An exploratory study of the effects of stormwater pipeline materials on transported stormwater quality

Matthias Borris, Heléne Österlund, Jiri Marsalek and Maria Viklander

ABSTRACT

Implications of three sewer pipe materials (concrete, galvanized corrugated steel, and polyvinyl chloride (PVC)) for stormwater quality were explored in laboratory experiments, in which three types of stormwater, SW1–SW3, were circulated in 0.5 m long sewer pipe sections. SW1 and SW2 represented synthetic rainwater, without and with fine street sediment added ($C_{TSS} = 150$ mg/L), respectively, and SW3 was actual stormwater with the same sediment addition as SW2. Following 20-min runs, with an equivalent distance of 500 m travelled by water particles, a number of statistically significant changes in the stormwater chemistry were observed: (i) pH of all the simulated stormwaters increased in the concrete pipe (from 7.0–7.3 to 8.1–9.3), (ii) turbidity decreased in two stormwaters with sediments (SW2 and SW3) in concrete and galvanized corrugated steel pipes (by 50 and 85%, respectively), (iii) the type of stormwater affected the observed copper (Cu) concentrations, with Cu_{diss} concentrations as high as 25.3 μg/L noted in SW3 passing through the PVC pipe, and (iv) zinc (Zn) concentrations sharply increased ($Zn_{tot} = 759$–1,406 μg/L, $Zn_{diss} = 670$–1,400 μg/L) due to Zn elution from the galvanized steel pipe by all three stormwaters. Such levels exceeded the applicable environmental guidelines.

Key words | heavy metals, stormwater pipeline materials, stormwater quality

Matthias Borris (corresponding author)
Heléne Österlund
Jiri Marsalek
Maria Viklander
Department of Civil, Environmental and Natural Resources Engineering,
Luleå University of Technology,
Luleå 97187,
Sweden
E-mail: *matthias.borris@ltu.se*

INTRODUCTION

The built drainage infrastructure of urban areas is designed to collect rainwater and convey runoff to receiving waters. The quality of stormwater runoff is influenced by pollutants, which are deposited on catchment surfaces, such as streets and roofs, during dry periods and then dislodged and transported during wet weather (US EPA 1983). The materials used in the construction of the built environment can have profound effects on the quality of stormwater runoff. Roof surfaces, including roofing materials, gutters, and downpipes, may contain heavy metals which could potentially be released as these surfaces are corroded (Clark *et al.* 2008). Roof surfaces have thus been identified as significant contributors to copper (Cu) and zinc (Zn) loads in stormwater runoff. For example, Charters *et al.* (2016) analyzed the runoff from copper roofs and measured a mean Cu concentration of 1,663 μg/L, and the Zn concentration in runoff from a galvanized metal roof was determined to be 397 μg/L. Similar processes can occur in connection with metal structures associated with roads, such as road signs and guard railings (Ogburn *et al.* 2012). Moreover, it has been shown that the quality of runoff can be affected by the properties of paving materials. For example, concrete pavements may retain copper from stormwater runoff. Bahar *et al.* (2008) tested the Cu retention capacity of concrete surfaces during various rain events and found them to retain between 10 and 40% of the total Cu releases during individual rainfall/runoff events. It has also been shown that overland flow systems can buffer acidic rain (pH 4–6), raising the pH value of stormwater runoff to the neutral value of 7 or above. This was mainly attributed to the dissolution of calcium from pavements, sewer pipes, and other surfaces (Novotny & Kincaid 1981).

Water running off urban surfaces is conventionally conveyed to receiving waters by sewer pipes. Existing stormwater pipelines are made of various materials including concrete, polyvinyl chloride (PVC) and corrugated steel (ASCE 1992). Each of these materials may affect stormwater quality in different ways. Wright *et al.* (2011) reported that concrete urban drainage systems can significantly worsen the urban stream syndrome by increasing

doi: 10.2166/wst.2017.195

pH of the transported stormwater and increasing its content of metal ions. Urban streams reportedly have neutral pH values, whereas non-urban streams may be acidic. Furthermore, the calcium concentrations in urban streams were found to be about six times higher than those in non-urban streams. Davies *et al.* (2010) observed that while both concrete and PVC pipes can increase pH of stormwater, the effect of stormwater pipelines was considerably stronger. Thus, circulation of roof runoff and stream water samples, with initial pH values between 4.8 and 7.4, in concrete and PVC pipes for 100 min yielded final pH values of 7.7–8.0 for concrete and 6.4–8.0 for PVC.

However, relatively few studies have addressed the effects of different sewer pipe materials on heavy metal transport. Perkins *et al.* (2005) investigated the effects of different pipe materials (concrete, PVC, and cast iron) on dissolved Cu concentrations in a Cu-spiked tap water solution (pH 5.6, hardness 13 mg/L as $CaCO_3$). PVC and cast iron did not remove Cu from the solution, but the concrete piping reduced the water's Cu concentration by 12–18%. However, no attempt was made to account for the different compositions of tap water and stormwater, and the reported results may not realistically reflect all the processes occurring in the urban environment, because stormwater contains particulates influencing heavy metal transport. Ogburn *et al.* (2012) studied metal elution from different sewer pipe materials by submerging pipe sections for up to 3 months in tanks filled with roof runoff buffered to pH values between 5 and 8. In these experiments, the release of Zn from galvanized steel after 1 day of exposure ranged between 45 and 720 mg/m^2, while the Zn release from concrete and PVC pipes was up to 5 and 22 mg Zn/m^2, respectively. However, the static nature of these experiments (i.e., non-moving water) raises questions to what extent these findings would apply to stormwater flowing through sewer pipes. It would, therefore, be desirable to examine the effects of different sewer pipe materials on the quality of transported stormwater by mimicking the conditions occurring in urban environments as fully as possible, including a close reproduction of the stormwater characteristics during runoff.

In light of the above knowledge gaps, the main objective of the study presented herein was to examine the effects of three sewer pipe materials (concrete, galvanized corrugated steel, and PVC) on the selected stormwater quality parameters during transport in sewers. The selected parameters included turbidity, pH, and the three most ubiquitous urban metals, Cu, lead (Pb), and Zn.

MATERIALS AND METHODS

Laboratory tests consisted in recirculating three types of stormwater in a testing apparatus mimicking stormwater flow in sewers. The description of laboratory procedures starts with the testing apparatus, followed by preparation of stormwater-sediment mixtures, and experimental runs.

The experimental apparatus consisted of a stand holding a 0.5 m-long test pipe section at a 3% slope (to ensure solids transport). The stormwater fed into the pipe at the upstream end was draining at the lower end into a polytetrafluoroethylene (PTFE) funnel, conveyed by gravity through marprene tubing to a peristaltic pump (Watson Marlow 520S), operating at a flow rate of 0.95 ± 0.03 L/min, and returned to the upstream end of the pipe. Such an arrangement allowed recirculating stormwater through the sewer pipe continuously. The duration of experimental runs was chosen as 20 min, allowing the stormwater to travel an estimated distance of 500 m. Flow velocities through the apparatus were sufficient to prevent sediment settling in the apparatus, as checked visually. Three types of prewashed commercially available pipes, made of concrete, galvanized corrugated steel, and PVC, were tested. A sketch of the apparatus is shown in Figure 1.

The apparatus was fed with three types of simulated stormwater, which are henceforth referred to as simulated stormwaters 1, 2, and 3 (or SW1, SW2, and SW3). Three stormwater types were used in order to mimic various processes that may occur during the transport of stormwater in sewer pipes; namely, metal release or retention by the sewer pipe materials, and the effects of different pipe materials on the selected water quality parameters (i.e., pH and turbidity; and the partitioning of heavy metals Cu, Pb, and Zn between the dissolved and particulate phases). This approach also made it possible to analyze the effects of sewer pipe materials on stormwater samples with different properties. The basic characteristics of SW1–SW3 are summarized in Table 1 and further explanations are offered below the table.

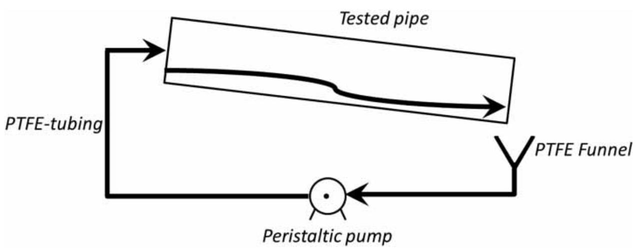

Figure 1 | Sketch of the experimental apparatus.

Table 1 | Characteristics of the simulated stormwaters SW1–SW3

Stormwater	pH	Source of water	Chemical additions	Sediment (solids) additions
SW1	7.0 ± 0.3	Deionized water	Chemicals added to reproduce Swedish rainfall chemistry[a]	None
SW2	7.0 ± 0.3	Deionized water	Chemicals added to reproduce Swedish rainfall chemistry[a]	Fine street sediments[b] added to attain TSS = 150 mg/L
SW3	7.3 ± 0.1	Filtered actual stormwater (d = 0.45 μm)	No	Fine street sediments[b] added to attain TSS = 150 mg/L

[a]After Granat (1990); it could be also referred to as synthetic rainwater.
[b]Sediment size D < 250 μm.

Sources of water. For preparing SW1 and SW2, a stock synthetic rainwater solution was prepared from deionized water (0.055 μS/cm), salts (i.e., $CaCl_2 \times H_2O$, KNO_3, $(NH_4)_2SO_4$, $NaNO_3$, $NaSO_4$, and $MgSO_4$), and H_2SO_4. The stock solution was diluted (1:1,000) to achieve the desired ion concentrations (SO_4^{2-}: 0.72 mg/L; NO^{3-}: 0.322 mg/L; NH_4^+: 0.322 mg/L; Na^+: 0.207 mg/L; K^+: 0.051 mg/L; Mg^{2+}: 0.034 mg/L; Ca^{2+}: 0.098 mg/L; Cl^-: 0.35 mg/L), and pH = 4. These concentrations were based on the Swedish Environmental Protection Agency (EPA) report (Granat 1990) on rainfall chemistry in Sweden, and the solution pH was adjusted by adding small quantities of aqueous NaOH.

For SW3, stormwater runoff was collected from a trafficked area at the inlet to the drainage system. The runoff was processed by filtering out the naturally occurring particulates, in order to achieve uniform conditions during the experiments. This was done by centrifugation followed by filtration through a 0.45 μm filter (Whatman membrane filter, 142 mm diameter). The processed stormwater runoff was analyzed for dissolved heavy metals by inductively coupled plasma sector field mass spectrometer (ICP-SFMS).

Source of sediment. In both SW2 and SW3, total suspended solids (TSS) concentrations were built up to a preselected value of TSS = 150 mg/L, which was slightly higher than the mean TSS reported by Kayhanian *et al.* (2007) for highway runoff (i.e., 113 mg TSS/L). For this purpose, street sediments were collected by vacuum cleaning from a road with traffic intensity of 7,800 vehicles/day (counted in one direction). The particles were sieved to separate the fine particles (i.e., <250 μm), which were added to SW2 and SW3. A size threshold of 250 μm was used because it represents the boundary between fine and medium sand classes, and larger particles are unlikely to be found in stormwater runoff, because they may not readily dislodge from surfaces or settle out rapidly (Andral 1999). The particles' total metal content was determined using an ICP-SFMS, after microwave digestion with 7M HNO_3, following the US EPA method 200.8 and Swedish method SS EN ISO 17294-1, 2. The reporting limits were 0.3, 0.1, and 1 mg/kg of dry mass for Cu, Pb, and Zn, respectively.

Similar testing procedures were used with each type of simulated stormwater. In all cases, batches of the simulated stormwater were circulated through the apparatus for four 20-min cycles, with the water from the first cycle being discarded. This was done to minimize the possibility that 'first wash' effects might yield misleading results, with too much material washed off surfaces of new pipe sections. After each cycle, the apparatus was emptied but not cleaned. In this way, four successive runoff events were simulated. Since the water flow in the pipes only wetted a small band of the pipe surface, it was possible to rotate the pipe sections after switching to a new stormwater type and thus provide a fresh pipe surface for each type of simulated stormwater. This was done in order to produce comparable results for the three types of simulated stormwaters. All experiments were performed in triplicate, with the same bands of pipe surfaces being used for all experiments with the same type of simulated stormwater. Given that none of the studied parameters showed clear increasing or decreasing trends in these triplicates, mean values of measurements were computed and used in further discussion and analysis.

For all testing cycles, pH, turbidity, and dissolved and total heavy metal concentrations (Cu, Pb, and Zn) were measured before and after stormwater circulation in the apparatus. Turbidity was measured with a calibrated turbidimeter (Hach 2100Qis) and the measured values were reported in nephelometric turbidity units (NTU). Dissolved metals were analyzed by ICP-SFMS (see above), with the reporting limits of 0.1, 0.01, and 0.2 μg/L for Cu, Pb, and Zn, respectively. For total heavy metals determined by ICP-SFMS, after extraction with 13 M HNO_3, the reporting limits were 1, 0.5, and 4 μg/L for Cu, Pb, and Zn, respectively. Additionally, the particle size distributions (PSDs) of simulated stormwaters 2 and 3 were measured before and after testing using a laser diffraction particle size analyzer (Horiba LA-960). All metal analyses were performed by an accredited laboratory.

RESULTS AND DISCUSSION

The presentation of results starts with a brief assessment of metals in the fine street sediment added to SW2 and SW3, followed by the effects of three pipe materials on stormwater pH, turbidity, particle size distribution, and total and dissolved metals.

Pre-selected quantities of fine street sediment (<250 μm) were added to SW3 to mimic actual conditions in stormwater pipelines transporting stormwater with sediment, because both the liquid and solid phases play important roles in metal transport (Zhang *et al.* 2016). The sediment added represented the sole source of the particle-bound metals studied in SW3, and hence it was of interest to assess the environmental significance of this source by comparing metal concentrations in added sediments against sediment quality and stormwater discharge guidelines, as shown in Table 2.

Table 2 | Heavy metal concentrations in fine street sediments (<250 μm) and processed stormwater; and sediment and stormwater quality guidelines

	Cu	Zn	Pb
Street sediments [mg/kg]	82.8	181	17.7
Processed stormwater (SW3)[a]: Dissolved metals [μg/L]	19.3	48.0	0.12
Processed stormwater (SW3): Total metals [μg/L]	28.5	81.9	7.80
(Canadian) Interim Sediment Quality Guidelines (ISQG)(TEL)[b] [mg/kg]	36.0	123	35.0
Stormwater discharge guidelines[c] (total metals) [μg/L]	18.0	75.0	8.00

[a]As described in Table 3 (filtered actual stormwater, with added solids, TSS = 150 mg/L).
[b]The threshold effects level (CCME 2001).
[c](Proposed) Swedish guidelines for stormwater discharges (Alm *et al.* 2010) adopted by several Swedish municipalities.

For assessing street sediment quality, the Canadian Interim Sediment Quality Guidelines (ISQGs) (Canada) (TEL) for freshwaters were used, because of the lack of comparable Swedish guidelines. The TEL levels were exceeded by street sediment concentrations for both Cu and Zn, and similar exceedances were noted for SW3 as well. The level of total Pb in SW3 was practically equal to that specified by Alm *et al.* (2010) in the guidelines. Thus, the levels of metals in the street sediment and SW3 used in the study were environmentally significant.

The effects of stormwater circulation in the tested pipes on stormwater pH and turbidity are presented in Table 3, containing the initial parameter values and those attained after the circulation.

Circulation of SW1 and SW2 through the PVC and corrugated steel pipes had no significant effect on the pH values. However, circulation through the concrete pipe significantly increased pH values of SW1–SW3 from approximately 7 to 8.1–9.3. Concrete pipes have previously been shown to increase the alkalinity and pH of transported water. For example, Davies *et al.* (2010) compared the effects of PVC and concrete pipes on the alkalinity (measured as bicarbonate concentrations) of different types of water. The alkalinity of roof runoff, which was initially low (0.5 mg/L), increased to 4 mg/L after passage through a PVC pipe, whereas passage through a concrete pipe raised it to 17.3 mg/L. In addition, passage through the concrete pipe caused a greater increase in pH (from 4.8 to 7.7) than in the PVC pipe (4.8–6.4). All three pipe materials had similar effects on pH of the simulated SW3, whose pH increased from 7.3 to 7.9–8.1 in all cases after circulation in the apparatus. The different behaviour of synthetic rainwater (SW1)

Table 3 | Stormwater pH and turbidity data: before and after circulation in the three pipes tested (concrete, galvanized corrugated steel, and PVC)

			After circulation		
Water quality parameter	Stormwater tested	Before circulation (initial value)	Concrete	Galvanized corrugated steel	PVC
pH	SW1	7.0 ± 0.3	**9.3**[a] ± 0.4	7.0 ± 0.2	6.8 ± 0.2
	SW2	7.0 ± 0.3	**8.9** ± 0.2	7.3 ± 0.2	7.1 ± 0.1
	SW3	7.3 ± 0.1	**8.1** ± 0.1	**8.1** ± 0.01	**7.9** ± 0.1
Turbidity (NTU)	SW1	1.4 ± 0.03	3.5 ± 2	1.4 ± 0.4	1.4 ± 0.3
	SW2	31 ± 2	**18** ± 2	**7.7** ± 1	**26** ± 1
	SW3	42 ± 3	**21** ± 3	**14** ± 3	36 ± 4

[a]Bold font indicates statistical significance ($p < 0.01$) determined by paired *t*-tests comparing the pipe exposure values against the initial values before circulation.

and processed runoff (SW3) may be attributed to their different buffering capacities. SW1 consisted of deionized water with added ions and thus had a low buffering capacity, which explains the pronounced increase in its pH after circulation through the concrete pipe. The addition of street sediments apparently did not affect this behaviour, because SW2 underwent similar changes in pH. Davies *et al.* (2010) performed similar tests with water from an urban creek having a relatively high initial alkalinity (36.3 mg/L) and found that its pH rose to around 8 after circulation in either PVC or concrete pipes. Their results agree well with those obtained for the simulated SW3, which was intended to mimic the properties of stormwater runoff that had been conveyed along a concrete curb and gutter and would attain a higher initial alkalinity than SW1 and SW2.

The turbidity of SW1 was mostly unaffected by circulation through all the pipes. A minor turbidity increase in the concrete pipe may be due to the detachment of small particles from the concrete surface. Turbidities of SW2 and SW3 changed in similar ways among the different pipes. For both water types, the turbidity was reduced modestly (by around 15%) after circulation through the PVC pipe, indicating minor changes in the transported suspended particles. However, significant reductions in turbidities of SW2 and SW3 were noticed after stormwater circulation through the concrete and corrugated steel pipes, with turbidities reduced by 42–50 and 67–85%, respectively. The reductions caused by passage through the concrete pipe may be attributed to two factors: (i) rough surface of the new concrete, which would encourage the retention of particles in the boundary layer and impair their transport; and (ii) possible flocculation of fine suspended particles encouraged by elution of flocculants from concrete. It should be noted that both processes may be strengthened in new concrete pipes used in the experiments herein, but may become less significant in older pipes.

Substantial particle deposition also appeared to occur in the corrugated steel pipe and was attributed to corrugations acting as sediment traps. The efficiency of such traps would be the highest in new pipes, with corrugation spaces empty. After a longer operation, the corrugations along the pipe invert would fill up with sediments, and these sediment reservoirs could function as either sediment sources or sinks, depending on sewer flow hydraulics. During minor storms and the later part of runoff hydrograph, the corrugated pipes may accumulate sediments, which would be susceptible to resuspension and wash out during intense runoff events accompanied by high runoff flows. Examples of measured PSDs (by particle number) for SW2 and SW3 are given in Figure 2.

The PSDs of simulated stormwaters 2 and 3 were quite similar. In both cases, the initial PSD was the coarsest, and passage through the PVC, concrete, and corrugated steel pipes yielded progressively finer PSDs. This is in good agreement with the turbidity measurements, since the largest reductions were achieved in the steel pipe. The distributions in Figure 2 are also consistent with the previously reported PSDs for highway runoff: Li *et al.* (2006) found that 90% of particles, by number, from highway runoff were smaller than 10 μm (i.e., their d_{90} value was 10 μm). The d_{90} values observed in this work ranged between 12 and 18 μm for SW2, while those for SW3 were between 9 and 15 μm.

Elution of the three metals studied (Cu, Pb, and Zn) from sewer pipe materials was also studied and the results are reported in Table 4 for all the three stormwaters (as concentrations of total and dissolved metals) and in Figure 3 as total, particulate, and dissolved metals in SW2 and SW3.

The metal concentrations in SW1 were also measured before the circulation in the test apparatus, but were below the limit of detection in all cases (Cu < 0.1, Pb < 0.01, and Zn < 0.2 μg/L). The slightly increased Cu and Zn concentrations observed after circulation through the concrete and PVC pipes may be due to the elution of metals from the pipe materials, but are all well below the European Union (EU) environmental quality standards (EC 2013) for priority pollutants in surface and fishery waters (Cu_{diss} = 22, 40, and 112 μg/L, for water hardness (<100), (=100),

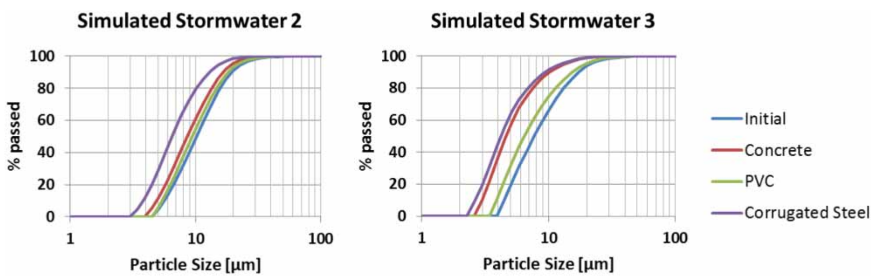

Figure 2 | PSDs by numbers of particles in simulated stormwaters SW2 and SW3 before (initial) and after circulation through the test apparatus.

Table 4 | Concentrations of total and dissolved metals in the stormwaters tested: before and after circulation in pipes made of concrete, galvanized corrugated steel, and PVC

			Concentration after circulation (μg/L)		
Heavy metals studied	**Stormwater tested**	**Concentration before circulation (initial value) (μg/L)**	**Concrete**	**Galvanized corrugated steel**	**PVC**
Cu_{tot}	SW1	<1	**4.74**[a] ± 1.86	**3.95** ± 1.26	**3.25** ± 0.28
	SW2	8.41 ± 0.43	**5.46** ± 0.71	**2.83** ± 0.62	9.77 ± 1.59
	SW3	28.5 ± 1.84	24.6 ± 2.53	**19.2** ± 0.7	26.8 ± 1.1
Cu_{diss}	SW1	n.a.	n.a.	n.a.	n.a.
	SW2	0.21 ± 0.13	**2.84** ± 0.64	**1.6** ± 0.44	**2.02** ± 0.45
	SW3	19.3 ± 0.86	23.6 ± 2.86	18.33 ± 0.58	**25.33** ± 0.33
Pb_{tot}	SW1	<0.5	<0.5	<0.5	<0.5
	SW2	5.71 ± 0.25	**1.2** ± 0.39	<0.5	2.67 ± 0.49
	SW3	7.8 ± 0.45	**1.31** ± 0.36	**0.99** ± 0.07	**2.25** ± 0.29
Pb_{diss}	SW1	n.a.	n.a.	n.a.	n.a.
	SW2	0.05 ± 0.03	0.02 ± 0.004	0.02 ± 0.005	0.02 ± 0.01
	SW3	0.12 ± 0.01	0.16 ± 0.01	0.18 ± 0.01	0.24 ± 0.04
Zn_{tot}	SW1	<4	**5.53** ± 3.46	**815** ± 59	**14.4** ± 3.51
	SW2	32.1 ± 1.18	**26.1** ± 2.03	**1,406** ± 159	49,53 ± 8.82
	SW3	81.9 ± 3.97	**54.2** ± 7.63	**759** ± 24.1	79.7 ± 3.27
Zn_{diss}	SW1	n.a.[b]	n.a.	n.a.	n.a.
	SW2	1.8 ± 0.54	2.44 ± 0.1	**1,400** ± 135	**15** ± 0.94
	SW3	48.1 ± 1.27	**28** ± 2.41	**670** ± 24.28	50.1 ± 1.2

[a]Bold font indicates statistical significance ($p < 0.01$) determined by paired t-tests comparing the pipe exposure values against the initial values before circulation.
[b]Data not available.

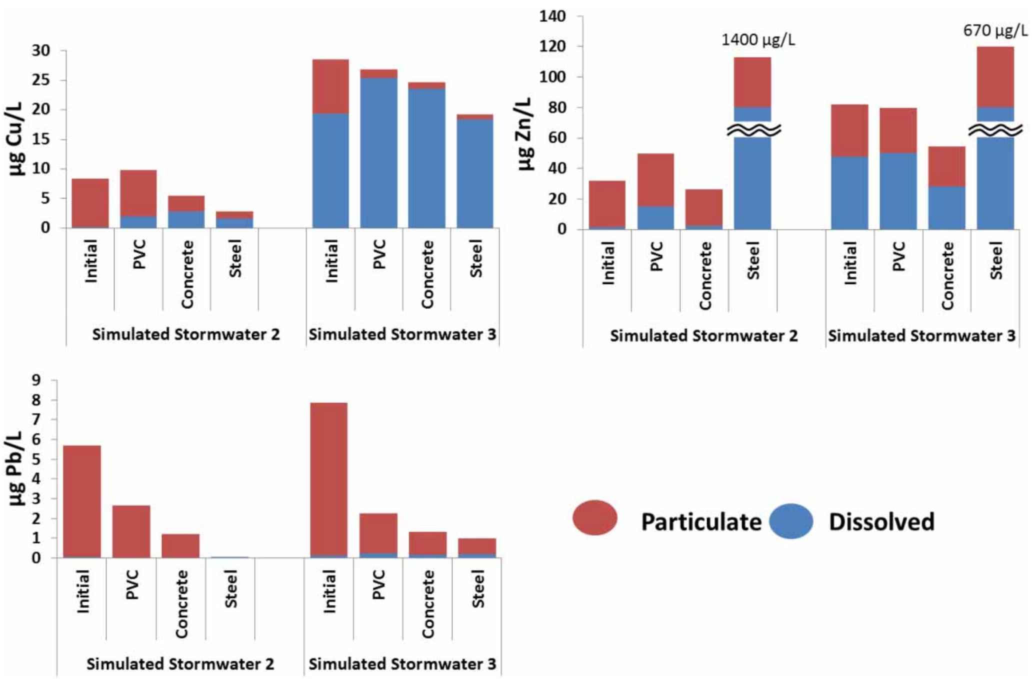

Figure 3 | Concentrations of dissolved (blue) and particulate (red) metals in stormwaters SW2 and SW3: before and after circulation in pipes made of concrete, galvanized corrugated steel, and PVC. Please refer to the online version of this paper to see this figure in colour: http://dx.doi.org/10.2166/wst.2017.195

and (>100) mg $CaCO_3$/L, respectively; Pb_{tot}=14 μg/L (hardness not specified); and Zn_{tot} = 200, 300, and 500 μg/L, for water hardness (<100), (=100), and (>100) mg $CaCO_3$/L, respectively). However, Zn concentration increases in galvanized corrugated steel pipes exceeded the EU standards (EC 2013) as well as the proposed guideline for stormwater discharges in Sweden (Alm *et al.* 2010).

Referring to the earlier research, Ogburn *et al.* (2012) studied the release of pollutants from various pipe and gutter materials by submerging them for up to 3 months in tanks filled with roof runoff buffered to pH 5 or 8. Although their experimental conditions differed significantly from those applied in this work, the patterns of metal release observed in both cases are quite similar. This was especially true for Zn, because galvanized materials were identified as the most important sources of this metal, releasing between 45 and 720 mg/m^2 after 1 day of exposure. Conversely, PVC and concrete pipes released up to 22 mg Zn/m^2 and 5 mg Zn/m^2, respectively. PVC also released up to 5 mg Cu/m^2, whereas the release of this metal from galvanized products and concrete was negligible. The release of Pb from galvanized materials was as high as 30 mg/m^2 in Ogburn *et al.*'s (2012) experiments, but no detectable Pb release was observed for PVC and concrete in this study. Also, the experiments presented here used new pipe materials, and it is likely that the observed rates of emission would decrease over time. However, Clark *et al.* (2008) demonstrated for roofing materials exposed to rainwater that they released several groups of chemicals, including metals, and the potential for metal releases existed even in the case of galvanized metal roofing materials more than 60 years old.

The total, dissolved and particulate (i.e., total minus dissolved) metal concentrations for SW2 and SW3, before and after circulation through the three pipes tested, are shown in Figure 3. The coefficients of variation, which were calculated from triplicate experiments, were highest for the galvanized corrugated steel (up to 32%), while the values for PVC and concrete were below 20%.

The trends in, and concentrations of, total, dissolved, and particulate heavy metals differed among the tested pipe materials, individual metals, and the two types of stormwater, SW2 and SW3, addressed in Figure 3. The trends in the total concentrations of Cu and Pb were generally similar to those observed for turbidity: the metal concentrations declined by progressively greater amounts when moving from PVC to concrete and then to corrugated steel pipes. However, the magnitude of this effect differed between the metal species: Pb exhibited stronger reductions than Cu. This may be because (according to the results obtained with SW1) Pb did not elute in detectable quantities from all three pipe materials. The findings for corrugated steel were dramatically different; for both stormwaters, SW2 and SW3, Zn concentrations in stormwater increased above the EU environmental standards (EC 2013).

The total metal concentrations in SW2 and SW3 were either unaffected by circulation through the PVC pipe, or slightly increased. In cases where increases occurred, they were generally accompanied by increases in the concentration of dissolved metals. Zn was an exception to the general rule: its concentration increased substantially after passage through the steel pipe, with all of the increase being due to an increase in the load of dissolved Zn. The steel pipe's ability to release Zn had previously been observed with simulated stormwater 1, although it should be noted that the magnitude of the release differed between the stormwater types, ranging from 670 μg Zn/L for SW3 to 1,400 μg Zn/L for SW2. Fresh pipe surfaces were used for each type of simulated stormwater, so it is possible that the conditions of the surfaces differed between runs; however, no such differences were observed by visual inspection. The particulate load of Cu in SW3 was reduced significantly by passage through all three pipe materials, whereas the dissolved load increased. This effect was not observed for SW2, for which the load of Cu in the particulate fraction remained unchanged after passage through the PVC pipe. Cu also behaved differently from Zn, because the loads of particle-associated Zn after passage through the PVC and concrete pipes were very similar. Zhang *et al.* (2016) studied the leaching of Cu and Zn from street sediments in the presence and absence of dissolved organic matter (DOM) and surfactants. The addition of these substances to synthetic rainwater was shown to promote the leaching of Cu but not that of Zn; in fact, in some cases their presence suppressed Zn leaching. The differences in properties of SW2 (synthetic rainwater) and SW3 (processed stormwater runoff) may thus explain their different behaviour, since DOM is usually found in runoff from highways and street surfaces (Kayhanian *et al.* 2007). It thus appears that the properties of the simulated stormwater affected both pH (as shown in Table 2) and the partitioning of heavy metals between the dissolved and particulate phases. This in turn influences the effects of different sewer pipe materials on stormwater quality.

CONCLUSIONS

Three sewer pipe materials (concrete, galvanized corrugated steel, and PVC) were examined to determine their potential effects on the quality of transported simulated stormwater. Recognizing the limitations of the laboratory experiments (short exposures during circulation through new pipes) and the exploratory nature of this study, the following conclusions may be drawn:

- Short-term exposures of simulated stormwaters to three sewer pipe materials caused changes in the stormwater quality described by pH, turbidity, and concentrations of Cu, Pb, and Zn. Such changes depended on the properties of the transported stormwater and the quality parameter under consideration.
- pH of all three simulated stormwaters (SW1–SW3 increased following their circulation through the concrete pipe; the highest increases were noted for SW1 and SW2 (from 7.0 to 9.3 and 8.9, respectively), because of their low buffering capacities. In the case of the actual stormwater SW3 this increase was just from 7.3 to 8.1, and was similar to the increases noted also for galvanized corrugated steel and PVC pipes. All the pH increases listed above were statistically significant.
- The PVC pipes with a smooth internal surface exerted least effects on stormwater turbidity. By contrast, circulation of SW2 and SW3 through the concrete and galvanized corrugated steel pipes reduced the turbidity of the stormwater by about 50 and 85%, respectively, with both reductions being statistically significant. Such stormwater clarification in the concrete pipe may be caused by elution of flocculants from concrete; and, in the corrugated pipe, it is caused by particle entrapment in pipe corrugations. Both influences may change with time; particularly in the latter case, after corrugations have become filled with sediment.
- Concerning metal transport, minor variations in Cu_{tot} concentrations were noted for all the stormwaters and pipe materials; however, only in one case, SW3 in the PVC pipe, a potentially environmentally significant level of Cu_{diss} (25.3 μg/L) was noted. No Pb elution was observed from any of the tested sewer materials, but Pb_{tot} slightly declined in both SW2 and SW3 in all the three pipes, in agreement with declines in turbidity. Small amounts of Zn_{tot} were either eluted or dissipated in the PVC and concrete pipes, but large amounts of this metal were eluted from the galvanized corrugated steel pipe. The resulting (statistically significant) Zn concentrations ($Zn_{tot} =$ 759–1,406 μg/L) were mostly in the dissolved fraction ($Zn_{diss} =$ 670–1,400 μg/L) and exceeded the European Commission (EC) environmental quality standards and the proposed (Swedish) guideline levels for stormwater discharges.
- The presented study should provide motivation for more extensive and robust investigations of the effects of sewer pipe materials on stormwater quality and the consideration of such effects in drainage design.

ACKNOWLEDGEMENTS

The financial support of this project by Sweden's innovation agency Vinnova and The Swedish Research Council Formas (Formas Grant number 2016-20073) is gratefully acknowledged.

REFERENCES

Alm, H., Banach, A. & Larm, T. 2010 *Occurrence and Treatment of Priority Substances, Metals and Other Substances in Stormwater (Förekomst Och Rening Av Prioriterade Ämnen, Metaller Samt Vissa Övriga Ämnen i Dagvatten)*. SVU, Stockholm.

Andral, M. C. 1999 Particle size distribution and hydrodynamic characteristics of solid matter carried by runoff from motorways. *Water Environment Research* **71**, 398–407.

ASCE 1992 *Design and Construction of Urban Stormwater Management Systems. ASCE Manuals and Reports of Engineering Practice No. 77*, ASCE, Reston, VA.

Bahar, B., Herting, G., Wallinder, I. O., Hakkila, K., Leygraf, C. & Virta, M. 2008 The interaction between concrete pavement and corrosion-induced copper runoff from buildings. *Environmental Monitoring and Assessment* **140** (1–3), 175–189. DOI: 10.1007/s10661-007-9858-0.

CCME 2001 *Canadian Sediment Quality Guidelines for the Protection of Aquatic Life*. Canadian Council of Ministers of the Environment, Winnipeg, Canada.

Charters, F. J., Cochrane, T. A. & O'Sullivan, A. D. 2016 Untreated runoff quality from roof and road surfaces in a low intensity rainfall climate. *Science of the Total Environment* **550**, 265–272. DOI: 10.1016/j.scitotenv.2016.01.093.

Clark, S. E., Steele, K. A., Spicher, J., Siu, C. Y. S., Lalor, M. M., Pitt, R. & Kirby, J. T. 2008 Roofing materials' contributions to storm-water runoff pollution. *Journal of Irrigation and Drainage Engineering, ASCE* **134** (5), 638–645.

Davies, P. J., Wright, I. A., Jonasson, O. J. & Findlay, S. J. 2010 Impact of concrete and PVC pipes on urban water chemistry. *Urban Water Journal* **7** (4), 233–241. DOI: 10.1080/1573062X.2010.484502.

European Commission (EC) 2013 *Directive 2013/39/EU of the European Parliament and of the Council of 12 August 2013 Amending Directives D2000/60/EC and 2008/105/EC as Regards Priority Substances in the Field of Water Policy*. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2013:226:0001:0017:en:pdf.

Granat, L. 1990 *Luft- Och Nederbördskemiska Stationsnätet Inom PMK (Station Network for Air and Rainfall Chemistry within PMK)*. Naturvårdsverket, Solna.

Kayhanian, M., Suverkropp, C., Ruby, A. & Tsay, K. 2007 Characterization and prediction of highway runoff constituent event mean concentration. *Journal of Environmental Management* **85** (2), 279–295.

Li, Y., Lau, S., Kayhanian, M. & Stenstrom, M. K. 2006 Dynamic characteristics of particle size distribution in highway runoff: implications for settling tank design. *Journal of Environmental Engineering* **132** (8), 852–861. DOI: 10.1061/(ASCE)0733-9372(2006)132:8(852).

Novotny, V. & Kincaid, G. W. 1981 Acidity of urban precipitation and its buffering during overland flow. In: *Proceedings of the Second International Conference on Urban Storm Drainage*. University of Illinois, Urbana-Champaign, IL. Vol. 2, pp. 1–9.

Ogburn, O., Pitt, R. & Clark, S. 2012 Pollutant releases from gutter and piping materials into urban stormwater runoff. World Environmental and Water Resources Congress 2012: Crossing Boundaries. In: *Proceedings of the 2012 Congress*, Albuquerque, NM.

Perkins, C., Nadim, F. & Arnold, W. R. 2005 Effects of PVC, cast iron and concrete conduit on concentrations of copper in stormwater. *Urban Water Journal* **2** (3), 183–191. DOI: 10.1080/15730620500236658.

US Environmental Protection Agency (EPA) 1983 *Results of the Nationwide Urban Runoff Program*. Vol. 1, Final Report. US EPA, Water Planning Division, Washington, DC.

Wright, I. A., Davies, P. J., Findlay, S. J. & Jonasson, O. J. 2011 A new type of water pollution: concrete drainage infrastructure and geochemical contamination of urban waters. *Marine and Freshwater Research* **62** (12), 1355–1361. DOI: 10.1071/MF10296.

Zhang, J., Hua, P. & Krebs, P. 2016 The influences of dissolved organic matter and surfactant on the desorption of Cu and Zn from road-deposited sediment. *Chemosphere* **150**, 63–70. DOI: 10.1016/j.chemosphere.2016.02.015.

First received 13 September 2016; accepted in revised form 20 March 2017. Available online 31 March 2017