualité de la neige ont été extrapolés aux estimations de charges de masses de neige (CMN) de la zone à l'échelle du bassin versant. En se basant sur les résultats, l'urbanisation réduit les équivalents en eau de la neige (EEN) de la zone mais augmente l'accumulation de polluants dans la neige : les CMN dans un bassin versant résidentiel de densité moyenne étaient deux à quatre fois plus élevées qu'en zone résidentielle de faible densité. Les sources principales de polluants sont liées à la circulation routière et à l'entretien des routes, mais les excréments des animaux de compagnie peuvent également fortement augmenter les concentrations. La neige déblayée peut contenir 50% de la masse de polluants de la zone emmagasinée dans la neige en dépit de sa faible surface dans un bassin versant. L'exportation de polluants depuis un bassin versant ne peut pas être estimée en se basant uniquement sur les mesures portant sur la neige ; cependant, le suivi de la neige à l'échelle du bassin versant a fourni des informations précieuses sur le type de polluants dans la neige, la capacité de pollution et la distribution spatiale de la masse de polluants.

ABSTRACT

Despite the crucial role of snow in hydrological cycle in cold climate conditions, the monitoring studies of urban snow quality often lack discussions about the relevance of snow in the catchment-scale runoff management. In this study, measurements of snow quality were conducted at two residential catchments in Espoo, Finland, simultaneously with continuous runoff measurements. The results of the snow quality were extrapolated into catchment-scale estimates of areal snow mass loads (SML). Based on the results, urbanization reduces areal SWE but increases pollutant accumulation into snow: SMLs in a medium-density residential catchment were two- to four-fold in comparison to a low-density residential area. The main sources of pollutants are related to vehicular traffic and road maintenance, but also pet excrement can increase concentrations to a high level. Ploughed snow can contain 50% of the areal pollutant mass stored in snow despite its small surface area within a catchment. Pollutant export from a catchment cannot be estimated solely based on snow measurements; however, the catchment-scale approach to snow monitoring gave valuable information on the type of pollutants in snow, the pollution capacity and the spatial distribution of the pollutant mass.

KEYWORDS

Pollutant mass load, Snow management, SWE, Urban runoff, Urban snow

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1 INTRODUCTION

Research on urban snow appears scarce although the need for research has been recognized by many authors (e.g. Semádeni-Davies 1999, Matheussen 2004, Ho and Valeo 2005). In urban catchments, snow properties are affected e.g. by the redistribution of snow by ploughing and additional pollutant sources such as the sand and salt used for traffic safety (Semádeni-Davies, 1999; Matheussen, 2004; Ho and Valeo, 2005; Reinosdotter and Viklander, 2005). Ideally, snow provides temporary detention/retention storage for pollutants within an urban catchment; by developing management strategies for urban snow, we have the opportunity to decide where these pollutants end up after melting (Viklander, 1999). Oberts et al. (2000) argued that, due to the high pollutant loads released during the spring thaw, runoff pollution studies should include locally collected estimates for the input from snow melt to aid in the development of suitable management techniques in cold climates. However, the previous studies of urban snow quality (e.g. Hautala et al. 1995, Viklander 1997, 1999; Sansalone and Glenn 2002, Reinosdotter and Viklander, 2005; Reinosdotter 2007, Engelhard et al. 2007) do not usually include catchment runoff monitoring and are based on point observations without catchment-scale considerations. Therefore, this study aims to provide a stronger link between point and catchment-scale monitoring approaches to aid discussion about the management needs of urban snow.

The objectives of this study are a) to collect data series for urban snow properties and show how these properties are affected by suburban development, b) to evaluate the pollution capacity of urban snow by extrapolating monitoring results into broader catchment perspective, and c) to determine whether urban snow monitoring could be used as a surrogate for runoff monitoring in the estimation of pollutant export via runoff.

2 METHODS

2.1 Study catchments and monitoring methods

The snow study was conducted at two small urban catchments located within the city of Espoo, in southern Finland. Laaksolahti (LL) is a low-density residential area of mainly detached housing (0.31 km^2 with 20% of impervious surfaces) and Vallikallio (VK) is a medium-density residential area consisting mainly of blocks of flats (0.13 km^2 with 50% of impervious surfaces) (Figure 1). At LL, a large part of driveways and yards is still without asphalt paving and drainage is mainly organized using open ditches. Stormwater from rooftops is mainly conveyed to nearby lawns. At VK, traffic-related areas and nearly all yards have an asphalt coating. A subsurface storm sewer network covers the whole catchment area. Both the traffic areas and most of the rooftops are directly connected to the storm drainage system. Elevation from sea level ranges from 29 to 50 m in VK and 30 to 60 m in LL. Based on Kotola and Nurminen (2003), the traffic load at VK is 10,200 vehicles/day and at LL 1,440 vehicles/day. Both sand and road salt are used for traffic safety at both catchments during winter.

A snow survey was conducted during the winter and spring of 2006. Within the study catchments, a total of six snow courses consisting of three to six measurement points were identified. The locations of the snow courses are illustrated in Figure 1. The snow courses included measurement points for different types of urban snow: both *untouched snow* in yards and parks, and *disturbed snow*, i.e. ploughed and piled snow. Also, reference measurements of rural snow were conducted in a forested catchment in Siuntio, 25 km from the city of Espoo. The reference measurements represented both an open clearing and a mature forest dominated by Norway spruce (*Picea abies*).

During every field survey, point measurements of snow depth, density, and SWE were conducted using a measuring rod and snow scales from all snow courses. The density of 900 kg/m^3 for ice was used in the calculation of SWE when there was an ice layer at the bottom of snowpack. Visual observations of a snow covered area were carried out during each survey. Monitoring started as soon as the permanent snow cover was established, and field surveys were carried out fortnightly during the mid-winter months and at least weekly during the spring melt. The snow study included a total of 14 snow surveys on both catchments during the period from 4 January to 13 April.

Samples of snow quality were collected from select measurement points. The samples were taken as vertical profiles of the snow pack using a plastic shovel and stored in 10-litre plastic lidded buckets. The samples were transported to the university laboratory for melting (usually over a weekend at room temperature), where analyses were done within a couple of days. In addition to pH and electrical conductivity (EC), the samples were analysed for total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN), and chemical oxygen demand (COD_{Mn}). At LL, the snow quality observations focused on the spring melt period and fewer samples were taken in mid-winter. Samples of snow quality were collected during 13 and 7 snow surveys in VK and LL, respectively.

During the snow study, simultaneous runoff and water quality monitoring was conducted at the catchment outlets. The methods for flow and water quality monitoring were previously described e.g. in Metsäranta et al. (2005). Flow measurements had a two-minute temporal resolution. Both catchments were equipped with an automatic sampler with 24, 1,000 ml sample bottles (ISCO series). Runoff samples were drawn at irregular time intervals based on the accumulated runoff volume.

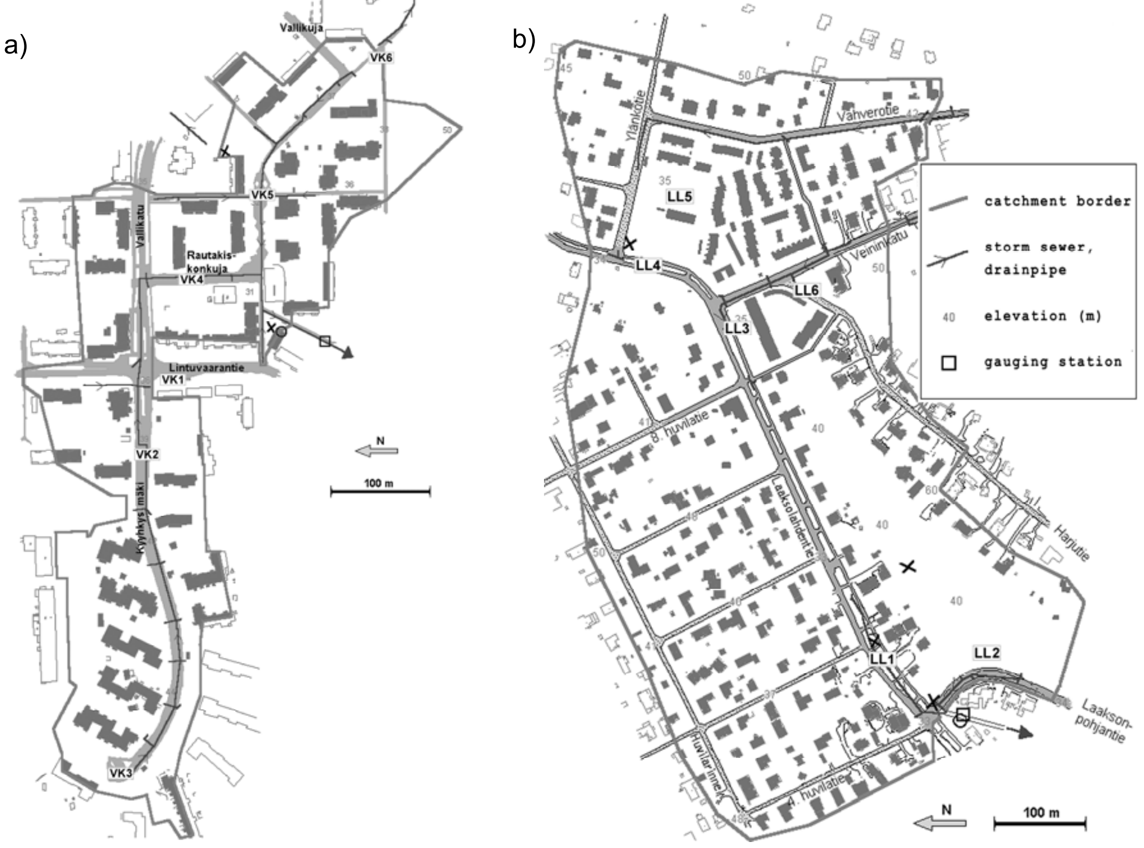

Figure 1. Illustrations of a) the medium-density catchment VK and b) the low-density catchment LL. Also the locations of snow courses are shown: the courses VK1-VK6 in VK and LL1-LL6 in LL.

2.2 Data processing

Temporal patterns and differences in the snow depth, density and SWE between snow types and catchments were investigated using the average values from each survey and their 95% confidence intervals based on the Student's t distribution. The highest survey averages were used to determine areal SWEs as area-weighted averages of different snow types at the onset of spring snow melt.

Snow quality was presented as pollutant concentrations, unit mass loads and areal snow mass loads. The unit mass load of a pollutant for a certain snow type was calculated using Equation 1:

$$ML_{snow} = C_{snow} \cdot SWE \tag{1}$$

where ML_{snow} is the mass load (mg/m^2), C_{snow} is the pollutant concentration in a melted snow sample (mg/l), and SWE is the snow water equivalent (mm). The areal snow mass load (SML), which describes the total amount of pollutants stored in snow within the catchment area (kg/km^2) was calculated using Equation 2:

$$SML = \frac{\Sigma\left(A_{snow} \cdot ML_{snow}\right)}{A} \tag{2}$$

where A_{snow} is the area of the snow type (ha), $\sum(A_{snow} \cdot ML_{snow})$ is the sum of the pollutant mass stored in different snow types, and A is either the total catchment area (ha) or A_{SCA}, which is determined as the snow covered area (ha). In the calculation for areal SWEs and SMLs, the values of untouched snow have been used for roof snow.

For runoff, pollutant loads (kg) were calculated using the *linear interpolation method* (e.g. Endreny et al. 2005). Thus, the missing concentration values for each flow observation were linearly interpolated between the observed concentrations. Pollutant export rates (kg/km^2) were determined as the ratios of the monthly pollutant loads to the total catchment area. The average pollutant concentrations for runoff (mg/l) were calculated as the ratios of the loads to the corresponding cumulative runoff volumes.

3 RESULTS AND DISCUSSION

3.1 Runoff generation within the study catchments

January 2006 was relatively warm and temperature rose above 0 ºC several times. In the middle of January, temperatures started to drop and mainly stayed below the freezing point until in the middle of March, snowmelt started with small amounts of daily runoff initiated by solar radiation and brief periods with temperatures above 0 ºC. The final snowmelt period commenced in late March and was accompanied by a two-week period of 60 mm of precipitation (about 45 % of the total precipitation for the period). During the snow study period (January-April), the ratio of total runoff to precipitation was 73% at VK and 77% at LL indicating only small differences in runoff generation between the catchments despite the rather different impervious coverage (50% and 20%). Previously it was estimated that during summer and autumn, about 52% and 27% of precipitation generated runoff at VK and LL, respectively, showing the distinct impact of impervious surfaces to the runoff response during the warm period. The higher runoff generation during the cold period is explained by the lowered evapotranspiration, but also indicated that runoff is generated from pervious surfaces, where most of the available snow is stored. Conclusions about the increase in runoff contributing area outside the impervious surfaces during snow melt are supported by several studies from Canada, Sweden, and Norway (Taylor, 1977; Westerström 1984, Thorolfsson and Brandt 1996, Ho and Valeo 2005). By the end of April, LL had generated about 9 mm more runoff than VK: this runoff excess can be explained by the transport of snow from VK and likely larger input from subsurface runoff in LL. Accurate information on the quantity of transported snow was not available while conducting the study. However, the city employees estimated that 100-200 truckloads of snow is transported from VK in a typical winter – this accounts for 3…7 mm of available water for snowmelt. In LL, less snow is transported outside the catchment area.

3.2 From point to areal SWEs

The main differences between the monitored snow types were the increased snow depths, densities and SWEs of ploughed snow in comparison to untouched urban snow and rural snow (Figure 2a-c). Also larger variability was observed in the properties of disturbed urban snow than in untouched snow. These results agree with the findings of the previous studies about the snow properties (Buttle and Xu, 1988; Semádeni-Davies, 1999; Matheussen, 2004; Ho and Valeo, 2005). However, only SWE had distinctively different maximums for the different urban snow types in both study catchments based on the 95% confidence intervals of the three studied snow properties in Figure 2c. The density of snow at the onset of spring snow melt did not indicate pronounced differences between the snow types although urban disturbed snow had the highest average values; urban snow types had overlapping confidence intervals and the average values for rural snow reached the confidence limits of the disturbed urban snow. Previously, Semádeni-Davies (1999b) concluded that density of snow increases with increasing land use intensity; this cannot be confirmed in light of the point snow observations for this study because the physical properties of the urban snow types were similar at both urban study catchments.

The areal SWEs at the beginning of the final spring snow melt were determined using the maximum SWEs in Figure 2c and surface areas for each snow type as untouched snow, disturbed snow, and snow-free areas in Table 1. Untouched or nearly untouched snow covered the largest area of all snow types. The second largest group comprised the surfaces with reduced snow cover, such as streets and parking lots. Ploughed snow comprised only 1.4% and 0.9% of the total catchment area at VK and LL, respectively. If only the snow covered area was considered, both study catchments had equal areal SWEs (~77…78 mm). Nevertheless, if the total catchment areas are considered, the areal SWEs were affected by the different amounts of snow-free areas, resulting in a lower areal SWE at VK than at LL (Figure 2d). This result is consistent with Matheussen (2004), who found out that the areal SWEs of the urbanized parts were lower than in park areas in a study catchment in Trondheim, Norway.

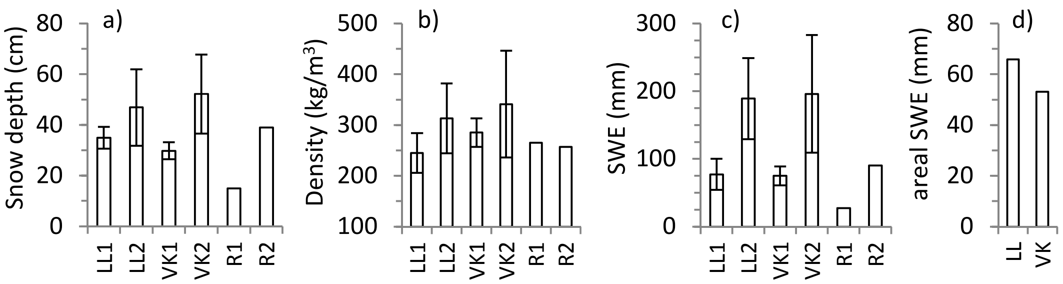

Figure 2. The maximum snow depths (a), densities (b), and the SWEs (c) as survey averages from point measurements (3-8 measurements per snow type) and their 95% confidence limits based on the Student's t distribution. Density values represent the situation at the end of March. Areal SWEs (d) calculated from the season maximums are shown for the urban study catchments. LL1/LL2 = untouched/disturbed snow in LL, VK1/VK2 = untouched/disturbed snow in VK, R1 = rural forest snow, R2 = rural clearing.

Table 1. Snow types and their surface areas in the study catchments (modified from Samposalo (2007)).

Snow type	**Example**	**VK**		**LL**	
		Area (ha)	**Area (%)**	**Area (ha)**	**Area (%)**
untouched snow	snow in forest, yard, park	6.3	48.2	21.4	69.1
untouched snow	snow on roofs	2.5	19.2	4.6	14.7
snow-free	street, parking lot	4.1	31.2	4.8	15.3
disturbed snow with little contamination	ploughed snow along a walkway	0.1	0.8	0.2	0.5
disturbed snow, significant contamination	ploughed snow along a street with vehicular traffic	0.1	0.6	0.1	0.4
	In total	*13.0*	*100.0*	*31.0*	*100.0*

In urban snow studies, the impact of urbanization has often been discussed from the perspective of point snow properties and the spatial redistribution of snow. For instance, Semádeni-Davies (1999) concluded that the proportions of both snow covered area and undisturbed snow decrease as the land use intensity increases. Buttle (1990), who investigated snow properties at an urbanizing catchment over a period of 14 years in Ontario, Canada, reported that the redistribution of snow by urban activities became more pronounced as the catchment developed. Based on the results of the current study, the most pronounced catchment-scale impact of urbanization on the studied snow properties is a lower areal SWE owing to larger snow-free areas despite the high point SWEs of disturbed snow. The larger snow-free areas are the result of winter maintenance, such as ploughing and de-icing, the snowdrift from rooftops, and the rapid snowmelt from heat-absorbing impervious surfaces and snow deposits with lower albedos (Oberts 1994, Bengtsson and Semádeni-Davies 2000, Matheussen 2004). In point scale, the changes caused by urbanization to snow properties are related to the winter maintenance practices and not directly to land use intensity. Under more snowy weather conditions, and in areas with less free space for snow storage, disturbed snow could have a stronger impact on the areal SWE.

3.3 Differences in point snow concentrations and unit mass loads

After a visual inspection of snow concentrations and their time series, the measurement points were classified into three snow groups of similar concentrations: 1) *street with traffic*, 2) *street without traffic*, and 3) *untouched snow*. Groups 1 and 2 consisted of disturbed snow: disturbed snow with a direct connection to vehicular traffic (group 1), or ploughed snow along walkways without a close connection to vehicular traffic (group 2). The average concentrations and unit mass loads for each snow type are illustrated in Figure 3 as an average value of all surveys and their 95% confidence intervals. Based on the confidence intervals, disturbed snow (groups 1 and 2) always had notably higher variability in concentrations and mass loads than untouched snow. All of the studied pollutants, except TN at the medium-density catchment VK, had the highest mean concentrations and unit mass loads for group 1, the second highest for group 2 and the lowest for group 3 (Figure 3). Hence, the results of this study agree with the previous studies of urban snow quality, that vehicular traffic and winter maintenance activities are a major source of pollution to urban snow (Hautala et al. 1995, Viklander 1997, Sansalone and Glenn 2002, Reinosdotter 2007, Engelhard et al. 2007). The maintenance practices, the choice between the use of sand and salt in slipperiness control in particular, have a considerable effect on snow quality (Reinosdotter and Viklander 2005). The use of road salt for deicing can be seen as higher conductivity for group 1 snow in Figure 3e. At LL, the mean conductivity of roadside snow was more than double the conductivity of roadside snow at VK. This can likely be explained by the location of sampling points rather than by different routines in the usage of de-icing salt – at LL, measurement points were located in the actual snow pile along vehicular streets, whereas at VK they were located along elevated walkways attached to the main roads. Road salt is mainly used for the safety of vehicular traffic, thus conductivity in group 2 remained closer to untouched snow (group 3) than group 1. The location of the measurement points in group 1 also explains the higher TSS concentrations at LL compared with VK (Figure 3d). Viklander (1999) also observed that the location of the snowpack influenced the quality of snow: higher TSS concentrations in ploughed snow were observed in a residential area compared with a central area. In the centre, snow was ploughed onto a downward-sloping bank away from the street, but in the residential area snow stayed on the side of the street until it melted or was transported away.

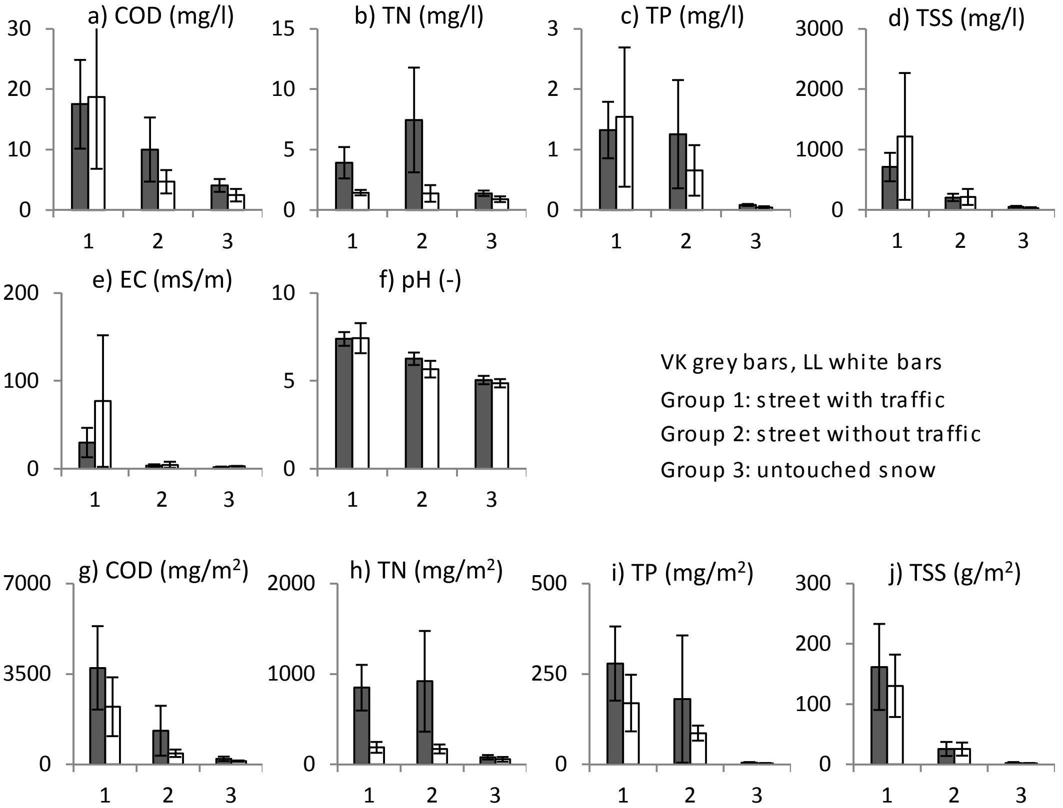

Figure 3. The arithmetic means of pollutant concentrations (a)-(d), conductivity (e), pH (f), and unit mass loads (g)-(j) in the three groups of urban snow based on the survey means. The 95% confidence intervals shown as error bars. Number of surveys means for different snow types: 11-13 in VK and 5-7 in LL.

In contrast to other pollutants, group 2 had the highest TN concentrations and mass loads at VK (Figures 3b and 3h). The sampling points at VK were located along pedestrian walkways in park and forest areas, where pet excrement was a major contributor to the high nitrogen levels. At VK, high TP concentrations were also observed for walkway snow, which is illustrated as larger confidence intervals for group 2 snow than for group 1 in Figure 3c. Unfortunately, reference values from the literature for similar snow type and TN concentrations were not found. The focus of previous urban snow studies on traffic areas and pollutants other than nitrogen might explain why these aspects of urban snow pollution have not been emphasized in previous studies.

Despite the different study locations, the concentrations of untouched snow (Figure 3) had a similar pH, electrical conductivity and TSS and TP concentrations as the untouched snow in the residential areas in Sundsvall and Luleå in Sweden (Viklander 1999, Reinosdotter and Viklander 2005, Reinosdotter and Viklander 2006). Reinosdotter and Viklander (2005) concluded that higher pollutant concentrations in untouched snow in city centres were influenced by the higher content of airborne pollutants. Also, the differences between the concentrations of untouched snow in the study catchments in Espoo are explained by the level of airborne pollution, which is likely higher at VK because of the higher traffic loads. The impact of atmospheric loading from longer distances was not evaluated in the present study. In the light of the results, urbanization affects the most the properties of ploughed snow exposed to anthropogenic activities. The quality of untouched snow appears to be mainly affected by the atmospheric deposition from both near and distant sources, which is also affected by the duration of the snow accumulation period.

Although the differences between the study catchments were not always consistent in terms of their pollutant concentrations, average unit mass loads for each snow type were usually higher at the medium-density catchment VK than at the low-density catchment LL (Figure 3g-j). In literature, fewer references to unit mass loads can be found than for pollutant concentrations in urban snow. Unit loads of snow were previously reported by Viklander (1997, 1999), Reinosdotter and Viklander (2005) and Reinosdotter (2007): when the mass unit loads were investigated, they increased the differences between the different study sites. Unit loads give more insight into snow pollution, because they take into consideration both the volume of water and the concentrations. In the current study, mass loads clarified the differences between the study catchments and snow types. Therefore, the investigation of mass loads instead of only concentrations is greatly recommended based on the study results.

3.4 Catchment-scale analysis of pollution capacity of urban snow

3.4.1 Areal pollutant mass loads

In Table 2, the estimates of areal pollutant mass loads (SML) are shown. A range of values is given, because two ways of choosing a representative unit mass load for each snow type was used. In any case, the estimates were based on the highest survey averages for each pollutant and represented the maximum mass storage capacity of a pollutant before the initiation of spring snowmelt. SMLs were estimated for both the total catchment area and the snow covered area. At the medium-density catchment VK, SMLs were about four-fold (COD), two-fold (TN), and three-fold (TP and TSS) compared with the low-density catchment LL because of the larger pollutant mass of ploughed snow even despite the larger snow-free area. The contributions of each snow type to areal pollutant mass loads (SML) depended on the unit mass loads, i.e. concentrations and SWE, and the surface areas of each snow type (Table 1).

Based on Figure 4, untouched snow comprised the largest percentage of SML owing to its large surface area at both study catchments. Still, nearly half of the pollutant mass load of TSS and TP was stored in ploughed snow in VK, and nearly 30% in LL despite its small proportion of the snow covered area (2% in VK, 1% in LL). Although not affected by vehicular traffic, group 2 snow contributed more TN than group 1 at both catchments. At VK, this was caused by high TN concentrations along pedestrian walkways. At LL, the obvious reason was the larger surface area of snow in group 2 compared with group 1.

Table 2. Areal pollutant mass loads (SML) based on the snow covered area and the total catchment area.

	Computational area	**COD (kg/km^2)**	**TN (kg/km^2)**	**TP (kg/km^2)**	**TSS (kg/km^2)**
LL	snow covered area	136…149	86.8…86.9	6.4…6.6	3176…3406
	total catchment area	115…126	73.4…73.5	5.4…5.6	2688…2883
VK	snow covered area	615…631	186…213	19.2…19.7	9834…10018
	total catchment area	423…434	128…147	13.2…13.6	6762…6889

3.4.2 Comparison of areal pollutant mass loads to pollutant export via runoff

Both higher pollutant export rates and pollutant concentrations were observed in the medium-density catchment VK in comparison to the low-density catchment LL based on runoff monitoring (Table 3). This difference can be, by part, explained by the larger SML in VK, because runoff volumes were similar at both sites (Chapter 3.1). Due to earlier snowmelt, 15-23% of the pollutant export at VK washed off already in March, whereas nearly all (94-96%) of the pollutant load was exported in April at LL (Table 3). The difference observed in runoff loads and concentrations between the catchments were smaller than those observed in SMLs.

The SMLs presented in Table 2 are smaller than the pollutant export reported for runoff in Table 3 at both catchments: only the TSS and TP SMLs at the medium-density catchment VK approximate the observed pollutant export rates in runoff. This finding is somewhat surprising, because it has previously been reported that snowmelt transports only a part of the pollutants from the snow pack (Oberts, 1994; Viklander, 1996; Reinosdotter, 2007), and thus, it was expected that the SMLs would exceed the pollutant export reported in Table 3. Consequently, it is not possible to evaluate the extent to which pollutants stored in snow are transported away from the catchments based on the study results. In light of the results, other sources in addition to snowpack contribute to the runoff pollutant loads. During winter, the bulk of solids and other pollutants are deposited on impervious surfaces outside the snow storage. Westerlund (2007) noted that high TSS loads in snowmelt runoff from a road area in Luleå, Sweden, were affected by the amount of available material for washoff, both in the snowpack and on the road surface in addition to the overland flow intensity. In April, for instance, it rained ~34 mm at the study catchments in Espoo, thus, rain-on-snow and rain-after-snow transported pollutants from both pervious and impervious surfaces.

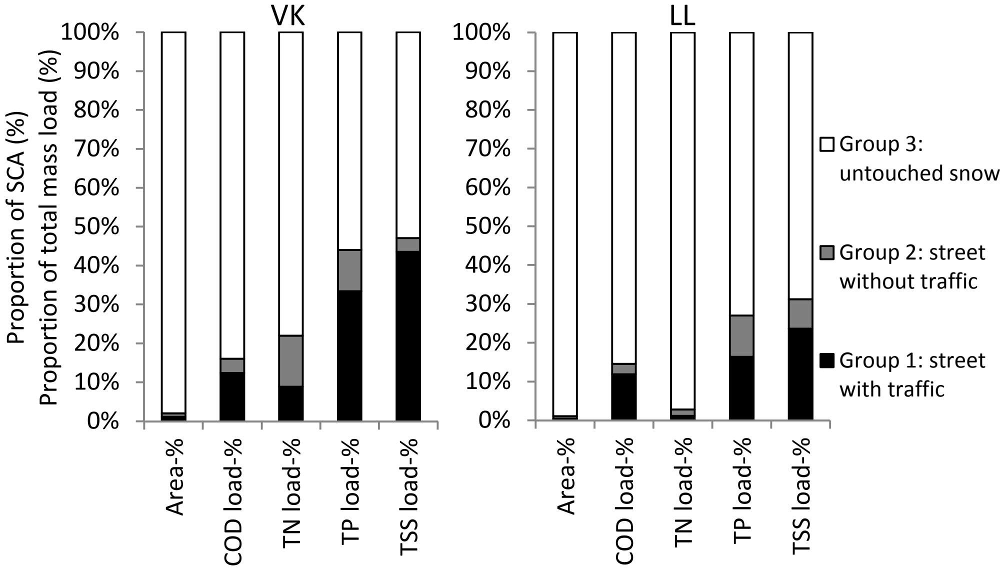

Figure 4. Contribution of different snow types to the areal pollutant mass loads of snow.

Table 3. Pollutant export from the study catchments during March-April 2006 (based on 54 and 56 runoff quality samples in LL and VK, respectively) and the average flow-weighted concentrations for runoff at the catchment outlets during the spring 2006.

	Pollutant export (kg/km^2)			
	COD	**TN**	**TP**	**TSS**
March-April 2006				
LL	489	149	9.9	5180
VK	639	271	14	6790
April 2006				
LL	465	140	9.4	4970
VK	544	225	11.8	5240

	Concentration (mg/l), Spring 2006			
	COD	**TN**	**TP**	**TSS**
LL	5.4	1.6	0.100	52
VK	9.9	3.3	0.230	97

The pollutant concentrations in runoff (Table 3) are clearly higher than those for untouched snow but usually notably lower than the concentrations for ploughed snow (Figure 3), indicating that ploughed snow, despite its small areal extent, increases runoff concentrations. Evidently, snowmelt from polluted snow near impervious surfaces is easily transported into the drainage system. Runoff concentrations are diluted by the melt of untouched snow and precipitation during the snow melt period, but both snow melt and rainfall-runoff also wash away deposited particles and other pollutants from the soil and road surfaces, which add to pollutant mass released from snow. In the low-density LL catchment, the larger amount of untouched snow diluted the pollutant concentrations in runoff, which in Table 3 are lower than those for VK. Furthermore, in the low-density catchment, lower traffic loads and smaller area of impervious surfaces probably provide less storage for additional pollutants outside the snow storage.

3.4.3 Comparisons of the results to stormwater quality criteria and snow management strategies

To demonstrate the degree of pollution of the studied snow types, average snow concentrations were compared with the stormwater quality criteria by Stockholm Vatten (2001). According to the Stockholm Vatten (2001), low pollutant concentrations do not require treatment whereas the exceedances of moderate and high concentration thresholds usually imply a need for treatment. Obviously, it should be kept in mind that the criteria are developed for runoff concentrations and not for snow. The average TSS and TP concentrations of ploughed snow in both catchments exceeded the threshold of high concentrations. For TN, only the average concentration of the group 2 snow in VK reached the high concentration class and the other snow types had either moderate or low concentrations. Especially ploughed snow contained high concentrations indicating treatment need, and high TSS concentrations also indicate the presence of other particle-bound pollutants, such as metals and PAHs. The high concentrations were also observed in runoff: in Table 3, the average concentrations for TN, TP, and TSS imply a need for treatment especially in VK according to the concentration thresholds of Stockholm Vatten (2001).

Already in the 1990s, the Swedish Environmental Protection Board recommended separating snow into heavily or less polluted snow to mitigate the adverse effects from winter maintenance and snowmelt (Viklander 1997), but it has been difficult to implement the strategy because of difficulties in identifying appropriate snow quality criteria (Reinosdotter, 2007). Reinosdotter and Viklander (2006) proposed management strategies for urban snow based on the expected level of pollution according to traffic loads. According to their treatment recommendations, the ploughed roadside snow at LL would not require treatment and snow should be stored on land at VK. On the grounds of the catchment-scale analysis in Chapter 3.4.1, the treatment of ploughed snow could have significant impact especially on TP and TSS loads from snow, which covered 1/3 to 1/2 of the total pollutant mass stored in snow. This approach could be especially effective at VK, where the treatment of snow from relatively small surface area could result in a large reduction in accumulated pollutants. In this way, the results support the recommendation of Reinosdotter and Viklander (2006). However, a catchment-scale assessment is recommended over simple evaluations based only on the roadside ploughed snow. For example, the increased runoff during snow melt in the low-density catchment LL resulted in comparable TSS export rates to the medium-density catchment VK in Table 3 despite the lower runoff concentrations and smaller SMLs.

4 CONCLUSION

Urbanization results in higher spatial and temporal variability in both physical and chemical snow properties (the objective a). The differences in the point snow properties are the most pronounced in SWEs and unit mass loads of ploughed snow. The properties of untouched urban snow can remain similar to rural snow. The point properties of snow are affected by several factors, which are not directly related to the catchment imperviousness: traffic load, type of snow (untouched/ploughed), type of street (street with/without vehicular traffic), the distance from the traffic (snow pile located directly along the vehicular road or behind an elevated sidewalk), other anthropogenic activities (road maintenance, pets), and atmospheric deposition. Imperviousness, however, has a pronounced impact on areal snow properties owing to the redistribution of urban snow. In catchment-scale, urbanization decreases areal SWEs but increases pollutant accumulation into snow.

The catchment approach utilized in the study provides valuable insight into to the evaluation of snow pollution and snow management (the objective b). The catchment with the larger extent of impervious surfaces had a greater mass of pollutants stored in snow and, hence, larger pollutant export in runoff. However, during the cold period, enhanced runoff generation increases pollutant export also in urban catchments with lower land use intensity. Ploughed snow increases the pollutant concentrations in runoff owing to its high concentrations and mass loads, and because of the close location of ploughed snow to impervious surfaces and drainage system. The pollutant concentrations of ploughed snow are high in comparison to stormwater quality criteria.

The treatment of ploughed snow could have significant impact especially on TP and TSS loads due to their abundance in snow (the objective b). The treatment of snow probably will not result as large reduction in runoff loads as could be estimated based on the areal snow storage, because the bulk of pollutants also originate outside snow storage, from both impervious and pervious surfaces. However, comparisons between snow and runoff measurements should be interpreted with caution, because uncertainties are related to the spatial and temporal representativeness of snow observations owing to the large heterogeneity observed at urban sites.

Although monitoring of snow requires less intensive monitoring than runoff, pollutant export cannot be estimated solely based on snow measurements (the objective c). Nonetheless, the snow measurements give valuable information on the type of pollutants in snow, the pollution capacity and the spatial distribution of snow and pollutant mass.

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