Occurrence and Concentration of 6 Metals and 28 Organic Micropollutants in the Forebays of Bioretention Facilities

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Abstract: Pollutant loads in urban runoff from anthropogenic sources contribute to degradation of downstream waters. Cities are turning toward green infrastructure to manage urban stormwater. Bioretention is popular as green infrastructure and is commonly installed to remove runoff pollutants. A significant proportion of pollutants in urban runoff are particulates or particulate-bound and are effectively removed in bioretention cells. Pollutants accumulate in concentrated areas of the bioretention (e.g., forebays, inlets, surficial filter layers), which require maintenance to restore effective treatment and to increase the operational lifespan. Particles trapped in forebays risk diminished effectiveness of the pretreatment, which may eventually lead to filter clogging and leaching of toxic pollutants. Studies have examined pollutant accumulation and distribution in bioretention filter media, but less is known about processes in bioretention forebays. In this study, 28 bioretention forebays were examined in urban areas of Ohio and Michigan (United States) as well as Stockholm and Malmö (Sweden) to investigate the occurrence and accumulation of metals (i.e., Cd, Cr, Cu, Ni, Pb, and Zn) and 38 analytes of organic micropollutants [OMPs, i.e., alkylphenols, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and phthalates]. Investigated metals were present in all 28 samples, except Cd detected in 27 samples. Of 38 OMP analytes, 31 were detected in at least one sample. PAHs and PCBs were the most frequently detected pollutants found at all examined sites. In general, high concentrations of pollutants were detected in all forebay sediments. Cu, Ni, Zn, PAHs with high molecular weight, and PCBs were detected at concentrations above US and Swedish soil quality guidelines. It was concluded that forebays regularly need to be excavated to maintain their function, and excavated sediments must be handled safely during maintenance work and disposal. **DOI: 10.1061/JSWBAY.SWENG-583.**

Practical Applications: High pollutant concentrations in forebay sediments have critical implications for bioretention operators and regulators. Previous studies indicate clogging as a limiting factor for long-term function of bioretention systems, and sedimentation forebays are used to reduce the sediment load reaching the filter surface. However, operators should consider that removed sediment may be contaminated, exceeding guidelines and soil screening levels, and that removed material should be handled accordingly. Zn was the metal most commonly exceeding the Eco-SSL and Swedish EPA guidelines, followed by Cu and Ni. PAH-H exceeded the US EPA Eco-SSL and Swedish EPA standards, PAH-M and Σ7PCBs exceeded Swedish EPA. Concentrations exceeding Swedish EPA may be classified as hazardous waste, need certification for transportation, and must be disposed of at licensed landfill. The large variation between the different forebays (land use, catchment characteristics) underlines that sediment removal frequency and disposal are site-specific and difficult to generalize. However, the recommendation for bioretention operators is regular monitoring and sampling to inform forebay maintenance procedures.

Introduction

Urban stormwater carries large amounts of anthropogenic pollutants, including nutrients, heavy metals, bacteria, hydrocarbons, and other emerging pollutants of concern, which contribute to degradation of receiving waters and pose risks to human health and safety (Müller et al. 2020). For example, metals in stormwater (e.g., Cd, Cr, Cu, Ni, Pb, Zn) have been recognized as contaminants of concern for humans and aquatic life (Eriksson et al. 2007) and are present at toxic levels (Cu, Pb, and Zn) in road runoff

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(USEPA 1983). Recently, studies have identified organic micropollutants (OMPs) as a pollutant group of concern in urban runoff that may have negative impacts on humans and aquatic habitats (Barbosa et al. 2012; Markiewicz et al. 2017). OMPs such as alkylphenols, phthalates, and polycyclic aromatic hydrocarbons (PAHs) are considered genotoxic substances (Markiewicz et al. 2020) while phthalates and nonylphenols as endocrine disruptors (Björklund et al. 2009). Similarly, petroleum hydrocarbons are suspected carcinogens (Fent 2003; LeFevre et al. 2012; Mastrangelo et al. 1996), while polychlorinated biphenyls have been shown to increase the risk of certain cancers and have adverse effects on human reproduction (Helmfrid et al. 2012).

Bioretention cells, also referred to as biofilters, biofiltration systems, or raingardens, are a common technique implemented by cities worldwide to treat urban stormwater (Kratky et al. 2017; McGrane 2016; Winston et al. 2020). Bioretention systems are landscape depressions backfilled with engineered soil media, generally topped with mulch, and planted with native plants (Tirpak et al. 2021). Paus et al. (2014) showed that a properly designed bioretention can maintain key functions such as infiltration and metal removal. Thus, many filtering systems are equipped with a sedimentation device or forebay to settle out pollutants before runoff reaches the filter (Maniquiz-Redillas et al. 2014). Kallin et al. (2004) and Blecken et al. (2017) recommended that biofilter design should incorporate a forebay for settling large suspended sediments.

A forebay (e.g., Figs. S1.1–S1.22) is an energy dissipation and sedimentation device (e.g., settling or sediment basin, inlet lined with large rocks, etc.) placed near the inlet to the bioretention cell that slows flow velocities and promotes sedimentation and large debris removal to minimize sediment transport into the filter, erosion, and clogging (Al-Ameri et al. 2018; Erickson and Hernick 2019; Maniquiz-Redillas et al. 2014; McNett and Hunt 2011; Winston et al. 2023). The size of bioretention forebays is often approximately 10% of the design surface area (City of Portland 2020; Minnesota Pollution Control Agency 2022); however, the design can vary depending on local statutes, policies, and practices. Scientific studies on the performance of forebays for pretreatment of stormwater are rare. Previous studies on large sedimentation basins have shown that a large proportion of particle-bound pollutants accumulate in sediments (German 2003; Grottker 1990) and sediments accumulate in forebays. Another study of stormwater wetlands and wet ponds (McNett and Hunt 2011) assessed concentrations of metals in forebay sediments and found potentially toxic levels of Cu, Ni, and Zn that may pose a threat to aquatic health. However, when comparing these concentrations with US EPA 40 CFR503 (USEPA 1993), they are below threshold values and thus would not pose a threat to the environment after subsequent excavation and land application. Nevertheless, potential presence of PAHs and PCBs [not assessed in the McNett and Hunt (2011) study] may make land application more difficult. However, since wetlands and wet ponds are commonly larger than bioretention, the forebays in wetlands and wet ponds (10%–20% of total area) are also larger than in bioretention facilities (10% of a smaller total area) (Maniquiz-Redillas et al. 2014; Schaad et al. 2008; Winston et al. 2013). While most metals are bound to small particle fractions that are not efficiently removed by small forebays, a significant portion of metals may be associated with larger particles (Karlsson and Viklander 2008b; Stone and Marsalek 1996) and thus may accumulate in the forebays of bioretention cells. Previous studies have emphasized the need for frequent maintenance and removal of accumulated sediments in pretreatment devices to restore storage volume and prevent contamination of downstream facilities and/or waterbodies (Blecken et al. 2017; Grimm et al. 2023; McNett and Hunt 2011). Since forebays regularly need to be excavated to maintain their function, it is important to know what contaminants and substances are present in the sediments to handle and dispose of them safely.

To date, several studies have focused on pollutant retention in the filter material; however, only a few studies have examined forebays in bioretention systems and little is known about the characteristics of forebay sediments. Given the potential risks to human health and aquatic ecosystems as well as possible impacts to bioretention performance associated with sediment accumulation in forebays, it is important to understand the pollutant composition in forebays and evaluate how sediments can be handled safely during maintenance and disposal. In the present study, we examined 28 bioretention forebays located in the United States (Ohio and Michigan) and Sweden (Stockholm and Malmö) to investigate the pollutant concentrations and characteristics of the sediments, targeting metals commonly occurring in stormwater (i.e., Cd, Cr, Cu, Ni, Pb, and Zn) and four groups of organic micropollutants (OMPs) (i.e., alkylphenols, PAHs, phthalates, and PCBs). Concentrations were compared with various regulatory guidelines to determine the environmental risks posed by pollutants accumulating in bioretention forebays.

Materials and Methods

Field Sites and Sampling Methods

In total, 28 bioretention cell forebays were included in this study: 18 in Ohio and two in Michigan (United States) and eight in Sweden (Fig. 1). The bioretention sites were located in urban areas with various land uses in their catchment areas (e.g., residential, parking/roads, downtown urban, industrial, fuel station; Table 1).

The examined forebays had surface areas that varied from 0.002% to 2% of the catchment area, while the filter areas varied from 0.3% to 20% of the catchment area (Table 1). At some sites, the forebay was comprised of a small (e.g., sites 5, 6, 8) or large (e.g., sites 1–4) settling basin by the inlet that only filled up during precipitation events. At other sites, the forebay was comprised of a small steel (e.g., sites 10, 21, 22, 23, 24) or concrete (e.g., sites 25, 26, 27, 28) settling basin or rock structure (e.g., sites 7, 14, 15, 16, 17, 18, 19, 20) by the inlet to reduce inflow velocity and prevent erosion. In some instances, other structures that allowed the settling and accumulation of sediments were used (e.g., sites 9, 11, 12, 13; see Figs. S1.1–S1.22).

Sediment samples were collected from the forebays in November 2019–April 2021. Samples were collected using a steel spade to dig or scrape approximately 1 kg of accumulated sediment from each forebay, which was subsequently placed in diffusion-tight plastic bags (18 cm × 35 cm) that were sealed shut with cable ties. The outdoor temperature during sampling was approximately −12°C to +6°C, and the samples were refrigerated prior to laboratory analysis.

Analysis

All samples were sent to an accredited laboratory for pre-treatment and analysis. Sediment samples from all 28 sites were analyzed for concentrations of Cd, Cr, Cu, Ni, Pb, and Zn. To determine the total metal concentration, samples were dried at 50°C and sieved (2 mm) according to Swedish standards (SS 2004, 1993). Drying at 105°C was conducted in parallel with sample analysis to correct to the dry matter (DM) concentration. Microwave-assisted digestion was performed on dried samples using 5 mL of concentrated HNO_3 and 0.5 ml of H_2O_2.

Sediment samples from 16 sites (marked with "a" in Table 1) were also analyzed for concentrations of four groups of OMPs

Fig. 1. Map of bioretention cells in: (a) Ohio and Michigan, USA, and in (b) Malmö and Stockholm, Sweden. (Map data ©2024 Google.)

(i.e., 16 PAHs, 7 PCBs, 13 phthalates, and 2 alkylphenols) using gas chromatography–mass spectrometry. Concentrations of 16 PAHs, i.e., naphthalene (Nap), acenaphthylene (Acyl), acenaphthene (Acen), fluorene (F), phenanthrene (Phen), anthracene (A), fluoranthene (Fluo), pyrene (Pyr), benzo(a)anthracene (BaA), chrysene (Chry), benzo(b)fluoranthene (BbF), benzo(k)fluoranthene (BkF), benzo(a)pyrene (BaP), dibenzo(a,h)anthracene (DahA), benzo(g,h,i)perylene (Bper) and indeno(1,2,3-cd) pyrene (IP), were analyzed according to US EPA 8270 (Pitt et al. 1994) and ISO 18287 (ISO 2006). Σ16PAHs was calculated as the sum of the concentrations of all 16 PAHs. The total PAHs with low molecular weights (PAH-L) was calculated as the sum of the concentrations of naphthalene, acenaphthylene, and acenaphthene; total PAHs with medium molecular weights (PAH-M) as the sum of the concentrations of fluorene, phenanthrene, anthracene, fluoranthene, and pyrene; and total PAHs with high molecular weights (PAH-H) as the sum of the concentrations of benzo(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, indeno(1,2,3-c,d)pyrene, dibenzo(a,h)anthracene, and benzo(g,h,i) perylene. Concentrations of seven PCB indicator congeners, i.e., PCB 28, PCB 52, PCB 101, PCB 118, PCB 153, PCB 138, and PCB 180, were analyzed following DIN ISO 10382 (DIN ISO 2002). Σ7PCBs was calculated as the sum of these seven PCBs. Concentrations of 13 phthalates, i.e., dimethylphthalate (DMP), diethylphthalate (DEP), di-*n*-propylphthalate (DPP), diisobutylphthalate (DIBP), di-*n*-butylphthalate (DBP), di-*n*-pentylphthalate (DNPP), di-*n*-octylphthalate (DNOP), di-(2-ethylhexyl)phthalate (DEHP), butylbenzylphthalate (BBP), dicyclohexylphthalate (DCP), diisodecyl phthalate (DIDP), diisononyl phthalate (DINP), and di-*n*-hexylphthalate (DNHP) were analyzed following E DIN19742 (DIN 2014). The concentrations of two alkylphenols, i.e., 4-tert-octylphenol (OP) and 4-nonylphenol (NP), were also analyzed.

Besides the metals and OMPs, total organic carbon (TOC) was measured using CSN EN 13137 (CSN EN 2018) and CSN ISO 10694 (CSN ISO 1995). Loss on ignition (LOI) was measured using gravimetric analysis based on CSN EN 12879 (CSN EN 2014), CSN 72 0103 (CSN 2009), and CSN 46 5735 (CSN 1991). Dry matter (DM) was measured using appropriate methods for each pollutant group.

For data analyses, comparisons, and to illustrate pollutant distribution and concentrations in bioretention forebays, boxplots and descriptive statistics (median, min, max) were created in Minitab 20.4.

Results and Discussion

Metals

Occurrence

All analyzed metals were detected in all 28 examined forebay samples (Table 2), except Cd (detected in 27 of 28 samples). The non-detectable levels of Cd were from Bioretention Site #23 (Table 1) located in Sweden. This site had only been in operation for two years and was among the youngest of the facilities included in the study. Maintenance of the forebay with removal of sediment had been performed at sites #21–#23 after one year of operation. In a previous review study of micropollutants in stormwater outlets, Mutzner et al. (2022) presented a top-10 list of pollutants with high

Table 1. Bioretention site, age, site location, catchment area characteristics, catchment area, forebay area, and filter area

Site	Age (year)	Site location	Catchment area characteristics	Catchment area (Ca; m^2)	Forebay area (FbA; m^2)	Filter area (FA; m^2)	FbA/Ca (%)	FbA/FA (%)	FA/Ca (%)
1[a]	9	Upper Arlington, Ohio	Residential	318,000	20	950	0.01	2.11	0.30
2	9	Upper Arlington, Ohio	Residential	1,250,000	20	1,200	0.00	1.67	0.10
3	9	Upper Arlington, Ohio	Residential	224,000	10	900	0.00	1.11	0.40
4	9	Upper Arlington, Ohio	Residential	146,000	10	1,900	0.01	0.53	1.30
5	8	Westerville, Ohio	Parking/roads	12,000	1.5	600	0.01	0.25	5.00
6	8	Westerville, Ohio	Parking/roads	2,000	1	50	0.05	2.00	2.50
7[a]	7	Westerville, Ohio	Commercial	4,000	8	170	0.20	4.71	4.30
8	9	Columbus, Ohio	Parking/roads	4,500	2	580	0.04	0.34	13.0
9[a]	9	Columbus, Ohio	Downtown urban	300	1.5	40	0.50	3.75	13.0
10[a]	8	Columbus, Ohio	Downtown urban	50	1	10	2.00	10.00	20.0
11	12	Hamilton, Ohio	Industrial	4,500	10	200	0.22	5.00	4.40
12[a]	12	Hamilton, Ohio	Industrial	4,500	10	300	0.22	3.33	6.70
13	12	Hamilton, Ohio	Industrial	4,500	10	200	0.22	5.00	4.40
14[a]	11	Lansing, Michigan	Downtown urban	500	1	50	0.20	2.00	10.0
15	14	Ann Arbor, Michigan	Parking/roads	2,250	3	156	0.13	1.92	6.90
16[a]	8	Parma, Ohio	Fueling station	2,500	10	200	0.40	5.00	8.00
17	11	Kent, Ohio	Fueling station	800	1	70	0.13	1.43	8.80
18	13	Akron, Ohio	Parking/roads	6,500	1	180	0.02	0.56	2.80
19[a]	12	North Canton, Ohio	Fueling station	1,250	8	180	0.64	4.44	14.0
20	12	North Canton, Ohio	Fueling station	1,000	4	100	0.40	4.00	10.0
21[a]	2	Stockholm, Sweden	Road	340	1.5	20	0.44	7.50	5.90
22[a]	2	Stockholm, Sweden	Parking	340	1.5	20	0.44	7.50	5.90
23[a]	2	Stockholm, Sweden	Road	370	1.5	20	0.41	7.50	5.40
24[a]	2	Stockholm, Sweden	Parking	340	1.5	20	0.44	7.50	5.90
25[a]	2	Malmö, Sweden	Downtown urban	350	1	20	0.29	5.00	5.70
26[a]	2	Malmö, Sweden	Downtown urban	350	1	20	0.29	5.00	5.70
27[a]	2	Malmö, Sweden	Downtown urban	350	1	20	0.29	5.00	5.70
28[a]	2	Malmö, Sweden	Downtown urban	350	1	20	0.29	5.00	5.70

Note: FbA/Ca is the forebay area as a percentage of catchment area, FbA/FA is the forebay area as percentage of the filter area and, FA/Ca is the filter area in percentage of catchment area. The site age was determined at the time of sampling (i.e., November 2019 for sites 1–20 and April 2021 for sites 21–28). All forebay sediment samples were analyzed for metals content.
[a]Sites were also analyzed for OMP content.

Table 2. Occurrence, concentration, and detection limit (DL) of metals

Group/units	Metal	No. of samples	Occurrence >DL		All data			
			No.	%	Min	Median	Max	DL
Metals (mg/kg, DM)	Cd	28	27	96	<0.10	0.29	0.75	0.1
	Cr	28	28	100	5.06	21.2	78.9	—
	Cu	28	28	100	9.22	50.9	95.2	—
	Ni	28	28	100	6.89	18.4	128	—
	Pb	28	28	100	6.48	23.7	72.2	—
	Zn	28	28	100	80.6	243	1,440	—

occurrence and risk for surface waters, which included Cu, Zn, and Hg. In our study, two (i.e., Cu and Zn) of these high occurrence and risk metals were found in all samples of forebay sediments.

Concentrations

Few previous studies have examined metals in bioretention forebays (for data of previous studies, see Supplemental Materials Tables S1 and S2), and only two assessed concentrations of metals accumulated in forebay sediments of stormwater wetlands, ponds, and bioretention (McNett and Hunt 2011; Johnson and Hunt 2016). Compared with the forebays sampled herein (Fig. 2 and Table 2), McNett and Hunt (2011) report similar concentrations for Cr (20.0–28.3 mg/kg) and Ni (13.0–15.9 mg/kg) as well as lower concentrations for Cu (15.1–23.0 mg/kg), Pb (11.4–13.0 mg/kg), Zn (44–75 mg/kg), and Cd (below DL). There is no clear reason to

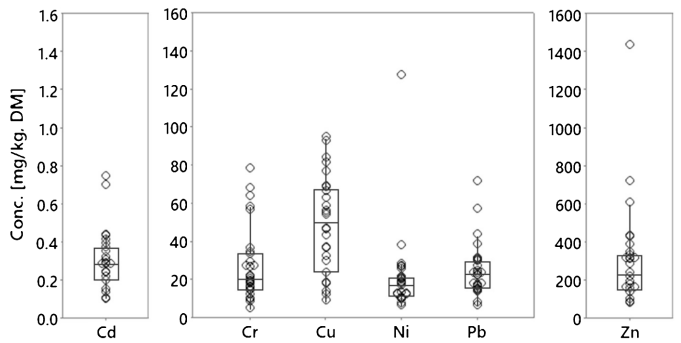

Fig. 2. Boxplots of concentrations of Cd, Cr, Cu, Ni, Pb, and Zn with the concentration of each sample should as an open symbol.

explain these generally lower concentrations in the McNett and Hunt (2011) study; however, sites were mainly younger in the their study (1–10 years) and the sites (draining institutional, commercial, and residential land uses) may have lower traffic intensity compared with a greater proportion of roads in our study. However, we cannot be certain of the reason for the differences.

Similarly, Johnson and Hunt (2016) found two to four times lower metal concentrations in the forebay of an 11-year-old bioretention facility (e.g., Cu mean: 11.16 mg/kg; Zn mean: 157 mg/kg).

Sediment from other stormwater treatment facilities, like ponds and sedimentation tanks, has been evaluated in other studies. Commonly, such larger facilities (e.g., evaluated by Karlsson et al. 2010), often trap finer sediments compared with the smaller forebays in this study. Metal concentrations are often inversely proportional to particle diameter; thus, the highest concentrations are found in the finest fractions (German and Svensson 2002). Consequently, Karlsson et al. (2010) in a study of sediments from stormwater ponds and sedimentation tanks report Cr (ca. 65–70 mg/kg), Cu (230–250 mg/kg), and Ni (28–34 mg/kg) concentrations of which were 2.5 times higher than the bioretention forebays herein. Cd (1.0 and 0.4 mg/kg in pond and tank sediments, respectively), Pb (80 mg/kg), and Zn (950–1,400 mg/kg) concentrations, however, were in the same range as in this study.

In contrast with ponds, catch basins (also referred to as gully pots) may be similar in size to forebays but are located underground. In a study of metal concentrations in sediments from stormwater catch basins, Karlsson and Viklander (2008b) concluded that most metals were associated with particles and dissolved) and reported median concentrations of Cd, Cr, Cu, Ni, and Zn similar or lower than those found in our study. Pun et al. (2019) reported that elevated Zn concentrations (267–3,700 mg/kg) were commonly found in road catch basin sediments, and high concentrations of Cu (27–1,020 mg/kg), Pb (21–332 mg/kg) and Cr (14–439 mg/kg) were also found), suggesting the possibility of sediment pollution with an ecological risk classified as considerable/moderate to high. In runoff sediments from stormwater traps in Bergen, Norway, concentrations were reported in a wide range between 0.02–11.1 mg/kg for Cd, 9–675 mg/kg for Pb, and 51.3–4,670 mg/kg for Zn (Jartun et al. 2008). Compared with these previous studies, metal concentrations in our study were found at lower levels than in Jartun et al. (2008), similar to levels in Karlsson et al. (2010), or higher levels than Johnson and Hunt (2016) and McNett and Hunt (2011). This underlines that variation between catchments and/or facilities can be high, which makes a generalized characterization of sediment from a specific type of sediment-trapping facility difficult.

OMPs

Occurrence

OMPs were detected in all samples (Table 3). In total, 31 of the 38 investigated OMP analytes were detected in at least one sample, including all 16 PAHs, all seven PCBs, both alkylphenols (i.e., OP and NP) and six of 13 phthalates (i.e., DIDP, DBP, DNPP, DEHP, DIDP, and DINP). PCBs were the most frequently detected OMPs and were found at all bioretention forebays with an average of 85% occurrence for the seven analyzed compounds. PCB analytes with high molecular weight (i.e., PCB138, 153, and 180) were detected in all samples, while PCB118, PCB101, and PCB52 were detected in 94% and PCB28 in 13% of all samples. PAHs were the second most frequently detected OMPs, and all samples contained at least one of 16 PAH compounds. The 16 PAH analytes (Table 3) were on average detected in 71% of samples, and the most frequent (BbF) was detected in all samples. OP was detected in 31% of samples and NP in 56% of samples. DEHP was the most commonly occurring phthalate, detected in 94% of samples, followed by DINP (38% of samples), DIBP (19%), DIDP (13%), and DBP and DNPP (both 6%). On average, the phthalates analyzed were detected in 13% of all samples.

Mutzner et al. (2022) presented a top-10 list of pollutants of high occurrence and risk for surface waters, including seven PAHs and three metals (i.e., BaP, Fluo, Pyr, Cu, Zn, Hg, BbF, Chry, Bper, DahA). In our study, these seven PAHs also had a high occurrence in forebay sediments (81%–100%, Table 3), underlining their importance for stormwater management as suggested by Mutzner et al. (2022). According to Σ16PAHs, analytes with high molecular weight (PAH-H) were detected in all samples (Table 3), PAHs with medium molecular weight (PAH-M) were detected in 94% of samples, and PAHs with low molecular weight (PAH-L) were detected in 44% of samples. Further, when comparing the 16 PAH analytes to those identified by Mutzner et al. (2022), similar trends were evident, i.e., PAHs with a larger number of molecular rings and higher molecular weight had a higher occurrence than PAHs with a low number of molecular rings and molecular weight. A similar tendency was also observed in our study regarding PCBs with high molecular weight (e.g., PCB180, PCB138, and PCB153), which were detected in all samples. Similarly, PCB118, PCB101, and PCB52 were detected in 94% of samples, while PCB28 was only present in 13% of samples. Flanagan et al. (2021) measured organic micropollutants in stormwater pond sediments and found a similar relationship between increased occurrence and decreased molecular weight, e.g., PAHs occurred in 53% of samples, phthalates, including DEHP in 66%, DiNP in 33%, DBP in 31%, and DiDP in 28% of samples, alkylphenols in 38% of samples, PCB101, 118, 138, 153, and 180 in 69%–75%, and PCB28 and PCB53 in 53% of samples. Also, in a study of catch basin sediments, Karlsson and Viklander (2008a) observed that PAHs with low molecular weight were more highly dissolved (<0.45 μm), whereas PAHs with high molecular weight were mainly associated with particulate matter. In contrast, in our study, the occurrence of phthalates and alkylphenols seemed to be related to catchment land use, with industrial land use driving higher concentrations rather than molecular weight, e.g., nonylphenol was more frequently detected than octylphenol, possibly because nonylphenols are more widely used in industry than octylphenols (Bergé et al. 2012). Despite the observed trend between molecular weight and concentration for OMPs, the occurrence and concentration of OMPs in forebay sediments may be influenced by other factors (e.g., discharge and mobilization from catchment areas and affinity of pollutants for particles), including hydrophobicity and solubility. For example, hydrophobic substances may accumulate more extensively in the sediments than more hydrophilic species (Flanagan et al. 2021; Furén et al. 2022), which is supported by results herein.

Concentrations

OMP concentrations in the forebays showed a wide variation between different bioretention cells (Table 3). Only a few previous studies have analyzed OMPs in of bioretention forebay sediments, whereas sediments in sedimentation tanks, catch basins, and bioretention filter material have been evaluated more frequently. Compared with a previous study of bioretention filter materials (Furén et al. 2022), median concentrations of OMPs in forebay sediments in this study were generally higher (Table 3, Fig. 3). However, top layer concentrations in filter material were closer to those in forebay sediments. Furén et al. (2022) reported median Σ16PAHs, PAH-H, PAH-M, and PAH-L in filter material of 1.90 mg/kg (8 mg/kg in top layer), 1.30 mg/kg (5.90 mg/kg in top layer),

Table 3. Occurrence, concentration, and detection limit (DL) of OMPs

Group/units	Substance name	No. of samples	Occurrence > DL		All data			DL
			No.	%	Min	Median	Max	
PAH	Naphthalene (Nap)	16	6	38	<0.05	<0.10	0.30	(0.05–0.30)
(mg/kg, DM)	Acenaphthylene (Acyl)	16	3	19	<0.05	<0.10	0.30	(0.05–0.30)
	Acenaphthene (Acen)	16	4	25	<0.05	<0.10	1.72	(0.05–0.30)
	Fluorene (F)	16	7	44	<0.05	<0.10	2.01	(0.05–0.30)
	Phenanthrene (Phen)	16	12	75	<0.10	0.65	35.7	(0.10–0.30)
	Anthracene (A)	16	10	63	<0.09	0.20	4.06	(0.10–0.30)
	Fluoranthene (Fluo)	16	14	88	<0.10	1.92	60.7	(0.10–0.30)
	Pyrene (Pyr)	16	15	94	<0.16	1.51	45.6	0.30
	Benzo(a)anthracene (BaA)	16	13	81	<0.05	0.66	17.0	(0.05–0.15)
	Chrysene (Chry)	16	15	94	<0.05	0.79	22.8	0.15
	Benzo(b)fluoranthene (BbF)	16	16	100	0.18	1.31	25.7	0.05
	Benzo(k)fluoranthene (BkF)	16	10	63	<0.05	<0.63	9.63	(0.05–0.70)
	Benzo(a)pyrene (BaP)	16	15	94	<0.08	0.75	16.6	0.15
	Dibenzo(a,h)anthracene (DahA)	16	13	81	<0.05	0.18	1.86	(0.05–0.15)
	Benzo(g,h,i)perylene (Bper)	16	15	94	<0.18	0.73	11.5	0.30
	Indeno(1,2,3-cd)pyrene (IP)	16	15	94	<0.11	0.76	9.12	0.15
	PAH sum Low weight (PAH-L)	16	7	44	<0.08	<0.15	1.90	(0.08–0.45)
	PAH sum medium-weight (PAH-M)	16	15	94	<0.19	4.45	150	(<0.19–0.75)
	PAH sum high-weight (PAH-H)	16	16	100	0.26	5.55	110	<0.26
	PAH 16 sum (Σ16PAH)	16	13	81	<1.30	9.95	260	(1.30–3.80)
PCB	PCB 28	16	2	13	<0.10	<0.15	3.60	(0.10–0.50)
(μg/kg, DM)	PCB 52	16	15	94	<0.10	0.32	27.0	0.10
	PCB 101	16	15	94	<0.10	1.10	61.0	0.10
	PCB 118	16	15	94	<0.10	0.75	64.0	0.10
	PCB 153	16	16	100	0.16	1.60	62.0	0.10
	PCB 138	16	16	100	0.14	1.60	54.0	0.10
	PCB 180	16	16	100	0.11	1.45	47.0	0.10
	Sum of 7 PCBs (Σ7PCB)	16	16	100	0.41	6.85	320	<0.40
Phthalates	Dimethylphthalate (DMP)	16	—	0	—	—	—	0.05
(mg/kg, DM)	Diethylphthalate (DEP)	16	—	0	—	—	—	0.05
	Di-n-propylphthalate (DPP)	16	—	0	—	—	—	(0.05–2.00)*
	diisobutyl phthalate (DIBP)	16	3	19	<0.05	<0.05	0.09	(0.05–0.10)
	Di-n-butylphthalate (DBP)	16	1	6	<0.05	<0.05	1.10	(0.05–0.10)
	Di-n-pentylphthalate (DNPP)	16	1	6	<0.05	<0.05	0.051	(0.05–0.30)
	Di-n-octylphthalate (DNOP)	16	—	0	—	—	—	(0.05–0.30)**
	Di-(2-ethylhexyl)phthalate (DEHP)	16	15	94	<0.05	1.50	5.70	0.05
	Butylbenzylphthalate (BBP)	16	—	0	—	—	—	(0.05–1.00)***
	Dicyclohexylphthalate (DCP)	16	—	0	—	—	—	0.05
	Diisodecyl phthalate (DIDP)	16	2	13	<2.50	<2.50	5.10	2.50
	Diisononyl phthalate (DINP)	16	6	38	<2.50	<2.50	11.0	2.50
	Di-n-hexylphthalate (DNHP)	16	—	0	—	—	—	(0.05–0.07)****
Alkylphenols	4-tert-octylphenol (OP)	16	5	31	<0.01	<0.02	0.10	(0.01–0.03)
(mg/kg, DM)	4-nonylphenols (tech.mixture) (NP)	16	9	56	0.06	<0.10	65.8	0.10

Note: Occurrence is reported as number (No.) above DL. *Of 16 samples, 14 nondetects were <0.05, 1 was <0.08 and, 1 was <2.00; ** of 16 samples, 10 nondetects were <0.05, 1 was <0.15, 2 were <0.20, 1 was <0.25 and, 1 was <0.30; *** of 16 samples, 14 nondetects were <0.05, 1 was <0.10 and, 1 was <1.00; and **** of 16 samples, 15 nondetects were <0.05 and, 1 was <0.07.

0.57 mg/kg (2.10 mg/kg in top layer), and <0.15 mg/kg, respectively. However, when comparing concentrations in stormwater sediments with different configurations, e.g., forebay versus filter material, care should be taken since filter samples consist of trapped sediments and filter material, whereas forebays contain only sediment from external sources.

Flanagan et al. (2021) investigated OMPs in stormwater pond sediments. Here, Σ16PAHs medians were 20 times lower (0.64 mg/kg), and median Σ7PCBs concentration of 3.2 μg/kg were about half the median concentration compared with the forebay sediments herein (Table 3). This is somewhat surprising given that ponds often remove smaller sediment fractions, which commonly carry a greater fraction of pollutants. However, in Flanagan et al. (2021), some ponds were included, which received runoff from nonurban land uses and which likely resulted in lower median concentrations. In studies of catch basin sediments, median Σ16PAHs was 4.0 mg/kg DM (Karlsson and Viklander 2008a) and 0.6–24.7 mg/kg (Pun et al. 2019), which is also lower compared with our study. Finally, for sediments from stormwater traps (catch basins) in Norway, Jartun et al. (2008) reported similar PAH (0.2–80 mg/kg) and Σ7PCBs (0.0004–0.704 mg/kg) concentrations to those observed in our study (Table 3, Fig. 4).

Studies on phthalates in stormwater sediment remain limited. Flanagan et al. (2021) reported phthalate DEHP concentrations of 0.05–33 mg/kg (median of 1.3 mg/kg) and concentrations of DiNP of ≤430 mg/kg, DBP of 0.79 mg/kg, and DiDP of 22 mg/kg, thus higher or comparable with those in the bioretention forebay sediments (Table 3, Fig. 5). Liu et al. (2018) assessed

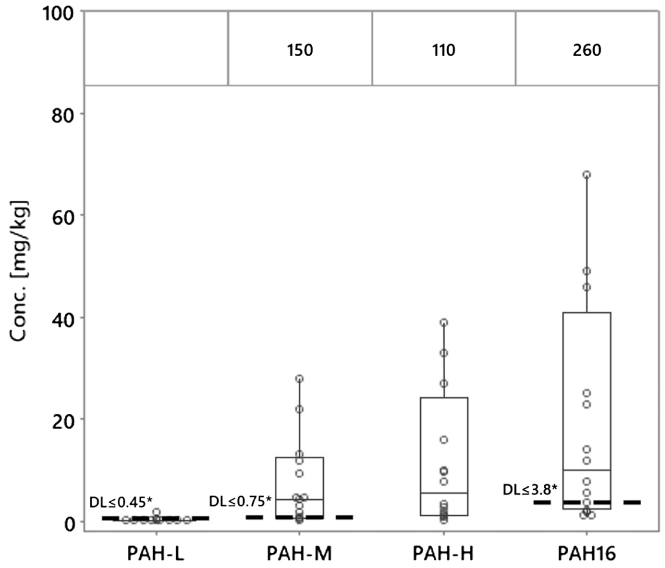

Fig. 3. Individual value plot and boxplot of PAH-L, PAH-M, and PAH-H, Σ16PAHs (mg/kg DM). *Highest DL for PAH-L, PAH-M, and Σ16PAH (Table 3). Outliers above 100 mg/kg DM are indicated as text above each boxplot for plotting purposes.

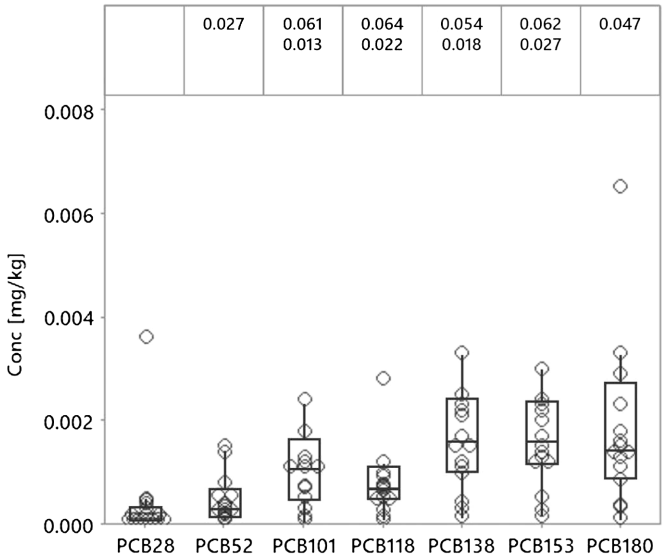

Fig. 4. Individual value plot and boxplot of concentrations of seven PCBs (DL in Table 3). Outliers above 0.008 mg/kg DM are indicated as text above each boxplot for plotting purposes.

removal of phthalates in a bioretention system and concluded that the main treatment of phthalates occurred due to filtration in the filter material rather than through sedimentation in the forebay. In general, concentrations vary with hydrophobicity (Flanagan et al. 2021), also correlated to molecular weight (i.e., heavier molecules showed higher accumulation and were better retained in the sediments), which could explain the high concentrations of PAH-H, PCBs with high molecular weight, DEHP, and NP in forebay sediments.

Comparison to Guidelines

To further assess the forebay sediments, concentrations were compared with national guidance limits. Comparison with the US EPA ecological soil screening levels (Eco-SSL), (USEPA 2023) showed that median concentrations of Cd, Cr, and Pb (Table 2) in the studied forebay sediments were lower than the limits (Table 4) for plants, and those of Cd, Ni, and Pb were lower than the limits for soil invertebrates (USEPA 2005a, b, 2007b). The median concentrations of Cu and Zn exceeded the Eco-SSL (USEPA 2007a, d) guidelines for plants and soil invertebrates.

Sweden has national guidelines (Swedish EPA 2022, 2009) for the classification of soils (Table 4), including "Soil for Sensitive Land Use" (abbreviated SLU) and "Soil for Less Sensitive Land Use" (abbreviated LessSLU). Cd and Cr concentrations did not exceed these limits in any of the forebay samples. Cu exceeded the limit for SLU in four samples and Pb in two samples. Ni exceeded the limits for SLU and LessSLU in one sample, while Zn exceeded the limits for SLU in 13 samples and LessSLU in three samples. A comparison with guidance from the Australian Government National Environment Protection Council (NEPC) and the Measure for Site Contamination (ASC NEPM 2013) in residential areas with garden/accessible soil showed that all concentrations in our study (Table 2; Fig. 2) were lower than the guideline values (Table 4). Similar conclusions were drawn when comparing with UK CL: AIRE (UK charity committed for sustainable land reuse) "Soil Guideline Values" (SGVs) for allotment, residential, and commercial areas (Martin et al. 2009a) and the US 40CFR503 land application standards (USEPA 1993). Thus, according to the US EPA Eco-SSL (USEPA 2023) and Swedish Environmental Protection Agency, Zn was the most concerning metal in the analyzed forebay sediments, i.e., leading to classification that may require disposal of the forebay materials and transport as hazardous waste.

OMP concentrations in forebay sediments were compared to US EPA Eco-SSL (USEPA 2007c) limits for soil invertebrates, which showed that PAH-H exceeded the limit in four samples, whereas PAH-L never exceeded these guideline values. Compared with Swedish national guidance limits for classification of soil (Swedish EPA 2022), PAH-H and PAH-M frequently exceeded the limits for SLU and LessSLU, whereas PAH-L did not exceed these limits. Σ7PCBs exceeded the LessSLU limit in one sample and SLU in seven samples. Thus, according to Swedish EPA guidelines (Swedish EPA 2022), there are environmental risks associated with bioretention forebay sediments.

Conclusions

This study investigated the occurrence and concentration of heavy metals and OMPs in forebays of 28 bioretention cells in the United States and Sweden. Most pollutants considered in this study (i.e., all metals and many OMPs) showed high occurrence and concentrations in the sampled forebay sediments. Compared with previous studies, concentrations of these pollutants were found at similar or higher levels herein. However, when comparing concentrations in forebay sediments with results from previous studies, it is important to distinguish between those in filter material, stormwater sediments, and pond/bottom sediments. Forebay samples mainly consisted of accumulated stormwater sediments, whereas samples of bioretention filter material consist of both of sediments and filter material. Therefore, it is likely that higher concentrations of particulate OMPs are present in forebay sediments compared with the mixture of filter material and accumulated sediments in the top layer of bioretention filter material, which may be one explanation for the high concentrations observed in this study. Moreover, larger stormwater treatment facilities (e.g., ponds and wetlands) often trap finer sediments compared with smaller forebay devices, which makes it difficult to compare the sediment

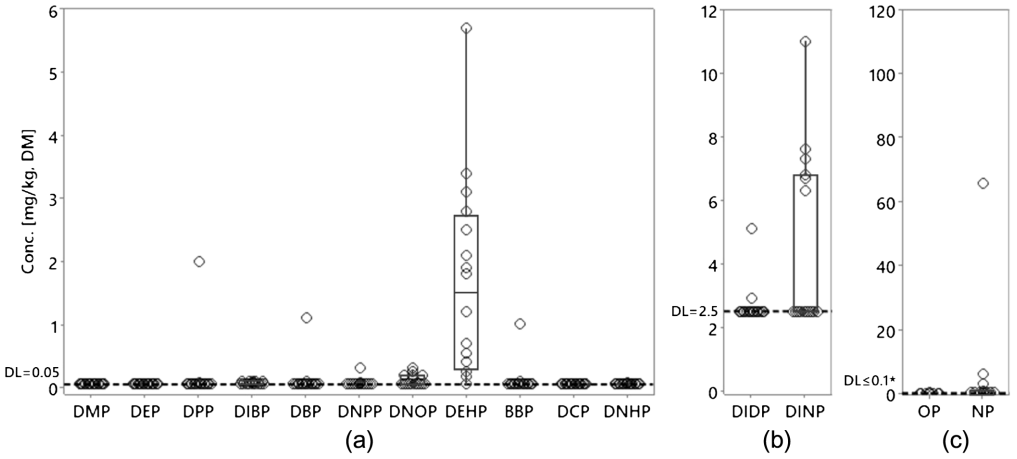

Fig. 5. Individual value plots and boxplots of concentrations of: (a and b) phthalates; and (c) alkylphenols (OP, NP). *Highest $DL_{OP} = 0.03$ mg/kg and $DL_{NP} = 0.1$ mg/kg (Table 3).

Table 4. Guideline limits of the US EPA Eco-SSL, Swedish EPA, Australian NEPC 1999, UK CL:AIRE and US EPA CFR503 together with the number of forebay samples in excess of each standard

Guideline	Classification	Unit	Cd	Cr	Cu	Ni	Pb	Zn	PAH-H	PAH-M	PAH-L	PCB7
US EPA Eco-SSL[a]	Plants	(mg/kg)	32	—	70	38	120	160	—	—	—	—
	Detection	(No)	0	0	5	2	0	23	—	—	—	—
		(%)	0	0	18	7	0	82	—	—	—	—
	Soil invertebrates	(mg/kg)	140	—	80	280	1,700	120	18	—	29	—
	Detection No.	(No)	0	—	4	0	0	25	4	—	0	—
	Detection %	(%)	0	—	14	0	0	89	25	—	0	—
Swedish EPA[b]	KM	(mg/kg)	0.8	80	80	40	50	250	1	3.5	3	0.008
	Detection	(No)	0	0	4	1	2	13	13	9	0	7
		(%)	0	0	14	4	7	46	81	56	0	44
	MKM	(mg/kg)	12	150	200	120	180	500	10	20	15	0.2
	Detection	(No)	0	0	0	1	0	3	5	3	0	1
		(%)	0	0	0	4	0	11	31	19	0	6
NEPC 1999[c]	Residential A	(mg/kg)	20	100	6,000	400	300	7,400	—	—	—	—
	Detection	(No)	0	0	0	0	0	0	—	—	—	—
		(%)	0	0	0	0	0	0	—	—	—	—
UK CL:AIRE [d]	Residential	(mg/kg)	10	—	—	130	—	—	—	—	—	—
	Detection	(No)	0	—	—	0	—	—	—	—	—	—
		(%)	0	—	—	0	—	—	—	—	—	—
	Allotment	(mg/kg)	1.8	—	—	230	—	—	—	—	—	—
	Detection	(No)	0	—	—	0	—	—	—	—	—	—
		(%)	0	—	—	0	—	—	—	—	—	—
	Commercial	(mg/kg)	230	—	—	1,800	—	—	—	—	—	—
	Detection	(No)	0	—	—	0	—	—	—	—	—	—
		(%)	0	—	—	0	—	—	—	—	—	—
40CFR503[e]	Land use	(mg/kg)	85	3,000	4,300	420	840	7,500	—	—	—	—
	Detection	(No)	0	0	0	0	0	0	—	—	—	—
		(%)	0	0	0	0	0	0	—	—	—	—

Note: Further description of the guidelines in Supplemental Materials Section 3.
[a]USEPA (2023).
[b]Swedish EPA (2022, 2009).
[c]NEPC (1999).
[d]UK, CL:AIRE (Martin et al. 2009b, c).
[e]40CFR503 (USEPA 1993).

concentrations in different studies. Despite the higher fraction of fine sediment in larger facilities, the sediments from the smaller forebay devices in this study had higher metals and OMP concentrations compared with previous studies.

Similarities and variations in concentrations in the forebay OMPs and metals concentrations occurred between and within pollutant groups (metals, phthalates, alkylphenols, PAHs, and PCBs). These may be related to different substance properties,

e.g., mobility, solubility, attachment to particles, and, for OMPs, hydrophobicity.

The main conclusions of this study are as follows:

- Most examined substances showed high occurrence in the sediment samples collected from the bioretention forebays. All six analyzed metals were detected in all forebay samples, except Cd (detected in 27 of 28 samples), and 31 of 38 investigated OMP analytes were detected in at least one of 16 samples.
- High concentrations were generally detected in the forebay sediments. Zn and PAHs with high and median high molecular weight and PCBs were frequently detected at concentrations above soil quality guidelines (Swedish EPA 2022; USEPA 2023). Cu and Ni were also detected above soil quality guidelines (Swedish EPA 2022).
- Pollutant concentrations in sediments herein were generally similar or higher than those found in previous studies. However, only a few studies have considered forebay sediments; comparisons with previously published values are complex and should be treated with caution. More research is needed to enhance the scientific understanding of toxic pollutant accumulation in bioretention forebays.
- Since forebays regularly need to be excavated to maintain their function, it is important that sediments are handled safely during maintenance work and final disposal.

Data Availability Statement

Some or all data, models, or code generated or used during the study are available in the data repository found in Beryani et al. (2024) in accordance with funder data retention policies.

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Supplemental Materials

Figs. S1.1–S1.22 and Tables S1–S2 are available online in the ASCE Library (www.ascelibrary.org).

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