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Hydraulic Performance and Pollutant Concentration Profile in a Stormwater Runoff Filtration Systems

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Abstract Stormwater filtration system has proven to be effective for the removal of dissolved and particulate pollutants from roadways and car parking areas. However, the long-term treatment performance of filtration systems strongly depends on the hydraulic conductivity and sorption capacity of the filter media. This paper sought to provide information regarding the hydraulic performance, characteristics and metal concentration profiles in sediments accumulated at the surface of filtration systems (SDPL) and core filter media (FMC). The lifespan of the filter media was used to estimate the lifespan of the filter media. The results showed that saturated hydraulic conductivity of the filtration systems have significantly reduced over the operational time, yet acceptable ($Kf = 5.9 \times 10^{-5}$ to 1.4×10^{-4} m/s). The accumulated sediments (SDPL) were predominantly composed of fine particles with 70 %<63 μm but the heavy metals were rather uniformly distributed in the different size fractions. The concentrations of heavy metals, particularly Cu, Pb and Zn were significantly higher in the SDPL and decreased with depth of the filter bed. However, Cr and Ni increased with depth of filter media demonstrating their removal was mainly by adsorption. Concentrations of Ba, Mn, Ti and V were comparable to Zn levels indicating comparable concentrations in roadway runoff. Simultaneous adsorption of multiple heavy metals in a column experiment demonstrated that the filter media could remain operational for over 34 years. However, there is a significant concern about their lifespan, particularly due to significant reduction in the hydraulic performance and the possibility of clogging of the systems over time. Therefore, to minimize hydraulic failure, the accumulated sediment be scraped off every 7 years.

Keywords Stormwater · Heavy metals · Filter media · Filtration · Hydraulic conductivity · Sorption

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1 Introduction

Stormwater runoff from vehicle trafficked areas (e.g. highway and parking lot) contains significant loads of metal elements, polycyclic aromatic hydrocarbons (PAHs) and fine particles/suspended solids (Fuerhacker et al. 2011; Göbel et al. 2007; Helmreich et al. 2010). Those pollutants are presented either dissolved in the stormwater or are bound to particulates, particularly in roadway runoff, a large fraction of heavy metals and

PAHs are adsorbed to fine particles (Sansalone and Buchberger 1997; Kayhanian et al. 2012; Gromaire-Mertz et al. 1999; Zgheib et al. 2011). Thus, in addition to the obvious water quality impairment caused by particles such as high turbidity, suspended solids act as the transport vector to downstream areas (Zgheib et al. 2011; Herngren et al. 2006). Numerous previous studies reported that significant loads of heavy metals and PAHs are associated with fine particles typically smaller than 50 μm (Ball et al. 1998; Furumai et al. 2002). For example, (Ball et al. 1998) reported that more than 50 % of the metals be sorbed to particles smaller than 43 μm, although this fine solid fraction only contributed to 5.9 % of the total solids collected. Despite large variations in concentration, most researchers agree that the concentrations of heavy metals and PAHs generally increased with decreasing particle size (Sansalone and Buchberger 1997; Herngren et al. 2006; Zandres 2005; Li et al. 2006; Zhao et al. 2010). In this regard, fine particles are of more concern than larger particles because they have relatively high surface area, which facilitates the adsorption of pollutants (Sansalone and Buchberger 1997; Herngren et al. 2006).

Therefore, the effectiveness of stormwater treatment system depends mainly on the partitioning of pollutants between dissolved and particulate as well as between size fractions of the particles (Kayhanian et al. 2012; Furumai et al. 2002; Zandres 2005). In order to optimize the design and performance of stormwater treatment systems, several researchers have investigated the characteristics of the pollutants in roadside-deposited sediments (Herngren et al. 2006; Zandres 2005; Zhao et al. 2010). Due to particle aggregation and preferential deposition of larger and denser particles, particle size distribution and associated pollutant distribution in sediments are not the same as those of suspended solids in the runoff (Kayhanian et al. 2012; Zandres 2005; Roger et al. 1998). For example, Furumai et al. (2002) showed that particles less than 20 μm accounted for more than 50 % of the particulate mass for runoff samples with TSS concentrations below 100 mg/l. However, for roadside-deposited sediment, Zhao et al. (2010) reported that the median particle size ranged from 100 to 200 μm which is significantly higher than that of highway runoff.

A stormwater treatment system has to ensure both drainage of the runoff and retention of a wide range of particulate and dissolved pollutant loads. A broad review of the international literature has revealed that numerous treatment systems have been constructed, operated and evaluated for the removal of inorganic and organic pollutants (Fuerhacker et al. 2011; Gill et al. 2014; Paus 2999; Ingvertsen et al. 2012). Treatment systems such as sedimentation basin, retention ponds and other structural facilities that mainly rely on sedimentation are not sufficient in the removal of fine particulate and dissolved pollutants. Therefore, different source control strategies such as bioretention (Paus 2999; Li and Davis 2008), infiltration basin (Ingvertsen et al. 2012), constructed wetlands (Gill et al. 2014), media filtration systems (Fuerhacker et al. 2011) and other structural facilities which rely on particle retention and physico-biochemical processes are of interest. Despite their effective performance, some treatment systems demand large areas and are hard to implement in area where available space is limited, for example constructed wetlands.

Infiltration/filtration systems with adsorptive filter media are increasingly considered as an effective alternative for use along highways and parking lots to provide effective removal of dissolved and particulate contaminants (Fuerhacker et al. 2011; Li and Davis 2008; Hatt et al. 2008). These systems are extremely compact and can be retrofitted into existing stormwater collection systems. There are several mechanisms through which contaminants are removed during passage through an infiltration/filtration system: sedimentation as contaminants are attached to solids, filtration, sorption, and transformation (Fuerhacker et al. 2011; Grebel et al. 2013). This indicates that the effectiveness of infiltration/filtration treatment system mainly depends on the hydraulic performance and adsorption capacity of the filter media. Numerous recent investigations relevant to the concentration profiles of heavy metals in in-service stormwater treatment systems showed that metal concentrations decrease with increasing depth of filter bed (Paus 2999; Ingvertsen et al. 2012; Li and Davis 2008). Ingvertsen et al. (2012) investigated the heavy metal profile and hydraulic performance of eight roadside infiltration swales which have been in operation for 6 to 16 years. They reported that the top layer (0–5 cm) of the filtration system was significantly enriched with Cr, Cu, and Zn, but Pb concentrations were similar throughout the soil profile. In another study, Li and Davis (2008) investigated the capture and accumulation of heavy metals in a bioretention media cell receiving parking lot runoff. Results of the study indicated that the heavy metals Cu, Pb, and Zn were predominantly accumulated in the surface deposited street particle layer and significantly decreasing with the media depth.

This research study was undertaken to assess the current state of two media filtration systems receiving parking lot and highway runoff. The objectives of this paper were to investigate (i) hydraulic performance and maintenance requirements,(ii) concentration profiles of metal elements captured in surface deposited particle layer (SDPL) and core filter media (FMC), (iii) size fractionation of surface deposited sediments and concentrations of heavy metals in the different size fractions, (iv) simulate the remaining operational lifespan of the filter media on the basis of the Austrian groundwater target values, QZV-Chemei GW (BMFLU. 98 2010) and or minimum heavy metal removal efficiency requirements as to ÖNORM B 2506-2 (2506-2, ÖNORM B 2012). The study outcomes will contribute to a greater understanding of the treatment performance of filtration systems and in turn enable improved design and maintenance of these systems.

2 Materials and Methodology

In the summer of 2012, a test program was set up to measure the infiltration capacity, composition of surface deposited particle layer (SDPL) and core filter media (FMC) and heavy metal sorption capacity of FMC of stormwater filtration systems.

2.1 Study Sites

Two media filtration systems, namely GSA-H and GSA-W located in upper Austria adjacent to the highway A-21, were investigated after 5 to 7 years of operation. Both systems are underground concrete structures with a sedimentation tank followed by a filter chamber filled with technical filter media, Aquafilt (Fig. 1). GSA-H has been in operation since October 2005 (i.e. 7 years at the time of sampling) and GSA-W has been in operation since 2007 (i.e. 5 years at the time of sampling). GSA-H has a filter drain area of 40.5 m^2 and receives stormwater runoff from a total impervious catchment area of 1.62 ha for which 1.22 ha is paved parking lot. For further details of the detail, see Fuerhacker et al. (2011). GSA-W has a filter drainage area of 65.5 m^2 and receives stormwater runoff from a highway and a bridge covering an impervious catchment of 1.76 ha. The filter media depth in both filter drains was 36 cm. The ratio of the impervious catchment area to the filtration system were 400 for GSA-H and 276 for GSA-W (i.e. GSA-H and GSA-W were sized at 0.25 and 0.37 % of their impervious catchment area, respectively) which is similar to high flow filters sized by Bratieres et al. (2012) to be 0.3 % of their impervious catchment area. To retain suspended solids and prevent early clogging of the system, a geotextile 300 g/m^2 was placed on top of the underlying filter media. Yet, no maintenance activities (e.g. media replacement, geotextile replacement or removal of surface deposited sediment) have occurred at these sites since they were constructed.

2.2 Infiltration Test

The hydraulic performance of the media filtration systems was evaluated by in situ measurement of the infiltration rate using a single ring infiltrometer (14.5 cm inner diameter and 50 cm long) according to Reynolds et al. (2002). Infiltration rate measurements were conducted at the centre of the filter chamber at two points: (a) whole filter bed (i.e. surface deposited particle layer (SDPL) + filter media bed) and (b) filter media bed without surface deposited particle layer. The cylinder was vertically straight pounded (inserted) into the filter bed to a depth of 5 cm and water was poured into the ring keeping a constant head of 10 cm. The volume of water poured into the ring was recorded every 5 min and the test was stopped 15 min after the infiltration rate reached steady state. The saturated hydraulic conductivity of the filter bed was calculated from the infiltration test using the mathematical expression (Reynolds et al. 2002) for a steady flow as follows:

$$K_{\mathrm{fs}} = \frac{q_s}{\frac{H}{(C_1 d + C_2 a)} + \frac{1}{a^*(C_1 d + C_2 a)} + 1}$$

K_{fs} (cm/s): is saturated hydraulic conductivity under field conditions

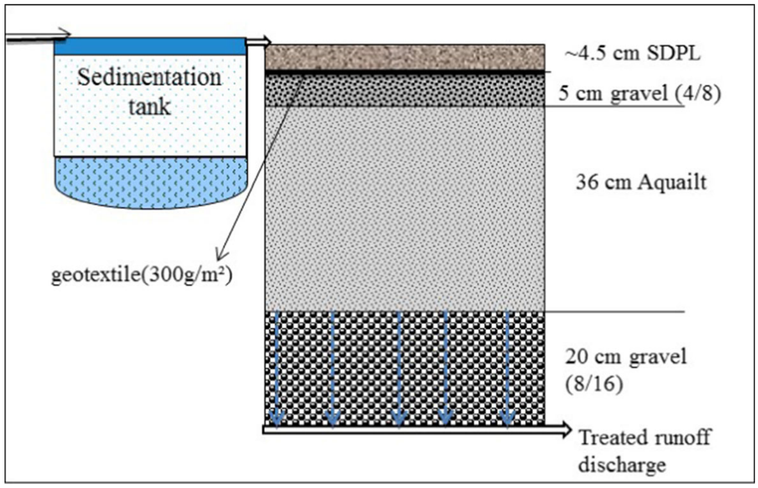
Q_s (cm/s): measured infiltration rate under submergence conditions

H (cm): height of the stationary water level (constant head)

C_1: dimensionless empirical constant, for $d \geq 3$ cm and $H \geq 5$ cm $C_1 = 0.316\pi$

C_2: dimensionless empirical constant, for $d \geq 3$ cm and $H \geq 5$ cm $C_2 = 0.184\pi$

Fig. 1 Overview of a parking lot runoff treatment system GSA-H, Austria



d (cm): inserted depth of the inner infiltrometer
a (cm): inner radius of the infiltrometer
[α*] (cm -1): macroscopic capillary length parameter. α* expresses the relative importance of gravity relative to the capillary force, where large values of α* show the dominance of gravity over the capillary force. α* ranges from 0.01 to 0.36

The determined hydraulic conductivity was then compared to the initial hydraulic conductivity of the filter media measured at laboratory before its installation.

2.3 Sampling

To assess the concentration profiles of pollutants, sediment (SDPL) and filter media core (FMC) samples were collected from GSA-H and GSA-W using precleaned infiltrometer cylinder. The average thickness of the SDPL was 4.5 cm at GSA-H and 2.5 cm at GSA-W, respectively. Since the area of the filtration system was relatively small (40.5 m^2 for GSA-H and 65.5 m^2 for GSA-W) and thickness of the deposited particle layer was uniform, spatial variation of pollutants was not considered. Therefore, two sampling points at the centre of the filter area were considered as representatives for the SDPL. To investigate the vertical variability of pollutant concentrations with depth, filter media cores (FMCs) were collected at three depths (0–8, 8–20, and 20–36 cm). Samples were collected in plastic bags and placed in a cooling room at 4 °C till analysis.

2.4 Particle Size Distribution of the Deposited Sediment

To assess the particle size distribution, the bulk sediment sample collected from the SDPL (GSA-H and GSA-W) and street dirt collected from road-deposited sediment (Lienz, Austria) were air-dried for 2 weeks to a constant weight. The air-dried SDPL and street dirt bulk sample were then gently crushed and dry sieved through a 2000-μm stainless-steel sieve. The particles with diameter less than 2000 μm were wet sieved into two fractions, i.e. particle size of less than 63 μm and greater than 63 μm. The greater than 63 μm sample was further wet sieved into fractions: 63–125, 125–200, 200–630, 630–1000 and 1000–2000 μm. The finer particles with diameter less than 63 μm were fractionated into four fractions <2, 2–6.3, 6.3–20, and 20–63 μm using a pipette method.

The distribution of heavy metals in the SDPL from GSA-H was analysed for fractions; <63, 63–200, 200–630, 630–1000 and 1000–2000 μm. Note that only 2 % of the bulk sediment sample has particle size of greater than 2000 μm in which its effect on the heavy metal fractionation could be negligible.

2.5 Heavy Metal Removal and Lifespan of Filter Media

To quantitatively determine the remaining metal sorption capacity (lifespan) of the filter media in operation, simultaneous adsorption of multiple heavy metals (Cr, Cu, Ni, Pb and Zn) was carried out in a fixed bed column experiment using core filter media (FMC) from GSA-H. The experiment was conducted in a glass column which had an internal diameter of 32 mm and filter bed height of 240 mm (i.e. empty bed volume (BV) of 193 cm^3). To minimize wall effect on sorption test results, Inczédy (1966) suggested that the column diameter on particle diameter ratio should be greater than 10. In this study, the diameter of the column was approximately 20 times greater than the mean particle size of the filter media, so the wall effect could be ignored. The FMC was packed in the column in a systematic way proportional to the layering of the filter bed in real system. A glass bead and fritted glass filter was placed at the bottom of the column to support the adsorbent. Multi-metal column feed solution containing Cr, Cu, Ni, Pb and Zn with desired concentrations was prepared using analytical grade 1000 mg/l stock solutions ($CuCl_2$, $CrCl_3$, $Pb(NO_3)_2$, $NiCl_2$ and $ZnCl_2$) and in distilled water. pH of the influent multi-metal solution was adjusted to 5.8 ± 0.2 using either suprapure HNO_3 or NaOH. This pH value was selected at least to resemble the minimum pH of highway runoff. A summary of the heavy metal concentrations in roadway runoff (Göbel et al. 2007; Helmreich et al. 2010) and column influent, calculated column annual load and filter media exhaustion point is given in Table 1.

The annual load of a target heavy metal in the column experiment was calculated based on the scaling of the filtration system using the following equation:

$$\text{annualload(mg per yer)} = C_{\text{in}}APr$$

Where C_{in} is mean roadway runoff concentration in μg/l obtained from literature (Table 1), A is surface are of the column in m^2, P is mean annual precipitation of the sites (720 mm per year) and r is the ratio of total impervious catchment area to filtration system which is 400 for GSA-W and 276 for GSA-W.

The experiment was conducted in up-flow modus (from bottom to top) which ensures saturated flow conditions and uniform hydraulic distribution of the sorbate to the filters (Athanasiadis 2005). Prior to loading with the feed solution, the column was slowly saturated and flushed with distilled water for 2 h, in order to remove entrapped air bubbles and leachable background concentrations. The feed solution was pumped using a peristaltic pump (ISMATEC IDEX) at a constant flow rate of 50 ml/min. Effluent samples were collected at designated time intervals, filtrated, acidified to pH <2 with 0.01 mM HNO_3 suprapure and analysed for heavy metal concentrations. Influent samples were also collected and handled similar to the effluent samples.

The performance of the FMC in reducing the heavy metal levels from synthetic solutions was assessed using the following equation:

$$\%\ \text{metal removal} = [C_i - C_e]\text{x}100$$

where C_i is the measured metal concentration of the column influent (initial) and C_e is the metal concentration of the effluent after a known volume of flow through.

The column was loaded till it reached the exhaustion point. In the present study, a filter media exhaustion was set to be equal or lower than the maximum effluent concentration defined in the Austrian regulation for ground water protection (BMFLU. 98 2010) or removal efficiency is below the minimum requirement according to the Austrian Standard (2506-2, ÖNORM B 2012) as indicated in Table 1.

2.6 Analytical Procedures

For the analysis of concentrations of metal elements in the SDPL and FMC, 500 mg of air-dried sample was added into 10 ml of ultrapure water and acidified using 3 ml 30 % HCl and 2 ml 65 % HNO3 in a closed Teflon vessel, and was digested in a Microwave Digestion System. The digested solution was then cooled for 2 h. After cooling, the digested samples were filtered and analysed for total concentrations using an inductively coupled plasma mass spectroscopy (ICP-MS; Perkin-Elmer, Sciex).

For the analysis of metal element concentration in the different size fractionations, SDPL sample was sieved through stainless-steel test sieves: 2000, 1000, 630, 200, and 63 μm. Material greater than 2000 μm was discarded because it contributes only <2 % of the total mass and also the fine fractions were of particular interest. 100 mg of SDPL dry sample was weighted in Pt-dishes and mixed with 2.5 ml HNO3 (65 %), 2.5 ml HClO4 (60 %) and 5 ml HF (40 %) and the acid was concentrated near dryness. After that, the residue was heated two times with 5 ml HNO3 (65 %) until the fumes were emitted. The last step was to take the residue with 0.5 ml HNO3 (65 %), diluted to 50 ml H2O and analysed for total concentrations using ICP-MS 7500 ce (Agilent). To guarantee the quality of measurement, some controlling standard was also measured. All concentrations were reported on a dry-weight basis (μg/kg). Because of their higher relevance regarding stormwater

Table 1 Concentrations of heavy metals, column annual load and material exhaustion criteria according to discharge limits and removal efficiencies

Metal	Concentration (μg/l)		Annual load (mg/yr)	Filter media exhaustion point	
	Highway runoff (Göbel et al. 2007; Helmreich et al. 2010)	Column	Column	GW limit (μg/l)[a]	RE (%)[b]
Pb	<5–405 (43)	50	9.68	9	–
Cr	6–50 (27)	50	3.93	45	–
Cu	11–604 (100)	250	22.5	1800	80
Ni	4–403 (35)	50	5.1	18	–
Zn	15–3470 (400)	1000	90		50

Values in bracket represent median concentration

[a] Maximum effluent concentration for the protection of groundwater according to the Austrian regulation (BMFLU. 98 2010)

[b] Minimum removal efficiency according to the Austrian Standard (2506-2, ÖNORM B 2012)

runoff from trafficked areas, particular emphasis was given to Ba, Cd, Cr, Ni, Cu, Pb, Ti, V and Zn.

3 Results and Discussion

3.1 Hydraulic Performance

The mean hydraulic conductivity of the whole layer (SDPL plus filter media layer) was 3.5×10^{-6} m/s and 4.8×10^{-5} m/s for GSA-H and GSA-W, respectively. After scraping of the SDPL, mean hydraulic conductivity of the filter media layer was 5.9×10^{-5} m/s and 1.4×10^{-4} m/s for GSA-H and GSA-W, respectively. Hydraulic conductivity of the fresh filter media tested at laboratory before its installation ranged 3.8×10^{-4} to 5.2×10^{-4} m/s (Haile 2008). The results indicated that hydraulic performance of the filtration system decreased in 1 to 2 orders of magnitudes after 5 to 7 years of operation. Infiltration rate at GSA-W was higher than that measured at GSA-H. The operational time and thickness of SDPL at GSA-H (4.5 cm) was relatively higher than at GSA-W (2.5 cm). The observed slight variation in hydraulic performance could be related to the operational time, thickness of SDPL and amount of fine particles strained within the filter media layer. The hydraulic conductivity of the SDPL plus filter bed was one magnitude lower than filter bed. This indicates that SPDL and particles strained in the filter bed have played a vital role in reducing the hydraulic conductivity of the filtration system.

The SDPL has an organic carbon content of 21 %. The very high organic carbon contents were mainly attributed to tire and break pad dusts, oil leaks, asphalt particles and other organic sources such as plant residues. After 7 years in operation, organic carbon content of the original filter media has increased from less than 1 % to 7 %. The increase could be a result of fine particulate matter transported by runoff being deposited in the filtration system. Sieve analysis and mass measurement of core filter media showed that 20 % of the pore volume was occupied by fine particles strained within the filter bed. Since particle straining in the filter bed has resulted in reduction of the pore volume, this in turn decreases the infiltration rate or hydraulic conductivity. The decrease in hydraulic conductivity could be also related to the compaction of the filter media due to hydraulic loading. Despite the significant decrease in hydraulic conductivity, these values still comply with the Austrian design standard value which ranged 1×10^{-3} m/s to 1×10^{-5} m/s (2506-2, ÖNORM B 2012). Thus, stormwater filtration systems like the ones investigated in the present study could remain operational for at least 7 years without maintenance.

3.2 Particle Size Distribution SDPL and Street Dirt

The particle size distributions of SDPL from stormwater filtration systems and street dirt from urban roadway are shown in Fig. 2. The characteristics and particle size distribution of SDPL from GSA-H and GSA-W were similar. The particle size distribution of SDPL ranged from <2 to 2000 μm with a median particle size (d50) of

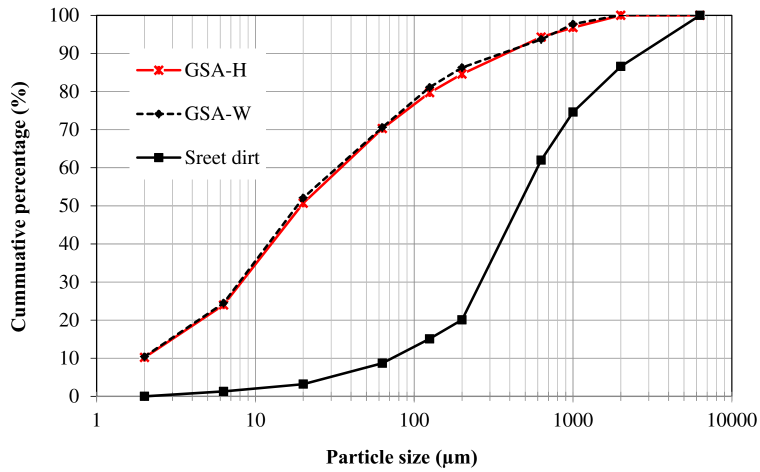


Fig. 2 Mass distributions of ten particle size range SDPL for two stormwater filtration systems, highway runoff and street dirt

20 µm. The particle size of street dirt ranges from <6.3 to 6300 µm and has a d50 of 480 µm.

A histogram of the size fractionations as a function of the particle size is shown in Fig. 3. The particle size distribution results showed that SDPL was predominantly composed of fine particles in which over 70 % the total mass was <63 µm, 23 % was <630 µm and only 7 % was >630 µm. Particle size distribution of the street dirt showed the following characteristics: 9 % of particles were <100 µm, <63 µm, 53 % were <630 µm, 25 % were <2000 µm and 13 % were <6300 µm.

Over all the results revealed that the size distribution for SDPL was narrower than the range for street dirt, indicating less variability in the particle size for SDPL. The observed significant variation between SDPL and street dirt can be explained by two main reasons. Firstly, the street dirt typically have accumulated over extended periods and they are generally enriched with coarser particles; secondly, the finer material having been lost through wind dispersion and/or washed away by rain (Zandres 2005). This means that the fine sediment fraction is underrepresented in street dirt. Secondly, the street dirt typically includes pollutant material derived from a range of sources, not just vehicle activity.

3.3 Metal Content of Surface Deposited Sediments and Core Filter Media

The total concentrations of metals measured in the bulk SDPL and FMC samples area are summarized in Table 2. The vertical distribution of the metals measured in the SDPL and FMC profile are presented in Fig. 4. From the vertical distribution, it can be seen that concentrations of Cu, Pb, V, and Zn were high in the SDPL and decreased with depth of the FMC. The concentrations in the SDPL were 2 to 4 times higher than the levels in the filter

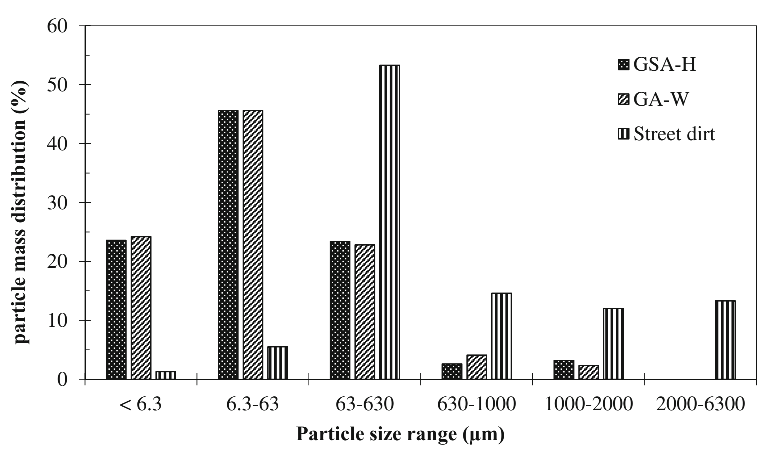


Fig. 3 Histogram of mean mass percentages of sediments from surface deposited particle layer versus grain size fraction

Table 2 Concentrations of metal elements in the SDPL and FMC

Metal	Unit	SPDL		FMC	
		GSA-W	GSA-H	GSA-W	GSA-H
Li	mg/kg	19	18	5.8	13
B	mg/kg	25	27	15	14
Ti	mg/kg	589	565		
V	mg/kg	43.6	37	3.4	7.8
Cr	mg/kg	86	81	37	83
Mn	mg/kg	499	744	160	350
Co	mg/kg	10.3	7.7	16	24
Ni	mg/kg	52	46	50	73
Cu	mg/kg	326	490	22	47
Zn	mg/kg	3016	1149	241	123
Sr	mg/kg	55	216	210	176
Cd	mg/kg	0.49	0.6	0.05	0.19
Ba	mg/kg	135	325	481	404
Pb	mg/kg	114	57	8.1	10.8
Bi	mg/kg	3.4	3	0.21	0.27
Al	g/kg	12.3	10.9	27	26
Fe	g/kg	32.9	37.9	18	28

media layer. Such vertical stratification of the pollutants was expected because as the runoff water infiltrates through the filter media layer, pollutant concentrations should decrease due to removal via filtration, precipitation, sorption and complexation processes. However, the contents of Cr, Co and Ni generally increased with depth from top to bottom (SDPL to FMC). The metals B, Ba, Mn, and Sr were uniformly distributed over the SDPL and filter media.

In the SDPL following Al and Fe, Zn was the next highest whose concentrations were significantly higher (i.e. 3–58 folds) than Cr, Ni, Pb and Cu concentrations (Table 2). This was also comparable to the concentration ratios in highway runoff. With respect to highway runoff, Cu and Zn are the most relevant and frequently measured heavy metals (Göbel et al. 2007; Zandres 2005; Ingvertsen et al. 2012; Li and Davis 2008). Considering the concentration ranges from Göbel et al. (2007), the concentration ratio of Cu/Zn ranged from 0.05 to 0.24. This was similar to the Cu/Zn ratio in the SDPL which ranged from 0.07 to 0.34. However, the Cu/Zn ratio in the FMC samples were higher ranging from 0.34 to 0.9 which indicates that Cu removal by adsorption process in the filter media layer is higher as compared to Zn.

As can be seen in Table 2, the heavy metal concentration dataset did not show any direct relation with the operation time (age of the treatment system), thickness of SDPL, or ratio of impervious catchment area to filter area. The levels of heavy metals, specifically Zn, Pb, and Cu varied among the sites. The thickness of the SDPL as well as age of GSA-H was relatively higher than that of GSA-W; however, the concentrations of Zn and Pb at GSA-W were 2 folds higher than that found at GSA-W, Cu was higher at GSA-H, but Cr, and Ni concentrations were very comparable. Grab runoff water sample analysis indicated that the concentrations of Cu and Zn measured at GSA-W were up to 3 folds higher than the levels at GSA-H (data not indicated).

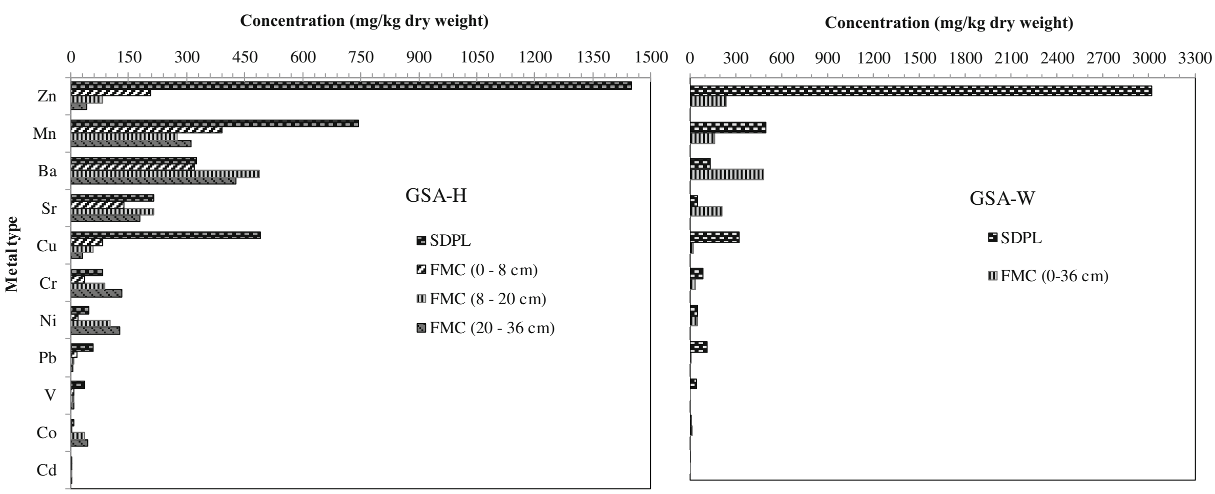


Fig. 4 Profiles of heavy metals in SDPL and filter media layer collected from two media filtration treatment systems

Average daily traffic density, seasonal influences, type of asphalt, motor vehicle types, frequent congestion, braking or acceleration are all factors that cause site-to-site variability in the concentrations of roadway runoff pollutants (Helmreich et al. 2010; Sansalone and Buchberger 1997; Ingvertsen et al. 2012). The variations observed in metal concentrations in SDPL and FMC samples could be attributed to the aforementioned factors. Despite those variations, the distribution of the heavy metals in both stormwater filtration systems was very similar.

3.4 Metal Concentrations as a Function of Particle Size

The average metal concentration in each particle size fraction is shown in Table 3. As can be seen, except for slight higher concentrations in the size fraction 200–630 μm, no clear trend in metal concentrations dependency on size fractionations could be observed. This indicates that the metals were uniformly adsorbed to the whole particle size range (0–2000 μm). The average concentrations of Cr, Cu, Ni, Pb, and Zn in all size ranges were in the range of 131–159, 301–342, 47–8, 105–148 and 2692–3265 mg/kg, respectively. It is important to note that over 90 % of the SDPL was comprised of particles with diameter smaller than 630 μm, thus most of the metal loads were captured in this fraction.

The metal load of the whole sample and the contribution to this load of each particle size fraction has been calculated using the metal concentration data (Table 3) and the particle size distribution (Fig. 2). The metal load contributed by each particle size fraction to this load is shown in Fig. 5. Results showed that the majority of metal masses resided in particles smaller than 63 μm (Fig. 5). In the particle mass distribution analysis, over 71 % of the total mass of SDPL was represented by the smallest fraction (<63 μm) and over 60 % of the trace metals were bound to the fine fraction (<63 μm) of SDPL. Low percentages of metal mass in the larger size fraction (>630 μm) were primarily due to the fact that less than 10 % of total mass of SDPL was associated with the particle size greater than 630 μm. The results indicated that particle treatments, specifically removal of the fine size fraction <200 μm plays a vital role in removing pollutants from roadway runoff. Several researchers reported that highest metal concentrations were consistently found in the fine particle size fractions (<250 μm) (Zandres 2005; Zhao et al. 2010). In road-deposited sediment samples, Zandres (2005) observed that a high percentage of the total metal load was associated with particles smaller than 125 μm (64 % of Zn, 57 % of Cu and 46 % of Pb). Similarly, Zhao et al. (2010) reported that 80 % of the heavy metals in road-deposited sediments were mainly associated with the <250 μm size fraction.

3.5 Remaining Heavy Metal Removal Efficiency

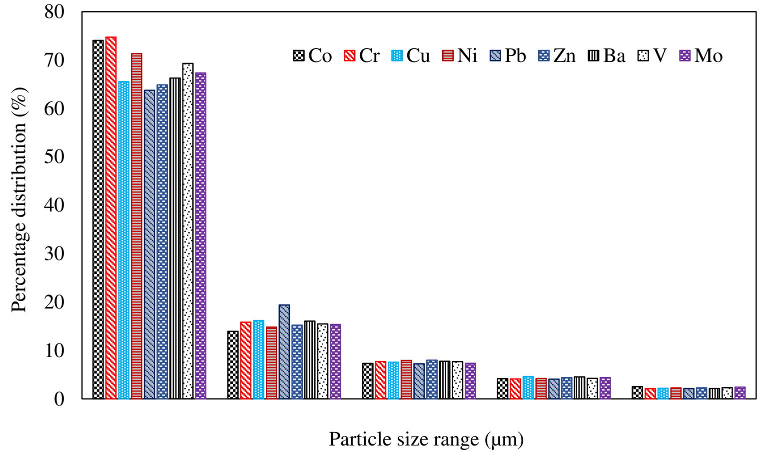
The performance of the core filter media from GSA-H in reducing the heavy metal levels from the synthetic solution is presented in Fig. 6. The column experimental data indicated that the filter media in operation still has high affinity for the removal of Cr, Cu, Pb, Ni and Zn. Over 90 % removal efficiency of all five tested heavy metals was achieved till a total flow through of 2800 BV

Table 3 Total metal concentrations determined for each particle-size fraction of SDPL collected from GSA-H and the metal concentration of the bulk SDPL sample

Particle size (μm)	Total metal concentration (mg/kg)														
	V	Cr	Co	Ni	Cu	Zn	Rb	Sr	Zr	Mo	Cd	Sn	Sb	Ba	Pb
<63	88	157	15	53	301	2692	46	135	153	11	<1	63	31	329	108
63–200	88	150	12	50	335	2847	51	142	122	11	<1	64	31	359	148
200–630	96	159	14	58	342	3265	58	141	114	12	<1	70	35	379	121
630–1000	81	131	13	47	321	2771	54	127	118	11	<1	62	30	342	105
1000–2000	89	136	15	51	304	2900	51	132	114	12	<1	64	31	323	109
Whole sample[a]	88	147	14	52	321	2895	52	135	124	11	<1	65	32	346	118

[a] Due to the uniform heavy metal distribution in different size fractions, the mean values were considered as concentration of the whole sediment

Fig. 5 The contribution of each particle size fraction to the total metal load in SDPL



(i.e. 540 l). A selectivity series can be determined as follows: Pb > Ni = Zn > Cu > Cr. The removal efficiency of Cr, Cu, Ni and Zn slightly decreased after a total flow through of 3500 BV (675 l). However, removal of Cr was significantly reduced to less than 20 % and after a total flow though of 4440 BV (860 l) and full breakthrough (i.e. $Ce/C0 = 1$) was achieved after applying 6520 BV (1260 l). Regarding road runoff treatment, the Austrian standard (2506-2, ÖNORM B 2012) has set a minimum removal requirements of 80 % for Cu and 50 % for Zn removal. After the passage of 5070 BV (980 l), the removal of Cu was consistently below 80 % but Zn removal was still greater than 77 % which is above the requirement.

The effluent concentrations of Cu, Ni, Pb and Zn were reduced to significantly low levels during the early loading but have slightly increased over the course of the experimental run (Fig. 6). Nevertheless, till the end of the experiment, the effluent concentrations of Pb and Ni were still below maximum effluent concentrations set in the Austrian regulation regarding groundwater protection (BMFLU. 98 2010). The column influent and stormwater concentration matrix for Cr is low (<50 μg/l) which is comparable to the maximum effluent concentration set in the Austrian regulation (i.e. 45 μg/l). As a result, Cr values might not be representative for the lifespan estimation. The test was subsequently terminated when 6800 BV (1310 l) feed solution has been applied, as the removal of Cu has remained consistently less than 80 % which is below the minimum requirement as to the (2506-2, ÖNORM B 2012). Therefore, in this study, the sorption capacity of the filter media used in the filtration systems would be limited by the removal of Cu.

3.6 Remaining Lifespan of Filter Media for Heavy Metal Removal

The column sorption data (Fig. 6) and annual load of heavy metals (Table 1) were used to estimate the remaining metal sorption capacities in the field filtration system. In roadway runoff, large fractions of the heavy metals, typically >50 % of Cr, Cu, Ni and Zn and >80 % Pb, exist in particulate form (Helmreich et al. 2010; Gromaire-Mertz et al. 1999; Ball et al. 1998). This was also evidenced in the present study that large fraction of the total load of Cu, Pb and Zn was particle bound being captured in the SDPL (see section 0). Therefore, to calculate the remaining lifespan of the filter media, it was assumed that only 50 % of the metal loads/concentrations are in dissolved fraction. The dissolved fraction of heavy metals could be effectively removed by the filter media mainly via mechanisms such as sorption, filtration, ion exchange and complexation reactions (Fuerhacker et al. 2011; Sansalone and Buchberger 1997). The lifespan of each metal was then obtain by dividing the total amount of a metal adsorbed till FMC exhaustion or experiment termination by the annual load. The remaining lifespan of the filter media simulated in column sorption is shown in Table 4. Over the experimental running time, filter media exhaustion was observed for Cu and Cr, but effluent concentrations of Ni and Pb as well as removal efficiency of Zn met the requirements. The results demonstrated that Cr and Cu sorption capacities are the determinant factors limiting the lifespan of the filter media. Thus, the filter media could remain operation for up to 34 years. It is important to note that removal of the dissolved fractions in the surface deposited sediment is expected by processes

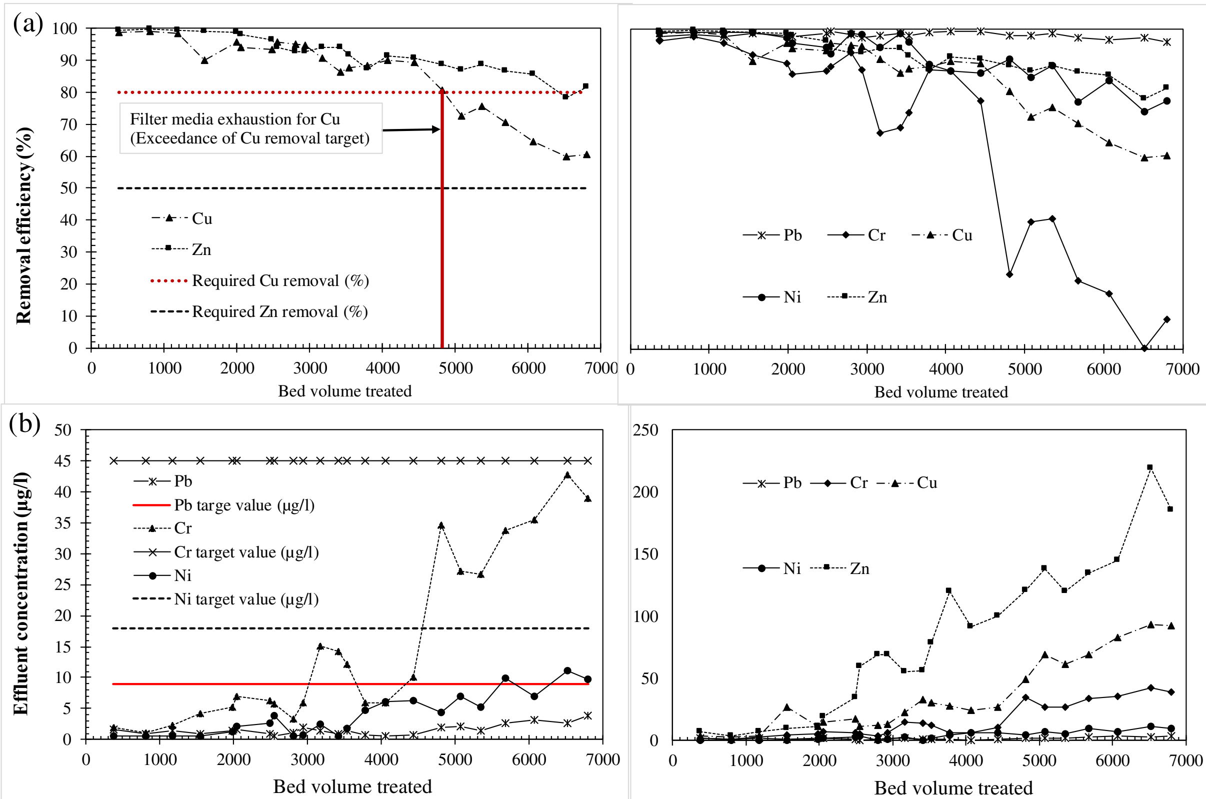


Fig. 6 Removal efficiency (%) of heavy metals (**a**) and effluent concentrations (**b**) versus column flow through number of bed volumes (1 BV = 193 ml). The lines are not fitting functions; they connect points to facilitate visualization

such as surface complexation and precipitation. As a result, the lifespan would be higher than the calculated ones.

Over the experimental running time, filter media exhaustion was observed for Cu and Ni, but effluent concentrations of Ni, Pb and removal of Zn met the requirements. The results demonstrated that Cr and Cu sorption capacities are the determinant factors limiting the lifespan of the filter media. Thus, the filter media could remain operation for up to 34 years. It is important to note that removal of the dissolved fractions in the surface deposited sediment is expected by processes such as surface complexation and precipitation. As a result, the lifespan with respect to heavy metal would be higher than the computed ones.

The long-term sorption capacity and lifespan of a filtration system depends on the composition of the filter media. The Aquafilt used in the investigated filtration

Table 4 Summary of the column sorption results and calculated lifespan of the core filter media from GSA-H

Heavy metal	Cr	Cu	Ni	Pb	Zn
Mean column influent (µg/l)	47	250	50	85	1020
Column annual load (mg)	3.93	22.5	5.1	11.3	90
Total loaded into column (mg)	88	380	91	166	1999
Column maximum effluent (µg/l)	43	93.7	16.1	3.8	219
Targeted maximum effluent (µg/l) (BMFLU. 98 2010)	45	1800	18	9	–
Removal efficiency at FMC exhaustion (%)	<10	<80	68	>97	>77
Minimum removal efficiency (%) (2506-2, ÖNORM B 2012)	–	80 %	–	–	50 %
Years to exhaustion	45	34	36	34	44

systems is composed of several filter media for which zeolite is one of the components. Numerous researchers reported that zeolite has promising performance for the removal of heavy metals from stormwater runoff (Fuerhacker et al. 2011; Wium-Andersen et al. 2012; Genç-Fuhrman et al. 2007). Column sorption experiment with fresh unloaded Aquafilt similar to that installed at GSA-H showed high heavy metal removal efficiencies (data set not indicated). The metal sorption capacity of the filter bed in the filtration system might possibly increase overtime due to the enrichment of organic matter content transported with the incoming runoff particles. In addition, filtration of particles in the pores of the filter bed will cause reduction in infiltration, and this in turn increase the rate so that the retention time of the polluted runoff. The increased retention time may result in greater adsorption of dissolved metals.

4 Discussion

The SDPL acts as a filter itself, which enhances pollutant removal, but it obviously reduces the hydraulic performance of the filtration system. The geotextile was placed on top of the filter media to act as a barrier to remove particles from reaching and clogging the filter bed. The accumulation of the fine particles in the SDPL appears to confirm that the geotextile itself was performing much of the filtration. Removal of the SDPL on a regular basis, (approximately every 7 years) and replacement of the geotextile 300 g/m^2 would be very important to maintain an acceptable infiltration rate. Geotextile layers placed in a stormwater treatment system enhanced treatment performance; however, it adversely impacted the hydraulic performance of the system (Paul and Tota-Maharaj 2015). Back flushing was recommended as an effective technique to remove the clogging particles deposited on the geotextile layer and recover the hydraulic conductivity (Paul and Tota-Maharaj 2015; Koerner and Koerner 1992). Based on laboratory experiments, some researchers (Hatt et al. 2008; Clark and Pitt 2009) suggested that scraping the top layers of sediment from stormwater infiltration systems periodically can reduce clogging and restore hydraulic performance, though hydraulic recovery was reported to be incomplete (Hatt et al. 2008) or unsustainable (Clark and Pitt 2009) in laboratory experiments. Mousavi and Rezai (1999) investigated infiltration basin (used for recharging to groundwater) constructed on sandy-loam soils and observed that scraping off the top 5 cm (deposited sediment layer and top soil) resulted in a restoration to about 40 % of the original infiltration capacity.

The particle size distribution of SDPL was generally in close agreement with the size distribution reported for highway and motorway runoff (Furumai et al. 2002); however, the median particle size of SDPL in this study was lower than those found for sediments accumulated on stormwater detention basin (Sébastian et al. 2014) and road-deposited sediments (Herngren et al. 2006; Zhao et al. 2010). Several previous studies found that in roadway runoff, fine particles less than 50 μm in diameter accounted for more than 70 to 90 % of the weight of the TSS load carried by runoff (Li et al. 2006; Haile et al. 2014; Andral et al. 1999). Furumai et al. (2002) reported that the median particle size of particles from urban highway runoff was 20 μm which is equivalent to the d50 of SDPL. However, the d50 of the SDPL was lower than that of sediments accumulated on stormwater detention basin which ranged from 24 to 50 μm (Sébastian et al. 2014) and d50 of road-deposited sediments ranged from 100 to 200 μm (Herngren et al. 2006; Zhao et al. 2010). This suggests that in road-deposited sediments, the particles with diameter smaller than 200 μm are of particular concern but in roadway runoff, the fine particles (<50 μm) are more important. The results of the present study and literature survey values (Haile et al. 2014) indicate that suspended solids carried by stormwater runoff and sediments accumulated within stormwater treatment systems are usually smaller in size than street dirt and road-deposited sediments. In the literature, the range and median particle size distribution of solids in roadway runoff, road-deposits and sediments accumulated on stormwater detention systems were significantly different from site to site or among different source areas. The reasons for these controversies are differences in sampling method and transport of particle (Sansalone and Buchberger 1997), analytical method (sieving analysis or particle counter method), climatic influences, atmospheric deposition, vehicular traffic density and road maintenance (Helmreich et al. 2010).

Concentrations of metals in sediment deposited within stormwater treatment systems can be highly variable. Several recent studies assessed the concentrations of heavy metals, particularly Cd, Cr, Cu, Ni, Pb, and Zn captured within stormwater treatment systems. Despite the large variations in concentration, most researchers agree that the majority of metals tend to accumulate in the top layer of stormwater treatment systems and concentrations decreased with depth of the filter bed (Paus 2999; Ingvertsen et al. 2012; Li and Davis 2008; Jensen et al. 2006). The concentrations measured in the present study compared to literature values are shown in Table 5. The concentrations of heavy metals, particularly Cu and Zn, in the SDPL were significantly higher than the levels found in FMC sample collected from bioretention and infiltration swales (Table 5).

Concerning the GSA-H, the concentrations of heavy metals in SDPL after 7 years of operation (sampling in 2012) were over two folds higher than the levels determined after 2 years of operation (sampling in 2008) as reported by Fuerhacker et al. (2011) (see Table 5), evidencing surface accumulation of heavy metals in the SDPL over the operation time. The mean concentrations of Cr, Cu, Pb and Zn found in the present study were well above the levels reported by several authors (Paus 2999; Ingvertsen et al. 2012; Li and Davis 2008). For example, the mean Cu and Zn concentration in the SDPL observed in this study were 3 to 60 times higher than those reported for the top layer (0–5 cm) infiltration systems aged 2 to 16 years (Table 5). Pb concentrations in the SDPL were within the range of the levels reported by Ingvertsen et al. (2012) and Jensen et al. (2006) but far below the concentration reported by Li and Davis (2008). It is apparent that the pollutant loads entering a stormwater treatment system could significantly vary from site to site due to differences in climatic influences, vehicular traffic density, atmospheric deposition, road maintenance and characteristics of the catchment area. The higher metal concentrations observed in this study could mainly be due to the small filtration system size compared to the impervious catchment area, so that input load is high compared to the input loads in bioretentions and road-side infiltration swales. For example, the roadside infiltration swales investigated by Ingvertsen et al. (2012) were sized at 7 to 28 % of their impervious catchment area which is by far larger than the sizing of the filtration systems (i.e. 0.25 to 0.37 %) examined in this study. Interestingly, the concentrations of heavy metals in the SDPL were comparable to the levels found in roadside-deposited sediments as reported by Gunawardana et al. (2014). The total concentrations of metals in sediments deposited on urban road surfaces were 11,710 mg/kg Al, 20,310 mg/kg Fe, 30 mg/kg Cr, 400 mg/kg Cu, 420 mg/kg Mn, 30 mg/kg Ni, 170 mg/kg Pb and 910 mg/kg Zn (Gunawardana et al. 2014).

Previous studies by several researchers focused mainly on heavy metals which are toxic (i.e. Cd, Cu, Cr, Ni, Pb and Zn) (Paus 2999; Ingvertsen et al. 2012; Li and Davis 2008). This study reports additional information regarding the presence of a wide range of heavy

Table 5 Concentrations of heavy metals (mg/kg dry matter) in sediment and filter media layer compared to literature values and sediment quality

Cd	Cr	Cu	Ni	Pb	Zn	Source
0.6	81	490	46	57	1449	SDPL (GSA-H)
0.03–0.34	35–131	30–83	19–126	5–19	40–206	FMC (GSA-H)
0.49	86	326	52	114	3016	SDPL (GSA-W)
0.03–0.1	24–49	20–24	31–69	6.1–10.1	152–168	FMC (GSA-W)
0.1	37	230		47	796	Fuerhacker et al. 2011[a]
		75		399–660	114–532	Li and Davis 2008[b]
0.13–0.71	11–67	12–57		20–108	44–259	Ingvertsen et al. 2012[c]
0.35–0.70	13–136	114–598		49–144	190–273	Jensen et al. 2006[d]
<0.88–1.87		9.7–37.8			44–89	Paus et al.[e]

SDPL surface deposited sediment 2.5 to 4.5 cm, *FMC* filter media core 36 cm

[a] Surface deposited particle layer from GSA-H after in operation for 2 years

[b] Bioretention media in operation for 5 years receiving parking lot runoff (USA)

[c] Roadside infiltration swales in operation for 6 to 16 years, (highway, Germany)

[d] Surface deposits in roadside swales in operation for up to 16 years (highways, Denmark)

[e] Bioretention media in operation for 2 to 8 years (metropolitan area, USA)

metals such as Ba, Mn, Sr, Ti, and V with high concentrations found in the sediments deposited at the surface of stormwater filtration systems. For example, the metals Ba, Ti, V are included in the Annex 2 of the Austrian groundwater guideline but not regulated with target values. Thus, there is a demand to further investigate the behaviour and mode of action of those heavy metals.

The concentration of heavy metals as a function of the particle size of sediments (roadway runoff and road-deposited) has been investigated by several researchers and invariably the highest concentrations were consistently found in the fine particle size fractions (Herngren et al. 2006; Zandres 2005; Zhao et al. 2010). Results from this study did not support the assertion that the heavy metals were rather uniformly distributed in the different SDPL size fractions (Table 3). In road-deposited sediment samples, Zandres (2005) observed that a high percentage of the total metal load was associated with particles smaller than 125 μm (64 % of Zn, 57 % of Cu and 46 % of Pb). Similarly, Zhao et al. (2010) reported that 80 % of the heavy metals (Cd, Cr, Cu, Ni, Pb and Zn) in road-deposited sediments were mainly associated with the <250 μm size fraction. The heavy metal distribution of road-deposited sediments indicated that particle retention (removal), specifically removal of the size fraction <250 μm plays a vital role in removing pollutants from roadway runoff. However, results of this study showed that despite the uniform concentration distribution over 60 % of the trace metals loads were bound to the fine fraction (<63 μm) of SDPL.

5 Conclusion

In this study, two stormwater (parking lot and highway runoff) filtration systems were investigated after 5 to 7 years in operation and the following conclusions are drawn:

- In situ infiltration test results showed that saturated hydraulic conductivity of the filtration systems decreased over the course of operational time but still acceptable in accordance with the Austrian standard design guidelines. This is mainly attributed to the deposition of suspended solids, straining of particles in the pores and compaction due to hydraulic loading.
- The hydraulic performance of the system could be recovered through removal of the accumulated particle layer and replacement or back flushing of the geotextile on periodic bases, approximately every 7 years.
- Particle size distribution of the solids deposited at the surface of the filtration system (i.e. SDPL) showed that 70 % of the masses comprised of particles smaller than 63 μm, and the particles smaller than 200 μm accounted for 85 % of the total mass. Metal concentration distributions along the different particle size fractions were uniform; however, the distributions of metal masses across particle size fractions followed patterns of particle mass distribution. For instance, 60 % of the trace metals were bound to the particles smaller than <63 μm.
- Concentration profiles of heavy metals, particularly those relevant in highway runoff (Cu, Pb and Zn), showed a high accumulation in the SDPL significantly decreasing with the media of filter media. This implies that large fractions of the input metal concentrations were particulate-bound and during stormwater treatment, removal of the fine particles plays an important role. Furthermore, other heavy metals (such as Ba, Ti, V, Sr) with concentrations comparable to the commonly investigated heavy metals (e.g. Pb, cu and Zn) were identified in the SDPL and core filter media which indicates comparable concentrations in runoff. There is still a demand to assess the sources, concentration ranges and potentials for toxic problems.
- Column test with FMC suggested that the filter media in operation is highly efficient for simultaneous adsorption of Cr, Cu, Ni, Pb and Zn from synthetic stormwater runoff. Based on the heavy metal loads applied in column test and computed annual input loads, the filter media can remain in operation for over 34 years. In addition, it is likely that the build of a particle layer on top of the filter media have a tendency for the sorption of dissolved heavy metals and a longer lifespan can be expected. Therefore, lifespans will be dependent mainly on the long-term hydraulic performance of the systems.

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