Seasonal variation in pollutant concentrations and particle size distribution in urban stormwater - design implications for BMPs

Variation saisonnière des concentrations de polluants et de la distribution de la taille des particules des eaux de ruissellement en milieu urbain - implications sur le dimensionnement des ouvrages de gestion alternative

Carlos Monrabal-Martinez [1*], Tone M. Muthanna[1], Thomas Meyn[1]

Department of Hydraulic and Environmental Engineering. Norwegian University of Science and Technology (NTNU)
*Corresponding author: carlos.monrabal@ntnu.no

RÉSUMÉ

Connaitre la granulométrie et la concentration des métaux dans l'analyse fractionnée des sédiments est essentielle au bon dimensionnement des procédés de traitement. Les variations saisonnières et les climats froids sont sources de variabilité lors de la caractérisation des eaux de ruissellement, ce qui a des conséquences importantes sur les critères de dimensionnement. Le but de cette étude est de caractériser les variations saisonnières dans la granulométrie et les concentrations de polluant pour la ville de Trondheim, ainsi que leurs effets potentiel sur le dimensionnement des systèmes de traitement des eaux de ruissellement, comme les bassins de décantation et les fossés, au regard de l'efficacité du traitement biochimique et de l'engorgement de ces systèmes. L'analyse des résidus solides des eaux de ruissellement urbain, collectés pendant la période hivernale, a montré des taux de concentration 8 fois supérieur aux concentrations relevées pendant la saison humide. La concentration de métaux toxiques excède les critères internationaux fixés sur la qualité de l'eau, et sont en accord avec les études antérieures conduites pour des climats similaires. Pour les pays à climat froid, un bassin de pré-décantation ou des bandes végétalisées sont des solutions pour piéger la majorité de cette quantité plus élevée de résidus lors de la combinaison d'évènements pluvieux et de fonte sur un tapis neigeux.

ABSTRACT

Understanding the particle size distribution and metal distribution within the particle size fractions are essential to design the correct treatment alternatives. Seasonal variation and cold climate creates additional variance in storm water characterization that has an important design implication. The objective of the study was to investigate the seasonal variation in pollutant concentrations and particle size distribution in the city of Trondheim, and how this might affect design parameters of storm water treatment systems, like bio retention areas and swales with respect to treatment efficiency and clogging problems. Total solids found in urban runoff during the wintertime showed around 8 times higher concentrations than in rainfall season. Toxic metal concentrations exceeded international water quality criteria, and were in agreement with other studies in similar climate. In cold climate countries, a pre-sedimentation basin or filter strip could be an option in order to capture the bulk of the considerably higher particle concentration of melting and rain on snow events.

KEYWORDS

COD, cold climate, heavy metals, particle size distribution, urban runoff

1 GOAL, SCOPE AND BACKGROUND

Pollution found in urban runoff represents an active hazard to aquatic environment if no treatment is done before reaching the receiving water body. Atmospheric deposition, chemical, and mineralogical characteristics of the surrounding soils, and traffic related activities are the principal sources of pollution on urban road surfaces as well as playing an important role in the fractionation of the contaminants (Gunawardana et al. 2011). Helmreich et al. (2010) monitored a high traffic density road in Munich (oceanic climate in the Köppen-Geiger classification) for 2 years and found that the fractionation of heavy metals did not vary significantly from season to season, however dissolved fractions above 90% were observed during rain events. Several studies have characterized particles size distribution, among others (Kayhanian et al. 2007; Sansalone et al. 1998). Regarding studies in cities where snow remains typically for 4-6 month in winter, Westerlund & Viklander (2006) showed that runoff events in Luleå (subarctic climate in the Köppen-Geiger classification) during the melt season had around 8 times higher concentration of metals compared with the rain period for all particle size fractions studied. Kayhanian et al. (2012) concluded that correlation between water quality parameters and mathematical relationships should only apply on local measurements because of large variations among data sets between continents and within each continent. Knowing that characteristics of the runoff may change from city to city caused by differences in traffic patterns, climate, land-use, maintenance, etc. local data is needed for designing Best management practices (BMPs) according to expected performances.

The goals of this study are to characterize the runoff in the city of Trondheim (oceanic climate in the Köppen-Geiger classification) and to understand the seasonal fluctuations and across traffic load gradients with the aim to improve design in cold climates. Understanding correlations between water quality parameters can be a useful tool for sample sets with reduced number of parameters available and/or limited analytical costs. The data set can provide crucial information for both predicting performances of local BMPs and sizing new systems. In addition, this study will contribute to enlarge the existing global information concerning runoff quality and, therefore help to interpret the impact of factors such as climate, traffic density, and land use.

2 MATERIAL AND METHODS

The sampling roads for the study were identified based on the annual traffic loads and possibility of retrofitting BMPs along the roadside. The different traffic intensities were chosen in order to study the effect of traffic density on the runoff quality.

In order to analyze the actual runoff and avoid mixing with previously deposited runoff or even with other sources of pollution such as wastewater, it was decided to grab the storm water right before entering a road manhole inlet. Runoff samples are being taken manually at 3 points in Trondheim with different traffic density patterns. Sampling point 1 corresponds with an arterial road (Jonsvannsveg, Annual Average Daily Traffic (AADT) = 10500 vehicles), sampling point 2 corresponds with one of the streets with more traffic in Trondheim (Prinsens gate, AADT = 22140 vehicles), sampling point 3 takes place in a residential street in downtown (Erling skakkes gate, AADT = 2900 vehicles).

Figure 1 Sampling point 1

Figure 2 Sampling point 2

Figure 3 Sampling point 3

The sampling points are all located maximum 500 meter from a rain gauge (tipping bucket, 0.2 mm resolution). Hyetographs provided by the rain gauges was used to identify at which moment within the event the samples were taken. The antecedent dry weather period (ADWP) was also obtained from the rainfall records of the closest rain gauge.

The characterization of the runoff included the following analysis; pH, conductivity, salinity, turbidity, total solids (TS), total suspended solids (TSS), total dissolved solids (TDS), and particle size parameters such as D_{50}, D_{10} and D_{90}. Toxic metals (Lead, Nickle, Copper, and Zinc) were analyzed in their dissolved and total form. Particle size variables are obtained with a Beckman Coulter LS230 Laser Diffraction Particle Size Analyzer. Determination of suspended solids was carried out with the method of filtration through glass fiber filters (average nominal pore of 1.2 micrometers) according to the Norwegian Standard NS-EN 872. Conductivity and salinity was measured with a conductivity meter LF537 and a probe WTW Tetracon 96. Values was corrected for a temperature of 20 degrees. Turbidity was measured with a turbidimeter HACH 2100N. Before the analysis of total metal concentrations, particles were digested with an acid mixture of 2 ml of HNO_3 and 1 ml of H_2O_2, and processed in a microwave oven for 50 min at a temperature of 160 °C. The solutions were analyzed in a dilution of 1:50 by ICP-MS (Agilent 7500ce). Additionally, samples were filtered through 5 µm filters and analyzed for the target metals at various dilutions by ICP-MS (Agilent 7500ce). .

Samples at site nr.1 were tended from the beginning of the runoff event and throughout different time intervals. The intervals were stretched as the runoff event progressed in order to collect a larger number of points in the early part of the runoff event. For the events where it was not possible to collect the first flush, a single composite sample at a known time was collected. In site nr.2 and nr.3 simply composite samples at known time were collected. In the wintertime, samples from rain on snow events as well as snow melting were collected. Collection of samples was performed with 50 ml disposable syringes. Samples were brought to the lab immediately after collecting and refrigerated until analysis.

Most parameters showed a non-normal distribution due to the large variations as well as presence of outliers. Therefore, the non-parametric Spearmen rank-order correlation was used to study relationships between constituents. Box-and-Whisker plots were carried out as visuals to reflect properties of the samples, to detect outliers and seasonal comparisons.

3 PRELIMINARY RESULTS

Table 1 shows the events sampled. Time column refers to the time, from the beginning of the event, at which the sample was collected. Due to analytical procedures, different subsamples were used to obtain TS, TDS and TSS, therefore the sum of TDS and TSS is not precisely the registered TS value. The D_{50}, D_{10}, D_{90} values are the mean of two subsamples with three replications

The first flush event sampled at site nr.1 the 20th of October of 2015 was covered during 90 minutes. Values of TS, TSS, and turbidity followed a typical trend for such events although the highest concentrations came after 10 minutes from the beginning of the runoff. This represents rather a mid-flush pattern that might be influenced by the hyetograph and corresponding hydrograph. This could have shifted the pollutograph slightly behind the expected point. Both TDS and toxic metals below 5 µm showed similar values along the event. A mid flush pattern was also detected in the rain on snow event the 2nd of December of 2015 for parameters such TS, TDS, salinity, and conductivity. The rain on snow event on the 13th of March of 2016 was sampled throughout approx. 9 h, at different intervals to observe the evolution over longer periods. TS became around 7 times lower after 6 hours of continuous precipitation and it seemed to stabilize from that point on. TDS and TSS showed similar behavior.

Table 1.Summary of parameters for all events.

Event	Sampling Point	Time	ADWP (days)	pH	Salinity	Cond. (µS/cm)	Turbidity (NTU)	COD (mg/l O_2)	Lead		Nickel		Cooper		Zinc		TS (mg/l)	TDS (mg/l)	TSS (mg/l)	D_{50} (µm)	D_{10} (µm)	D_{90} (µm)
									Total (mg(l)	<5µm (µg/l)	Total (mg(l)	<5µm (µg/l)	Total (mg(l)	<5µm (µg/l)	Total (mg(l)	<5µm (µg/l)						
Rainfall 01.07.2015	1	+3h	2	7.48	0	135.1	1168	476		0.21		0.84		3.8		5.2	1313.9	104.5	1253.0	11.1	1.91	29.3
	3	+5h		5.44	0	233	94.3	2330	0.0029	1.84	0.013	5.7	0.021	4.4	0.236	78	1652.6	1371.8	276.9	11.4	3.22	81
	2	+5h		7.19	0	150.6	722	361		<0.1		<0.6		8.7		6	1072.4	106.7	1033.3	14.4	1.79	35.8
Rainfall 05.08.2015	1	+10h	8	7.95	0	122.8	622.6	260		<0.1		1.4		8.5		10.1	465.85	97.6	373.17	8.41	1.21	22.3
	2	+10h		7.87	0	204	2644	566		0.27		2		22.4		15	1267.06	156.5	1038.82	8.92	0.911	24.9
	3	+10h		5.33	0.2	517	147.6	4440	0.0041	2.66	0.019	10.7	0.028	6.06	0.25	173	3987.06	3337.1	340.00	8.4	3.03	112
First flush 20.10.2015	1	+0min	12	7.64	0	227	668	418	0.0251	<0.1	0.095	4.8	0.193	20.5	0.77	23.1	664.7	178.4	513.6	9.75	1.52	30.2
		+5min		7.6	0	230	723	391		<0.1		5.3		17.7		13.2	665.0	174.2	528.1	8.76	1.33	25.2
		+10 min		7.86	0	200	1225	638		<0.1		4.6		15.6		17.4	1060.2	173.3	938.9	8.73	1.28	27.3
		+20 min		7.71	0	230	1173	749		<0.1		5.13		20.5		17.1	1158.8	185.1	967.8	9.14	1.4	32.5
		+30 min		8.1	0	169.3	1270	436		0.35		4.3		17.8		21.3	996.5	108.0	839.8	7.95	1.26	22.5
		+40 min		7.94	0	141.5	654	300		0.54		4.4		17.2		33.8	614.3	136.0	532.6	7.65	1.18	21.8
		+60 min		7.81	0	126.1	507	265	0.0185	0.3	0.079	3	0.118	13	0.399	13	503.6	101.1	406.9	9.15	1.35	135
		+90 min		7.76	0	125.1	593	281		0.32		3.4		14.7		24.6	546.5	111.9	486.9	9.51	1.34	223
Rainfall 05.08.2015	2		3	8.2	20.8	33600	3390	656		0.165		3.4		6.3		13.6	24973.1	24273.8	2473.8	5.79	0.83	19.2
Rain on snow 02.12.2015	1	+0min		8.35	6.2	11020	3780	593	0.0313	<0.1	0.152	1.29	0.207	3.4	0.781	7.7	8044.3	6383.6	1686.6	5.8	0.9	18.9
		+15min		8.32	6.9	12430	3078	774		<0.1		2.5		4.7		14.2	9340.8	7139.7	2130.1	6.5	0.9	20.1
		+20 min		8.35	6.7	11960	3780	899		<0.1		1.43		3.86		6.7	9671.8	6872.2	2669.4	6.7	1.0	21.3
		+25 min		8.37	6.2	11060	3264	827		<0.1		1.37		3.6		7.1	8227.3	6251.7	2315.0	6.2	0.9	20.6
		+30 min		8.39	5.4	9830	2277	712		<0.1		1.51		4.1		9.7	7422.0	5533.3	1814.7	6.3	0.9	20.6
		+40 min		8.47	4.4	8040	2385	691		0.17		0.993		2.9		6	6532.5	4510.8	2006.2	6.8	1.0	21.7

Event	Sampling Point	Time	ADWP (days)	pH	Salinity	Cond. (µS/cm)	Turbidity (NTU)	COD (mg/l O_2)	Lead		Nickel		Cooper		Zinc		TS (mg/l)	TDS (mg/l)	TSS (mg/l)	D_{50} (µm)	D_{10} (µm)	D_{90} (µm)
		+60 min		8.56	3	5600	4464	934	0.0536	0.21	0.279	0.81	0.355	2.7	1.26	5.4	6296.5	2973.6	3102.8	6.4	0.9	20.2
		+90 min		8.59	2	3930	2958	695		0.28		0.71		2.7		5.3	4072.5	2094.4	2336.1	7.1	1.0	22.2
		+120 min		8.59	1.8	3450	2544	662		0.27		<0.6		2.3		4.7	3943.2	1853.6	2042.9	7.1	1.0	22.2
Rain on snow	2			8.5	1.6	3170	5829	496		0.53		1.82		6.3		8.7	4788.0	1698.6	2909.9	4.7	0.7	18.2
02.12.2015	3			7.57	0.1	404	576	103		0.33		1.16		5.1		12	350			17.6	2.9	55.1
Snow Melting	2			8.15	1.5	2920	9250										26690.0	1686.4	23913.6	17.4	1.9	79.5
	3			7.69	9.1	15600	1570										11456.3	9429.0	1751.6	6.7	0.9	23.1
17.02.2016	1			7.75	23	36300	5740										29741.1	23200.0	5912.1	4.6	0.7	16.9
Rain on snow	1			7.21	5.2	9360	1162										6347.3	5504.1	942.9	3.9	0.7	15.5
	2			7.79	2.3	4380	3200										6734.4	2603.8	3915.4	5.3	0.8	21.8
22.02.2016	3			7.27	0.9	1794	1192										2074.2	950.0	1159.6	6.5	0.9	20.6
Snow melting	1			8.23	2.8	5270	3900										7015.9	2944.8	4255.2	5.7	0.8	21.6
	2			8.13	2	3850	610										3383.8	2271.2	694.9	5.2	0.9	16.5
08.03.2016	3			7.45	5.2	9360	1660										6757.6	5594.9	1174.6	4.0	0.6	11.0
		+30 min		8.07	6.3	11040	3340										10655.4	8171.0	3016.1	4.2	0.8	17.2
Rain on snow		+ 90 min		8.31	1.5	2930	4620										5405.9	1490.9	3750.0	4.4	0.7	17.0
13.03.2016	1	+ 4 h		8.49	0.6	1345	2520										2317.6	687.3	1796.8	4.5	0.8	16.6
		+ 6.5 h		8.29	0.8	1627	870										1695.3	771.0	734.8	5.0	0.8	19.4
		+ 8.5 h		8.41	0.6	1249	806										1221.4	625.7	630.0	4.9	0.8	22.1
Rain on snow	2			7.15	7.1	12470	946										8451.5	8295.1	601.6	3.5	0.6	9.0
13.03.2016	2			8.21	3.5	6350	3460										6246.4	3413.6	2748.5	3.6	0.7	12.8

pH values ranged from 5.3 to 8.6, with an average value of 7.85. Lowest pH values were detected in site nr.2 in summer and autumn seasons. Organic matter from the nearby park might acidify the runoff stream. The COD measured in site nr.3 was considerably higher than the other two sites. Salinity was detected from the end of November on. At this point, winter salt application had already started due to near freezing temperatures. Salinity values ranged from 0 to 23, with an average of 4.9. Highest values in site nr.1 were registered in samples close to the beginning of the runoff. Both site nr.2 and nr.3 registered equally high values.

In figure 4, the difference in conductivity and TS between rainfall season and winter and early spring is noteworthy. Presence of salts as well as settling and accumulation of particles on the roadside snow explain the increase in such variables, which in average are 10 times larger than in pre-freezing period. D_{50} and D_{10} had an average of 7.37 and 1.16 µm, respectively. For the same event, no significant differences between sites were detected particle size wise. Values below the mean were registered in rain on snow and melting events in practically all events. D_{90} ranged from 8.98 to 223 µm and appreciable discrepancies were registered among sites and events as the quartiles show. However, D_{90} was generally lower and with less variation in winter season.

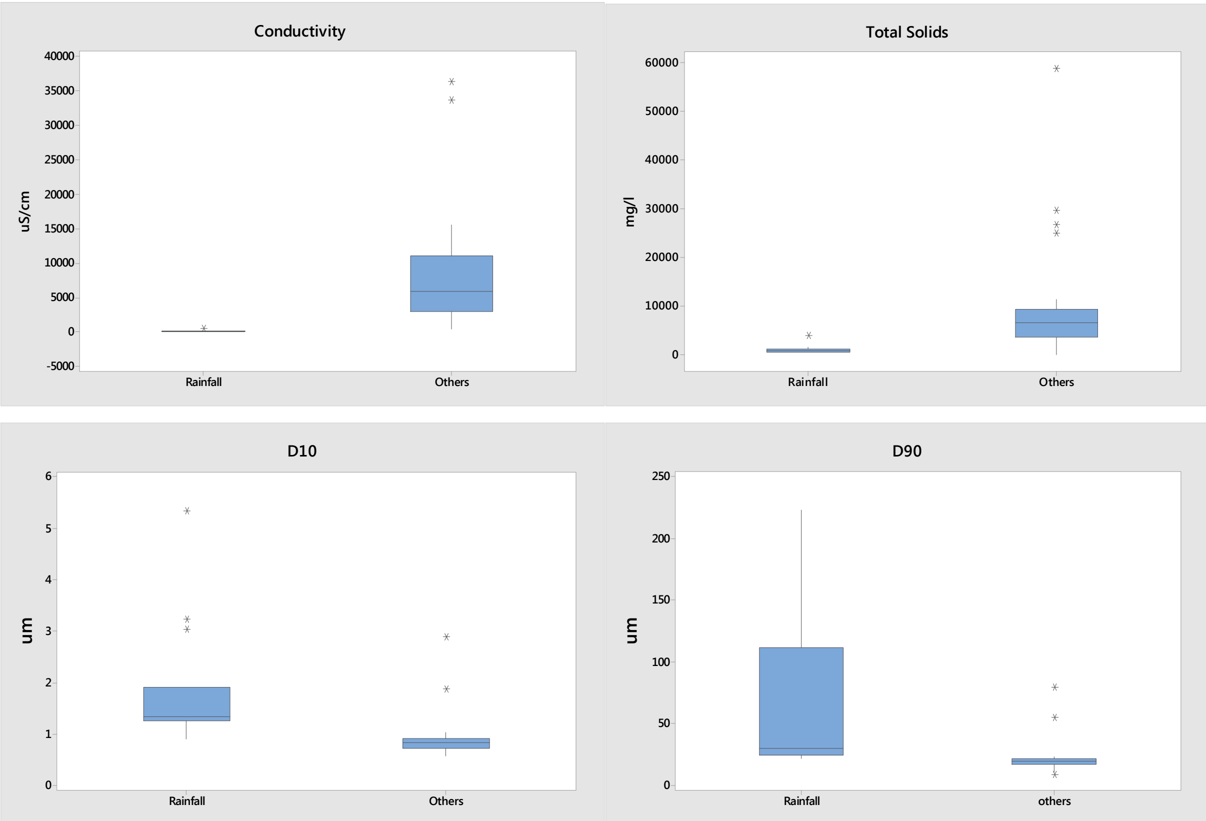

Figure 4. Box-Whisker plots for conductivity, TS, $D_{10,}$ and $D_{90.}$ Others refers to rain on snow together with snow melting events.

Special attention must be paid when designing BMP's in cold climate countries. In melting and rain on snow events, the amount of particles is considerable higher and the size of the particles found in the runoff approximately half. This fact will accelerate the clogging process of the upper layers leading to inoperative filters eventually. Therefore, a pre-retention basin or filter strip are required in order to capture the bulk of the suspended fraction. Length of the filter will influence the retention performance of particles, and a minimum of 10 meters is recommended in order to trap particles smaller than 25 µm (Backstrom 2002).

A strong correlation was found between TDS and COD (ρ =0.720) even though the variance was large for some sample points. In Table 2, conductivity and TS also showed a strong positive correlation (ρ =0.918). Toxic metals < 5 µm registered strong positive correlations with each other, because wear of tires and brake linings are coupled. On the other hand, Zn < 5 µm showed negative correlation with conductivity, TS, TDS, and TSS, which explains that other metals contributes to a bigger extent to these constituents. Conductivity, TS, TDS, and TSS showed also statistically significant correlations among each other.

Table 2. Spearman correlation coefficients between several parameters. Only significant correlations at $p < 0.05$ are shown in the table.

	Conductivity	TS	TSS	TDS	Ni < 5 µm	Cu < 5 µm	Zn < 5 µm
Conductivity	1	0.918	0.610	0.976			-0.592
TS	0.918	1	0.728	0.921			-0.602
TSS	0.610	0.728	1	0.53	-0.518	-0.634	-0.514
TDS	0.976	0.921	0.53	1			-0.565
Ni < 5 µm			-0.518		1	0.892	0.716
Cu < 5 µm			-0.634		0.892	1	0.709
Zn < 5 µm	-0.592	-0.602	-0.514	-0.565	0.716	0.709	1

Total metal concentration were highest in the rain on snow event of the 2nd of December of 2015. Values of 0.0536 mg/l, 0.279 mg/l, 0.355 mg/l, and 1.26 mg/l for lead, nickel, cooper, and zinc, respectively, were detected. These values exceeded considerably recommended water quality criteria (USEPA, 2002). In average, total metal concentrations registered up to date are 0.022 mg/l, 0.106 mg/l, 0.154 mg/l, 0.616 mg/l, respectively. These values are in agreement with mean values from melt period in Luleå (Westerlund & Viklander 2006), as well as with values from roadside snow in Trondheim (Muthanna et al. 2007). This indicates regional similarities, which could be explored for design criteria.

LIST OF REFERENCES

Backstrom, M. (2002). *Sediment transport in grassed swales during simulated runoff events*. Wat. Sci. & Tech., 45(7),41–49.

Gunawardana, C., Goonetilleke, A., Egodawatta, P., Dawes, L. and Kokot, S. (2011). *Role of Solids in Heavy Metals Buildup on Urban Road Surfaces.* Journal of Environmental Engineering..

Helmreich, B., Hilliges, R., Schriewer, A. and Horn, H. (2010). *Runoff pollutants of a highly trafficked urban road--correlation analysis and seasonal influences*., Chemosphere, vol. 80, no. 9, pp.991–7.

Kayhanian, M., Fruchtman, B.D., Gulliver, J.S., Montanaro, C., Ranieri, E. and Wuertz, S. (2012). *Review of highway runoff characteristics: comparative analysis and universal implications*. Water research, vol. 46, no. 20, pp.6609–24.

Kayhanian, M., Suverkropp, C., Ruby, A. and Tsay, K. (2007). *Characterization and prediction of highway runoff constituent event mean concentration*. Journal of environmental management, vol. 85, no. 2, pp.279–95.

Muthanna, T.M., Viklander, M., Blecken, G. and Thorolfsson, S.T. (2007). *Snowmelt pollutant removal in bioretention areas*. Water Research, vol. 41, pp.4061–4072.

Sansalone, J.J., Koran, J.M., Smithson, J.A. and Buchberger, S.G. (1998). *Physical Characteristics of Urban Roadway Solids Transported during Rain Events*. Journal of Environmental Engineering, vol. 124, no. 5, pp.427–440.

Westerlund, C. and Viklander, M. (2006). *Particles and associated metals in road runoff during snowmelt and rainfall*. The Science of the total environment, vol. 362, no. 1-3, pp.143–56.